

Carbon Footprint of Food Products

Elin Rööös, Cecilia Sundberg and Per-Anders Hansson

Abstract The food system has been identified as one of the major contributors to climate change. The main sources of greenhouse gas emissions are nitrous oxide (N₂O) from soils, methane (CH₄) from enteric fermentation in animals, and carbon dioxide (CO₂) from land use change, such as deforestation. Emissions also arise from manure management, mineral fertilizer production, rice cultivation, and energy use on farms and from post-farm activities such as processing, packaging, storage, distribution, and waste management. With increasing awareness of climate change, calculating the carbon footprint (CF) of food products has become increasingly popular among researchers and companies wanting to determine the impact of their products on global warming and/or to communicate the CF of their products to consumers. This chapter discusses issues that are especially relevant when calculating the CF of food products, such as the choice of functional unit, which is challenging owing to the multifunctionality of food. Other issues concern how to include emissions arising from indirect land use change and removal of CO₂ from the atmosphere by carbon sequestration in soils into CF calculations. Causes of the large uncertainties associated with calculating the CF of food products and ways to handle this uncertainty are also discussed and examples of uses and results of CF of food products are presented. Despite the large uncertainties, it is clear that the differences in CF between different types of food products are very large. In general, the CF of livestock-based products are much larger than those of plant-based products. CF information on food products may be useful in business-to-business communication, for professionals in the retail sector and in public procurement.

Keywords Functional unit · Land use change · Methane · Nitrous oxide · Uncertainty

E. Rööös (✉) · C. Sundberg · P.-A. Hansson
Swedish University of Agricultural Sciences, Department of Energy and Technology,
Box 7032 750 07 Uppsala, Sweden
e-mail: elin.roos@slu.se

1 Introduction

The food chain in the Western world is highly industrialized. Manpower has been replaced by mechanical power, fueled by fossil energy. As a consequence of farm industrialization and production of mineral fertilizers using fossil natural gas, the amount of food produced has greatly increased, making nutritionally rich food products available to large populations. However, this ‘green revolution’ is placing serious stress on ecosystems. Agriculture is resource-intensive, requiring large amounts of land, water, and finite resources such as fossil fuels and phosphorus. Losses of nitrogen from the agricultural system contribute to global warming, and to eutrophication and acidification in surrounding ecosystems. Biodiversity is threatened by the use of pesticides and in some areas by the rationalization and intensification of agriculture, which is causing the disappearance of the traditional mosaic agricultural landscape that is home to a number of red-listed species. Expansion of agricultural land into natural forests, scrubland, and savannah in other areas poses a serious threat to many endangered species. Post-farm stages in the food chain include processing, packaging, transport, storage, food preparation, and waste management, all requiring the use of energy.

The food system has been identified as one of the major contributors to climate change (EC 2006). In Sweden, it is estimated that approximately 25 % of greenhouse gas (GHG) emissions from private consumption are related to the activity of eating (SEPA 2008). In the European Union (EU), the corresponding figure is estimated to be 31 % (EC 2006), while EU member states have reported values in the range 15–28 % (Garnett 2011). Unlike GHG emissions from the energy and transport sector, the emissions from agriculture are not dominated by carbon dioxide (CO₂) from fossil fuel combustion, but by methane (CH₄) and nitrous oxide (N₂O). The CO₂ from land use change, such as deforestation driven by the demand for agricultural goods, is also a major contributor to GHG emissions from the food system (Figs. 1, 2).

CH₄ emissions arise predominantly from enteric fermentation in ruminants, but also from manure management and rice cultivation. Enteric fermentation is the

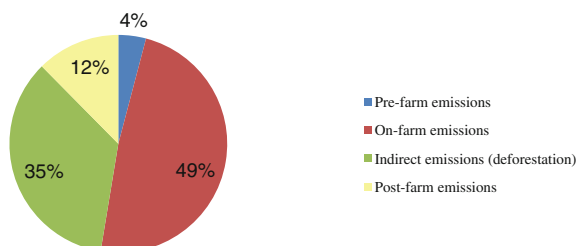
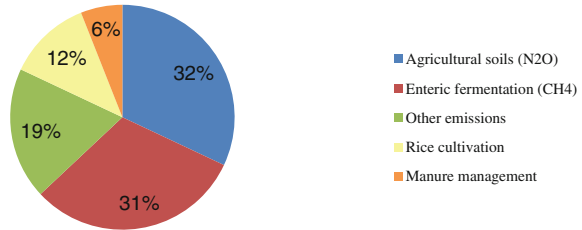


Fig. 1 The contribution of emissions of greenhouse gases in the food system (CCAFS 2013). On-farm emissions are further subdivided in Fig. 2. Pre-farm emissions are dominated by emissions from fertilizer production. Post-farm emissions include refrigeration, storage, packaging, transport, retail activities, production, waste disposal, etc.

Fig. 2 Contribution of global on-farm (direct) emissions of greenhouse gases from agriculture (CCAFS 2013)



process by which the carbohydrates in the feed are broken down by microorganisms in the rumen, a multi-chambered stomach of animals such as cattle and sheep, into simple molecules that can be taken up by the blood. This enables ruminants to digest feed rich in cellulose, such as grass and straw, which is not possible for humans or other monogastric (single-stomach) animals, such as pigs and poultry. However, CH₄ is formed in the rumen as a by-product of the fermentation process and released to the atmosphere with the exhaled air. CH₄ has a 25-fold higher global warming potential (GWP) than CO₂ in a 100-year perspective and 72-fold higher GWP in a 20-year perspective (IPCC 2007). N₂O is an even more potent GHG, with 298-fold higher GWP than CO₂ in a 100-year perspective. N₂O is formed through nitrification and denitrification, two biological processes that are naturally occurring in all soils to a greater or lesser extent, depending primarily on the amount of available nitrogen, but also on soil carbon and water content, pH, and temperature. Due to the high rates of mineral and organic fertilizers applied to agricultural soils, N₂O emission from soils is a major contributor to climate change within food production. N₂O is also formed and released during the production of mineral fertilizers and during storage of manure in aerobic conditions (Smith et al. 2007). Global emissions of GHG from agriculture are illustrated in Fig. 2.

With the increased awareness of climate change, spurred by the release of the Fourth Assessment Report of the IPCC in 2007, calculating the carbon footprint (CF) of food and other products has become increasingly popular. The CF is now being calculated by companies wanting to learn more about the impact of their products on global warming and/or to communicate the CF of their products to consumers (e.g., Tesco 2012; Lantmännen 2013; MAX 2013). Research into the CF of food products has also increased in recent years. It has included studies of the methodological complexities in calculating the CF of food and calculations of the actual CF of different food products and foods from different production systems (Roy et al. 2009; de Vries and de Boer 2010; Nijdam et al. 2012; Rööß et al. 2013).

This chapter examines some issues that are especially relevant when calculating the CF of food products, with the emphasis on the causes and consequences of uncertainty. The functions of food are multiple: it can provide different types of nutrients and/or pleasure, act as a status marker, or form part of cultural traditions. Therefore, choosing the functional unit is not easy as discussed in Sect. 2.1. Challenges as regards drawing system boundaries and allocating climate impacts arise in all CF calculations and some examples of how these challenges can be handled in

food CF calculations are given in [Sect. 2.2](#). Food production requires large areas of land, so direct and indirect effects on carbon stocks and emissions arising from land use change (e.g., deforestation) and carbon sequestration are discussed in [Sects. 2.3](#) and [2.4](#). The risk of pollution swapping when focusing on one environmental aspect only, e.g., the impact on climate change, is discussed in [Sect. 2.5](#). [Section 3](#) provides a more lengthy discussion of different types of uncertainties and variations when assessing the CF of food products, while [Sect. 4](#) gives some examples of uses and results. Some conclusions are given in [Sect. 5](#) while the chapter ends by highlighting some future challenges and research needs in [Sect. 6](#).

2 Challenges in Calculating the Carbon Footprint of Food Products

The CF describes the amount of GHG emissions that a particular product or service will cause during its lifetime, typically expressed in CO₂ equivalents (CO₂e) and including emissions of CO₂, CH₄, and N₂O. A CF can be seen as a subset of a life cycle assessment (LCA) in which only the climate change impact category is studied. LCA is a standardized method for quantifying the environmental impact caused during production, use, and waste management of a product or service.

2.1 Functional Unit

Food has several functions, but the functional unit (the reference unit used in the calculations) most commonly used in LCA and CF studies on food products is based on mass (e.g., 1 kg of the food product being studied) (Schau and Fet 2008). A reference to the system boundaries ([Sect. 2.2](#)) is sometimes included, so the functional unit can be, for example, “*the production of 1 kg of tomatoes at the farm gate.*” As in all LCA studies, it is important that the functional unit is chosen so that products can be compared fairly. LCA studies on milk, for example, commonly use a metric that accounts for differences in nutrient content, such as Energy Corrected Milk (ECM), which includes a measure of the fat and protein content in the milk (Sjaunja et al. 1990).

The basic function of food is to provide nutrients. Because the nutrient content varies between food products, the function of food is different for different food-stuffs. For example, most would agree that comparing 1 kg of tomatoes with 1 kg of meat is not a fair comparison, because the meat provides different nutrients than the tomatoes and considerably more energy. Fundamentally, different foods such as meat and vegetables could be compared more fairly using a nutritional index that includes a number of nutrients, such as proteins, carbohydrates, fats, vitamins, and minerals, and weighing these together, such as according to their recommended

daily intake (Kernebeek et al. 2012; Saarinen 2012). For comparing food products that are more similar in nutrient content, a simpler functional unit could be used. For example, in the Western diet, livestock products are important sources of protein, so “*the production of 1 kg of protein*” has been used as a functional unit for comparing different livestock products and other protein-rich food products suitable for use as alternative protein sources (e.g., Nijdam et al. 2012).

Another important function of food is to provide pleasure. Food is also an important part of many cultural celebrations and can act as marker of status and class (Guthman 2003). In the affluent world with its abundance of food, these other functions of food might be more important than the pure nutritional aspect for certain products and in certain situations. Dutilh and Kramer (2000) include the emotional value of food in the functional unit to account for this aspect. Additionally, for populations in which obesity is a major health threat, the most nutrient-dense food products should perhaps not be valued highest. Rather, food products providing as little energy and as much pleasure as possible may be demanded (Tillman 2010).

An illustrative example of the importance of reflecting on the function of food concerns beverages, which can have many functions; to provide nutrients, intoxication, water, or just to wash down food. Smedman et al. (2010) argued the need to include the nutritional aspect when comparing milk with other beverages such as orange juice, soy drink, beer, etc., and developed an index (Nutrient Density to Climate Impact) which included 21 essential nutrients and the GHG emissions from a life cycle perspective from the production of the beverage. According to this index, milk was the most beneficial beverage of all those included in the study, although milk had a CF per unit mass (kg) that far exceeded that of orange juice, mineral water, soy, and oat drink. It is questionable whether using this nutritional index is relevant in all contexts. Obviously, if the beverage is to be consumed in areas with protein and micronutrient deficiency, it is highly relevant to include nutritional aspects in the functional unit. However, in areas with overconsumption of most nutrients, it could be argued that the function of milk as a beverage is rather to wash down food and provide water, in which case a more appropriate functional unit could be 1 kg or 1 L of beverage when comparing milk with other beverages.

Although the production of food is usually the prime function for keeping livestock, animals can have other important functions too. One function could be to avoid afforestation in order to preserve land for future agricultural production. In some areas, grazing livestock is kept to help preserve biodiversity by providing a grazing pressure that keeps highly competitive grasses short so that other plants can flourish. From the farmer’s perspective, income is the key function of keeping livestock (Nemecek and Gaillard, 2010). In developing countries, livestock may supply various functions such as draft power, soil management, and financial insurance.

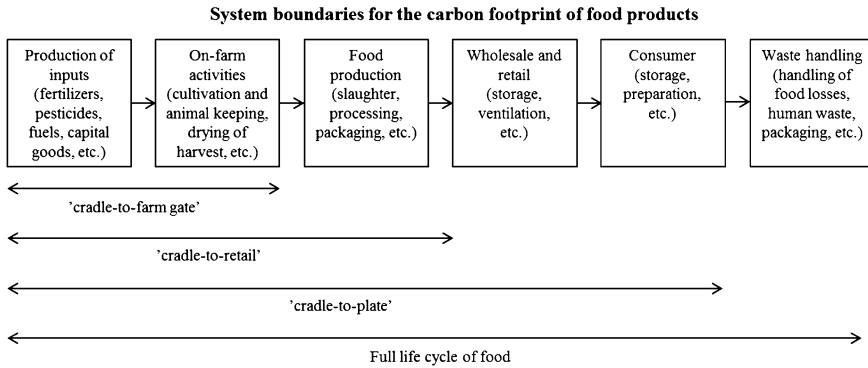


Fig. 3 Different ways of setting the system boundaries commonly used when calculating the carbon footprint of food products

2.2 System Boundaries and Allocation

In LCA and CF calculations, the system under study needs to be isolated from the natural system and the surrounding technical system. In the strictest sense, a CF study should include all emissions from the entire life cycle (Fig. 3). However, emissions beyond the point at which food ends up on the plate are very rarely included in CF calculations on food products (Munoz et al. 2008). Even ‘cradle-to-plate’ studies tend to be scarce, with the majority of studies being ‘cradle-to-retail’ or ‘cradle-to-farm gate’ (Schau and Fet 2008). The reasons for ending at retail are two-fold. First, the emissions from transporting the food products to the household, i.e., by foot, bicycle, car, or public transport, and from preparing the food (e.g., by either eating the food raw, frying or cooking it), as well as the amount of food wasted can vary greatly, therefore making it difficult to include these phases in a representative way. Second, although producers can somewhat influence (e.g., the energy needed when preparing the food), these post-retail steps are primarily controlled by the consumer, so it is justifiable to end the analysis before these consumer-oriented phases when looking for, for example, mitigation options for the producer. There are also several reasons why many studies end at the farm gate. One is that post-farm emissions have been shown to be small, and/or highly variable, for example, depending on transport distance, compared with emissions arising at the farm or from up-stream processes, especially for livestock products (Schau and Fet 2008). In addition, in some cases, such as if the purpose of the study is to evaluate, for example, different feeding strategies for pigs or different ways of heating a greenhouse, there is no need to include post-farm stages as these would be the same for all scenarios. The purpose of the study usually determines the phases in the life cycle that need to be included and those that can be omitted.

An interesting boundary consideration with regard to food arises when wild game meat is considered (i.e., meat from animals not controlled by humans). Many game animals such as moose and deer are ruminants and emit CH₄ from enteric

fermentation. Although these emissions are smaller than those from farm animals, they are not negligible on a per animal basis (IPCC 2006a). However, emissions from wild animals are not reported in national inventories under the Kyoto protocol because they are considered part of the natural ecosystem and their emissions are not anthropogenic. Should they then be included in the CF of meat from wild game? And if game animals feed on arable crops, should part of the emissions from the cropping system be allocated to the game meat? There is no obvious answer to these questions, but one basic reason for not including these emissions is that the amount of wild game is maintained at a 'natural' level. If game numbers are deliberately increased, such as by feeding, it is much more difficult to justify exclusion of the emissions from the game animals from the CF of the game meat.

As in most LCA, issues regarding co-product allocation (how to divide emissions from a joint production system on the co-products) arise in CF studies of food products. Livestock production results not only in food, but also, for example, in manure, leather, and wool. During production of many plant-based food products, animal feed is produced as a by-product, such as molasses from sugar production, oilseed meal from vegetable oil production, and stillage from ethanol production. The allocation problem is solved using classical LCA strategies, such as system expansion and economic and physical allocation.

One of the most widely researched areas when it comes to the allocation problem in food CF is the allocation of emissions between milk and meat in milk production systems that inevitably also produce meat and calves as by-products. Flysjö et al. (2011) investigated six different ways of allocating emissions between milk and meat for dairy farms in Sweden and New Zealand, comparing allocation based on the mass, protein, economic value, and amount of feed needed to produce milk and meat, respectively. Furthermore, two ways of system expansion were investigated. In the first of these, it was assumed that meat originating from the milk production system replaced suckler beef on the market, while in the other it was assumed that dairy beef replaced a mixture of suckler beef, pork, and poultry. The CF values obtained varied between 0.63–0.98 kg CO₂e/kg ECM for milk from New Zealand and between 0.73 and 1.14 kg CO₂e/kg ECM for Swedish milk depending on how allocation was made. This considerable variation shows the importance of using the same allocation method when comparing different food products.

2.3 Land Use Change

Agricultural production differs from industrial production in the very important regard that it uses and affects large areas of land. Use of land causes direct emissions of CO₂, CH₄, and N₂O, as discussed in the introduction to this chapter. Increased demand for food due to an increasing global population and an improved standard of living in many developing countries is leading to increased demand for agricultural land. This is leading in turn to the conversion of forests and scrubland

into pastures and cropland, and of natural grassland into cropland. This process is called land use change (LUC) and accounts for approximately 10 % of global CO₂ emissions (Global Carbon Project 2013). These emissions of CO₂ originate from standing biomass that is either burnt on the spot, removed and burnt, or used elsewhere. Considerable amounts of CO₂ are also released from soils once they are cultivated, as the carbon bound in the soil starts to oxidize.

Currently, most of the deforestation driven by demand on the global food market is taking place in Southeast Asia, in order to make way for palm oil plantations, and in South America, in order to make way for pasture for beef production and cropland for soybean production (UCS 2011). The production of soybean is driven by the demand for soybean meal as a protein feed for livestock, especially for dairy cows, pigs, and poultry. The EU imports over 20 million tons of soybean meal annually for use in livestock production (Eurostat 2011).

Deforestation cannot be blamed solely on increased demand for food on the global market because there are also other causes, including demand for lumber and biofuels, as well as subsistence farming in some parts of the world. However, there is now a growing consensus in the scientific community that a large proportion of the emissions from LUC should be attributed to food products (UCS 2011; Houghton 2012). However, quantifying the emissions from LUC and allocating them to food products involve a number of methodological challenges (Sect. 3.4).

2.4 Carbon Sequestration in Soils

Cultivation of soils can result in either net emission of CO₂ to the atmosphere or net sequestration of carbon, depending on soil characteristics, carbon input, and management practices (Powlson et al. 2011). Soils that are rich in carbon require large inputs of organic material in order to remain at carbon equilibrium and not lose carbon when cultivated. Organic soils (i.e., soils containing 20–30 % organic matter or more) are most commonly net emitters of CO₂ when cultivated. In contrast, many mineral soils (i.e., soils containing only a few percent of organic matter) lose as much carbon as they sequester during cultivation and hence remain at carbon equilibrium and do not contribute to climate change by releasing CO₂ to the atmosphere. Natural grassland, which has fast-growing biomass and undisturbed soils, is capable of sequestering large amounts of carbon (Soussana et al. 2007). When this sequestration of CO₂ from the atmosphere is taken into account in calculating the CF of meat products from animals grazing natural grassland, the CF value obtained can be heavily reduced because the carbon uptake compensates for the emissions from enteric fermentation and feed production (Pelletier et al. 2010; Soussana et al. 2010; Veysset et al. 2011). However, inclusion of carbon sequestration in the CF of food products raises several methodological issues. Perhaps the most important of these is that sequestration of carbon is a reversible process. If management practices are changed, for example, if the grassland is later

plowed under and cultivated or if biomass growth is hampered by drought, the sequestered carbon will slowly be emitted to the atmosphere as CO₂ again (Soussana et al. 2007). Furthermore, measurements of carbon sequestration are highly uncertain and it is unclear whether the sequestration process can continue indefinitely. Current knowledge in soil science states that the potential for soils to sequester carbon will cease with time as the soil reaches a new equilibrium (Powlson et al. 2011; Smith 2012). In addition, animals are not essential for retaining grassland, as the biomass could potentially be used for energy production (e.g., in a biogas reactor). Hence, there is as yet no consensus on whether and how carbon sequestration in soils should be included in the CF of food products.

2.5 Risk of Pollution Swapping

The use of CF as a sustainability indicator has been criticized by both industry and the research community because it focuses solely on the environmental aspect of global warming. Rockström et al. (2009) noted that several areas of environmental pressure need urgent attention. Agriculture and food production affect the environment in several ways. The nitrogen and the phosphorus cycles are placed under heavy stress due to the large amount of fertilizers used on fields, which cause eutrophication due to leakage of nutrients into waters and surrounding land. Ammonia emissions from manure handling cause both eutrophication and acidification, and pesticide use causes the spread of toxic substances in the ecosystem. Modern agriculture also uses considerable amounts of energy and is dependent on finite resources such as fossil fuels. In areas where irrigation is used, freshwater resources are often overused and in many areas soils are depleted or eroded. Agricultural land expansion has also been identified as the main cause of global biodiversity loss (MEA 2005). Hence, it is important to include not only the CF but more environmental categories in a full sustainability assessment, especially for food, which has such a large impact in many impact categories (Röös and Nylinder, 2013).

To investigate how well the CF functions as an indicator of the wider environmental impacts from the production of meat, Röös et al. (2013) carried out a study in which results from a large number of LCA on meat were compared with regard to how the CF correlated with other environmental aspects. It was found that in most cases there was a good correlation between the CF and the eutrophication and acidification potential. Hence, for products having a large CF, the emissions of eutrophying and acidifying substances were also high. This is explained by all these impact categories being involved with the nitrogen cycle. Hence, using nitrogen efficiently in agricultural systems, such as by applying a well-adapted amount of fertilizer at a time when plant uptake is high and by reducing losses from manure management, is beneficial for both reducing N₂O and substances causing eutrophication and acidification, such as ammonia and nitrate. However, it is important to remember that the severity of the actual impact on the ecosystem from the release of eutrophying and acidifying substances is heavily

dependent on local conditions, such as proximity to streams and coasts. Rööös et al. (2013) also found that energy use and land use were correlated to the CF in most cases, with the important exception of extensive beef production, which can have very low energy use but a high CF due to emissions from enteric fermentation.

In the case of impacts on biodiversity and ecotoxicity, however, care must be taken when using the CF as a sustainability indicator for food products. It is unclear how CF correlates to biodiversity, and it is probably very difficult to establish this on a general level because biodiversity is a very complex and highly site-specific impact category. Beef production can have a very negative impact on biodiversity if it leads to deforestation (Cederberg et al. 2011), but it can have a positive effect on biodiversity if grazing conserves semi-natural pastures supporting many endangered species that need open areas to thrive (Cederberg and Dareljus 2001; Cederberg and Nilsson 2004). Regarding leakage of toxic substances from agriculture causing ecotoxicity effects, there is also a risk of conflict when focusing on decreasing the CF of food products. Pesticide production and use cause small GHG emissions, but pesticide use can heavily influence yield levels. Because high yields are beneficial for low CF per kg of food product, there is a risk of a reduced focus on minimizing pesticide use if the prime focus is reduction of GHG emissions.

3 Uncertainties and Variation

3.1 Introduction to Uncertainties and Variation

The accuracy and precision of the CF of food products are affected by uncertainty and variability in input data and uncertainty in the models used to calculate emissions from soils, animals, manure, and LUC, for example. Added to this is the uncertainty introduced by LCA modeling choices, such as the choice of functional unit, allocation strategies, and system boundaries.

Uncertainty arises due to lack of knowledge about the true value of a parameter. Uncertainty can be improved by more and better measurements. Consider, for example, the uncertainty in potato yield from one specific hectare of land during a certain year. The yield is commonly estimated by calculating the number of boxes filled in the field at harvest. On average, one full box has an established weight and the total yield per hectare can be calculated by multiplying the number of boxes filled by this weight and divide that the number by the number of hectares in the field. The uncertainty in this measurement could be reduced by weighing every box of potatoes coming from a specific hectare of land. That would increase the accuracy in yield measurement and reduce the uncertainty to that deriving mainly from the measuring equipment.

Uncertainty in measurement should be distinguished from variability. Variability arises from the inherent heterogeneity of a parameter. Consider the potato

yield estimate again. The yield can vary considerably between and within fields, farms, and years due to a number of uncontrollable and controllable reasons, such as weather and soil conditions, access to water and nutrients, variety used, management practices, and pest attacks. Variability cannot be reduced by improved measurement because it is a property of the parameter described. However, improved measurements can help to more accurately describe the variability of a parameter, such as using a probability distribution.

3.2 Variability in Agricultural Systems

Variability in agricultural systems is very large. Varying soil conditions give rise to different amounts of GHG being emitted from the soil (Sect. 3.3) and to some extent determine what crops can be cultivated, how much fertilizer is applied, etc. Organic soils, which are very rich in carbon, give rise to very large emissions of CO₂ and N₂O (Berglund and Berglund 2010), while some soils, especially those used for permanent pasture, can take up CO₂ from the atmosphere and store it as stable carbon compounds in the soil (Sect. 2.4) (Soussana et al. 2007; Powlson et al. 2011).

Yield is an important variable when calculating the CF of food products, as the emissions from soils, machinery, and inputs used on an area of land are distributed across the output from that area. Hence, greater yield gives lower GHG emissions per kilogram of product. Yields can vary greatly even within the same area. For example, Rööös et al. (2011) studied wheat production in southern Sweden and found that the yield on approximately 300 farms varied between 3.7 and 11 tons per hectare (95 % confidence interval) during a period of 8 years. The amount of nitrogen fertilizer applied varied between 49 and 357 kg per hectare. The amount of nitrogen fertilizer applied is an influential variable for the CF, as it stimulates N₂O emissions from soil and gives rise to CO₂ and N₂O emissions from the production of mineral fertilizers.

In livestock systems, yield in terms of milk, eggs, and meat produced per year and animal also influences the CF of livestock products. Livestock animals that grow rapidly or produce large amounts of milk or eggs in relation to the feed consumed are favorable from a climate perspective, as less feed needs to be produced. For meat from ruminants, the lifetime of the animal is crucial, as emissions are dominated by emissions from enteric fermentation. The longer the animal lives, the more CH₄ is released.

Variation in livestock yield is very large. From a global perspective, variation in milk yield is enormous, as shown Fig. 4. This reflects the great variation in agricultural management systems globally, from subsistence systems in which the animals provide several functions (milk and meat for food, manure for fuel, draft power, and financial insurance) to the highly industrialized and specialized systems of the developed world. However, even within regions the variation is large. For example, Henriksson et al. (2011) studied milk production in Sweden and

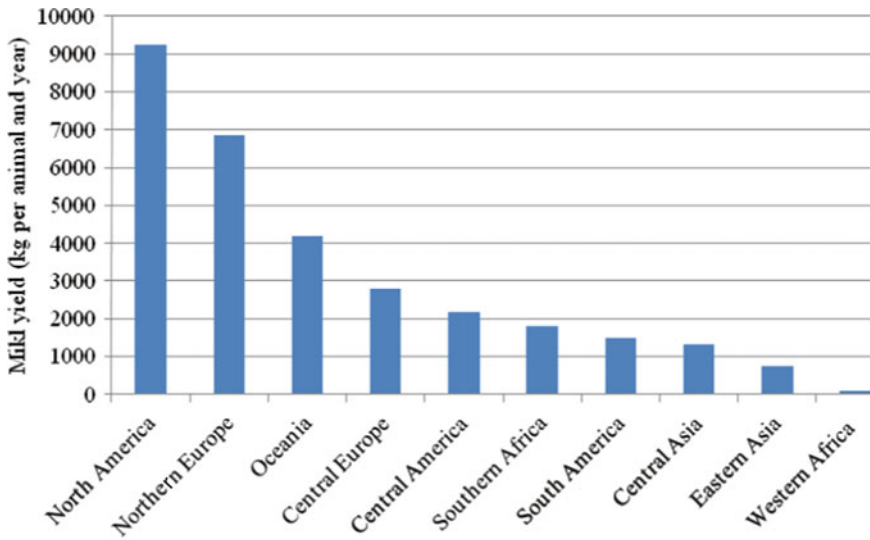


Fig. 4 Average milk yield in 2011 in different parts of the world (FAOSTAT 2011)

found that average farm-level yield varied between 6,000 and 12,000 kg ECM per cow and year.

Apart from yield levels, variability is also large when it comes to feeding strategies, manure management, fertilizer use and energy use in field machinery, greenhouses, and barns. In addition, when food ingredients leave the farm and are processed into food products sold in retail or to restaurants, food ingredients from different sources and places are mixed and are often difficult to trace back to the farm, making the CF of the finished food product uncertain for that reason. For example, wheat that is milled to flour is often a mixture of wheat from several different farms and even countries to establish an appropriate quality of the flour. Furthermore, in baking, pasta making, etc., several kinds of flour and other ingredients are commonly used in recipes.

The inherent variability in agricultural production systems makes it difficult to establish general conclusions regarding the CF of different types of food products, although a general division between livestock-based and plant-based products can usually be made for most products. This is further exemplified and discussed in [Sect. 4](#).

3.3 Uncertainties in Emissions from Soil, Animals, and Manure

Figure 5 shows emissions from the production of pasta. The processes that contribute most to the CF of pasta are N_2O emissions from soil and the production of mineral nitrogen fertilizer (CO_2 from energy consumption and N_2O formed as a

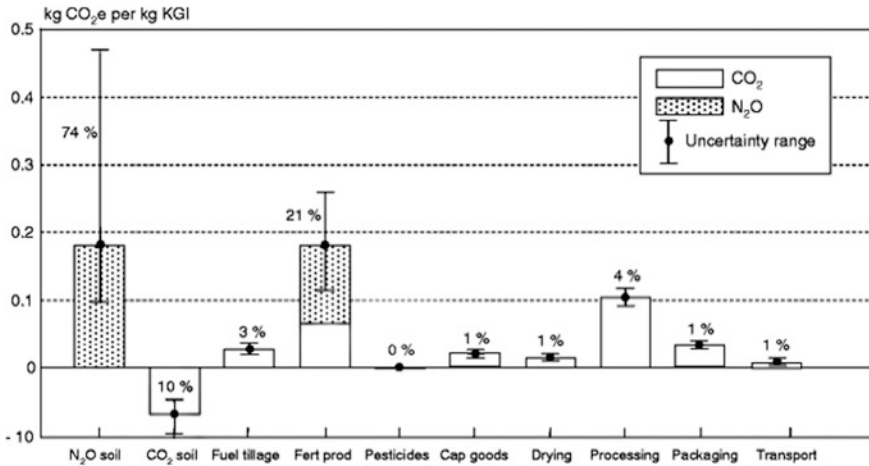


Fig. 5 Emissions of GHG from the production of Swedish pasta (KGI is short for Kungsörnens Gammeldags Idealmakaroner, which is a pasta variety made from Swedish wheat) (from Rööös et al. 2011)

by-product during the production of nitric oxide). These two processes also show the largest uncertainty; the uncertainty range for N₂O emissions from soil is 74 % of the total CF and that for mineral fertilizer production is 21 %.

The large uncertainty in the emissions from fertilizer production stems from the uncertain origin of the mineral fertilizer. If the production plant is equipped with N₂O cleaning, emissions are greatly reduced. It is difficult to know at the farm level where fertilizer has been produced, hence the large uncertainty in this process. However, this uncertainty could be reduced with labeling of fertilizers or improved traceability in some other way.

The emissions of N₂O from soil, on the other hand, are difficult to model with higher precision. In the pasta example used here, as in most LCA and CF studies, the IPCC model for calculating N₂O emissions from soil was used (IPCC 2006b). This is a very simplified model of the complex soil processes giving rise to N₂O emissions. It only considers application of nitrogen through mineral and organic fertilizers and crop residues, although it is well established that the formation of N₂O depends on many factors, such as the carbon and oxygen availability in the soil, temperature, and soil pH. In the IPCC model, 1 % of applied nitrogen is assumed to be lost as direct N₂O emissions from agricultural fields, while N₂O is also lost due to nitrogen leakage and volatilization (indirect emissions). IPCC (2006b) also provides uncertainty ranges for the N₂O emission factors, which when used by Rööös et al. (2011) in the study on pasta gave large uncertainty in the emissions of N₂O from soil (Fig. 5). There are several more advanced models that can be used to predict N₂O emissions, such as the Coup model (Jansson and Karlberg 2004), which models heat and water flows in a deep soil profile with plant and atmospheric exchange. However, most of these models require detailed

soil and climate data that are not readily available at farm level. In addition, although advanced models are highly valuable when trying to understand the underlying processes leading to N₂O formation, they are less useful when it comes to calculating CF due to the great variability in N₂O emissions. The variability in emissions can be just as large as the IPCC uncertainty ranges (Nylinder et al. 2011), so when estimating annual N₂O emissions in order to calculate the CF of a food product, more precise estimates are not guaranteed just because a more complex model is used.

For food products originating from ruminants (milk and beef), total emissions are dominated by emissions from enteric fermentation. Such emissions are known to depend on the amount of feed consumed by the animal and the type of feed, especially its digestibility (Shibata and Terada 2010). Emissions from enteric fermentation can be measured by either enclosing the complete animal in an airtight chamber or by using tracer techniques (Johnson and Johnson 1995). Such measurements are used for developing empirical models that can be applied to predict the emissions from enteric fermentation (e.g., Moe and Tyrrell 1979; Kirchgessner et al. 1995; Mills et al. 2003; IPCC 2006a). These models take different feed characteristics as input, such as the amount of fiber, protein, fat, and cellulose. The ability of these methods to accurately predict CH₄ emissions is limited; when evaluated against different datasets of measured emissions, most equations show a mean square error of 20–40 % (Wilkerson and Casper 1995; Mills et al. 2003; Ellis et al. 2007, 2010).

Emissions from manure handling also arise due to biological processes that are difficult to control and model. Most LCA and CF studies use emissions factors provided by the IPCC, but the uncertainty in these models is substantial. For example, the emissions factor for direct N₂O emissions from manure management has an uncertainty range of –50 % to +100 % (IPCC 2006a).

3.4 Modeling Land Use Change

When modeling emissions from LUC, the concept is commonly divided into direct LUC and indirect LUC. Direct LUC is directly associated with the production of food or feed. For example, if natural forests are cleared and the land used to grow soybeans, it could be argued that the soybean grown on that land should bear some, or all, of the burden of emissions from deforestation. That would represent accounting for emissions from direct LUC. The question of ‘amortization period,’ i.e., the number of years after deforestation over which the emissions from deforestation should be divided, is an arbitrary choice. The period is commonly set to 20 or 30 years. The choice of amortization period can greatly influence the results (Cederberg et al. 2011).

There is still no consensus in the scientific community regarding how emissions from LUC should be included in the CF. Some studies that included emissions from direct LUC did not simply allocate the emissions from deforestation to the

crops produced on the newly deforested land. Rather, they took yearly emissions from deforestation of land later used to grow a specific crop, such as soybean, and divided these emissions across all soybean produced in that region or country, irrespective of whether it was produced on newly deforested land or existing cropland (Meul et al. 2012; van Middelaar et al. 2013). This is not direct LUC emissions in its strictest sense, which would involve allocating emissions from deforestation solely to soybean grown on the newly deforested land. It could be wise to introduce different terminology, such as semi-direct LUC emissions, for this way of handling emissions from LUC (Röös and Nylander 2013).

Emissions from indirect LUC arise when the demand for one crop causes other crops to be displaced into areas that are deforested. Emissions from indirect LUC are very difficult to estimate because they cannot be directly observed. In the field of biofuels, the issue of indirect LUC has been studied intensively (Broch et al. 2013). Advanced economic equilibrium models have been frequently used in attempts to predict how the global agricultural sector will react to the increased demand for different crops, based on actual economic data and statistics on agricultural productivity, land availability, and other constraints in different countries. The results obtained using these models have been highly variable, ranging from emissions of -90 to $+220$ g CO₂e per MJ fuel from LUC (Di Lucia et al. 2012). The large variation is partly a consequence of the different studies having varying scopes and using different assumptions about future development, but also because modeling such a complex system as the global agricultural market is highly challenging and greatly dependent on modeling choices.

When it comes to accounting for emissions from indirect LUC for food, apart from using economic modeling two fundamentally different ways of approaching the issue have been applied in the literature. Some authors (Leip et al. 2010; Gerber et al. 2010; Ponsioen and Blonk 2012) burden the crops that show large expansion in a region or a country with all the emissions caused by deforestation, regardless of the land use on the newly deforested land, on the basis that it is the crops that are increasing, which are pushing other crops out into the natural ecosystems or leading to cultivation of grassland. For example, Ponsioen and Blonk (2012) first allocated yearly emissions from deforestation, estimated using trend analysis based on historic data, between lumber and the cleared land based on lumber prices and the return on agricultural goods produced on the cleared land. The emissions allocated to the cleared land were then allocated to different crops based on the share of the total expansion on all types of land, existing cropland and non-cropland, for which a specific crop was responsible. Hence, crops that were not increasing in area were not burdened with any emissions from LUC, while crops that showed a large expansion, such as soybean, were burdened with emissions from LUC that were several hundred percent higher than the direct emissions from cultivating the soybean.

Another approach to indirect LUC is to consider all use of agricultural land as responsible for driving global LUC and therefore divide total emissions from deforestation globally on all products produced on agricultural land. Audsley et al. (2009) divided all emissions from global LUC that can be attributed to commercial

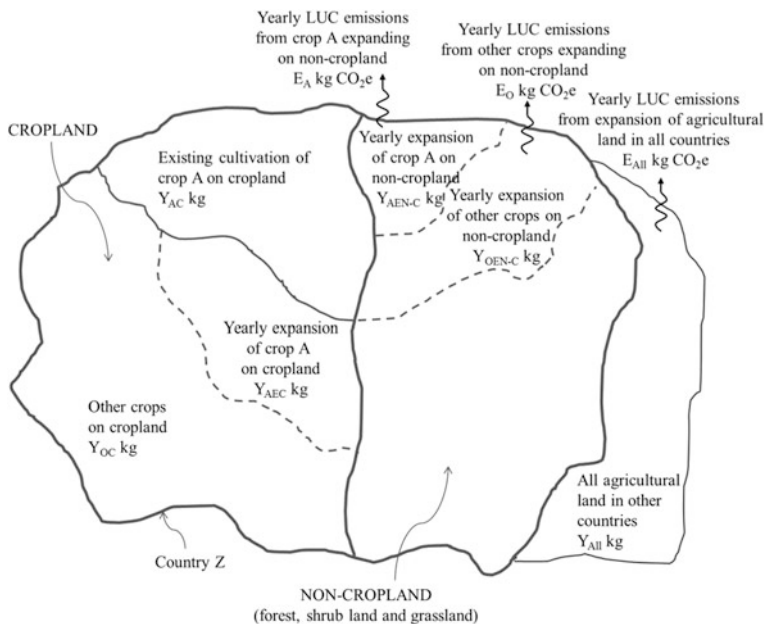


Fig. 6 Simplified example of how GHG emissions from land use change can be allocated to crops in different ways (Y is the yield of crops from different land areas and E are the annual emissions from LUC on that piece of land). Three different approaches to accounting for emissions from LUC are possible: (1) Only expansion into non-cropland of a specific expanding crop A is considered and LUC emissions are calculated for this crop as $E_A / (Y_{AEN-C} + Y_{AEC} + Y_{AC})$; that is, emissions from LUC due to the expansion of crop A into non-cropland (E_A) are divided across all crop A from country Z, regardless of where in the country crop A is grown ($Y_{AEN-C} + Y_{AEC} + Y_{AC}$). (2) The expanding crop A is considered to be responsible for all LUC because its expansion on existing cropland pushes other crops out on non-cropland. Emissions from LUC for crop A are then calculated as $(E_A + E_O) / (Y_{AEN-C} + Y_{AEC} + Y_{AC})$. Hence, all emissions from LUC, regardless of what is grown on the newly deforested land, are attributed to crop A. (3) Based on a viewpoint that all use of land is responsible for LUC, regardless of where the land is located or what is grown on the land, emissions from LUC are allocated to all crops as $(E_A + E_O + E_{All}) / (Y_{AEN-C} + Y_{AEC} + Y_{AEN-C} + Y_{OC} + Y_{OEN-C} + Y_{All})$. That is, all emissions from LUC, both within the country ($E_A + E_O$) and outside the country (E_{All}), are divided across all crops grown globally

agriculture (58 %) evenly across all land used for commercial production. This resulted in emissions of 1.4 tons of CO_2 per hectare of land from LUC, which had to be added to direct emissions from fuel combustion and use of fertilizer. Schmidt et al. (2012) adopted the same basic viewpoint that all activities occupying land are responsible for LUC, irrespective of where they take place. However, Schmidt et al. (2012) used a more sophisticated way of allocating emissions to land that takes land productivity into account.

These different approaches to handling emissions from LUC are illustrated in Fig. 6.

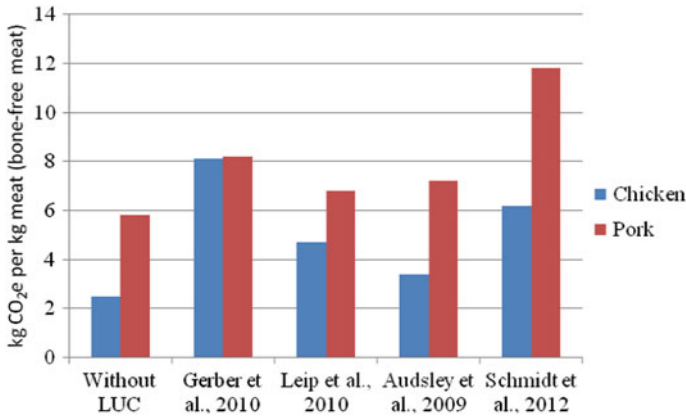


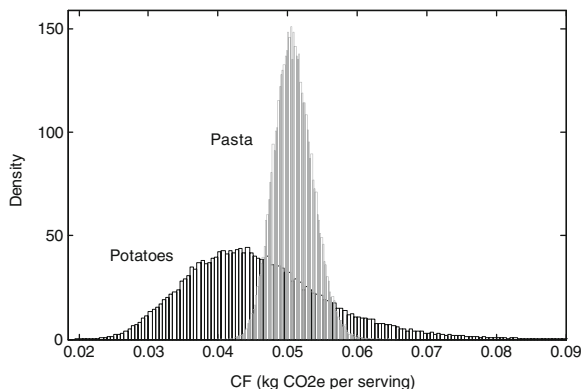
Fig. 7 Carbon footprint of chicken and pork meat calculated using different methods of accounting for greenhouse gas emissions from land use change (LUC). (Data on feed consumption from Cederberg et al. 2009.)

The method used to estimate emissions from LUC heavily influences the results. Figure 7 shows the CF of Swedish average chicken and pig meat calculated using three different ways of estimating emissions from LUC. Generally, when emissions from LUC were included, the CF is greatly increased. Chickens had a smaller CF than pig meat for all LUC methods, but the Gerber et al. (2010) method, which only assigns LUC emissions to soybean, gave very similar emissions for chicken and pig meat, due to the considerable amounts of soybean meal in the diet of Swedish chickens.

3.5 Handling Uncertainties

The first step in handling uncertainties in the CF of food products should be to try to minimize uncertainty as much as possible. One way of making CF assessments more consistent, less error-prone, and more easily comparable is to follow some kind of standard. There are some general standards or specifications in the field of CF that could be used, such as PAS 2050 (BSI 2011), the Greenhouse Gas Protocol Reporting Standard (WRI & WBCSD 2011), and the ISO CF standard (ISO 14067) that is under development. There are also standards that apply to food products specifically. PAS 2050-1 is a specification for the production of horticultural products (BSI 2012) and the ENVIFOOD Protocol aims at providing a harmonized environmental assessment methodology for food and drink products (FoodDrink Europe 2012). 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). Furthermore, the international Environmental Product Declaration (EPD) system contains a framework for developing

Fig. 8 Uncertainty ranges for the carbon footprint of one serving of potatoes and one serving of pasta (data from Rööös 2011)



rules for specific products, that is, product category rules (PCR). Within this system, PCR have been developed for, for example, meat from mammals (EPD 2013). Reducing uncertainty by standardization means that different CF assessments will be more consistent and comparable. However, there is a risk that results are biased by the selection of methods and data. Other ways of reducing the uncertainty in LCA and CF calculations include improved data collection, validation of data, and critical review by a third party (Björklund 2002).

Uncertainty in measured data can never be reduced to zero and uncertainty due to modeling choices will always exist in CF calculations, as will uncertainty due to the great variability in agricultural systems. Therefore, when uncertainty cannot be further reduced, it is important to state the remaining uncertainty in the results. Uncertainty analysis can be used to assess the uncertainty range of the final CF. One way of performing uncertainty analysis that has been commonly applied in LCA is stochastic simulation, such as Monte Carlo (MC) simulation (Rubinstein and Kroese 2007). In MC simulation, the uncertainty in input data and/or model parameters is described using a probability distribution. The CF is calculated a large number of times, with each time randomly drawing values from the probability distribution. The outcome is a large number of possible CF values that describe the uncertainty in the final CF. Rööös (2011) used MC simulation to compare one serving of cooked pasta and one serving of cooked potatoes and found that when only the deterministic CF values were used to compare the two, the potatoes were preferable from a climate perspective. However, when uncertainty in the farm gate CF values for potato and pasta and uncertainty in the preparation stage and amount of losses were included, it was not as easy to select a winner. This is illustrated in Fig. 8, where the outcomes from the MC simulations on pasta and potatoes are plotted in histograms showing possible CF values based on uncertainty and variability in input data.

Sensitivity analysis can be used to illustrate uncertainty due to choices, such as to identify the parameters that have a great or small influence on the final result, by varying input parameter individually by, for example, ± 10 or 20 %. By testing how different choices regarding CF modeling and model and input data affect the

results, the robustness of these results can be evaluated. Figure 7 (Sect. 3.4) presents an example of a sensitivity analysis on calculating the CF of chicken and pig meat depending on the method used to estimate emissions from LUC. From this analysis, it can be concluded that regardless of the methodology used to include emissions from LUC, Swedish chicken has a lower CF than Swedish pork, but that the differences in emissions are less pronounced for some LUC methods.

4 Examples of Uses and Results

4.1 Identification of Hotspots and Mitigation Options

One important reason for calculating the CF of food products, as in all LCA and CF calculations, is of course to identify hotspots and mitigation options. An important insight that has emerged from a number of LCA on food products is that the majority of the GHG emissions from the production and use of food originate from the on-farm and pre-farm phases. This is especially the case for livestock products, for which emissions from post-farm activities such as slaughter, packaging, transport, storage, and preparation are small in comparison with the emissions from primary production (Fig. 9).

In relative terms, emissions from post-farm phases can make a substantial contribution to the CF of root crops, cereals, and vegetables, especially for products that are transported long distances. Figure 10 shows the GHG emissions from different phases in the production of tomatoes in the Netherlands and Spain, including their transport to Sweden. Emissions from the tomatoes from the Netherlands are dominated by emissions from fossil energy used to heat the greenhouses, while emissions from the Spanish tomatoes are dominated by emissions from transport (Röös and Karlsson 2013).

However, because the difference in CF between livestock-based products and plant-based products is so large (Fig. 11), choosing a diet based on local produce has a limited effect on total emissions from all the food consumed in a typical

Fig. 9 GHG emissions from the production of beef meat (data from LRF et al. 2002)

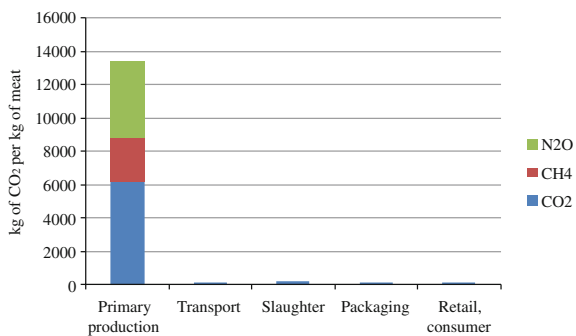
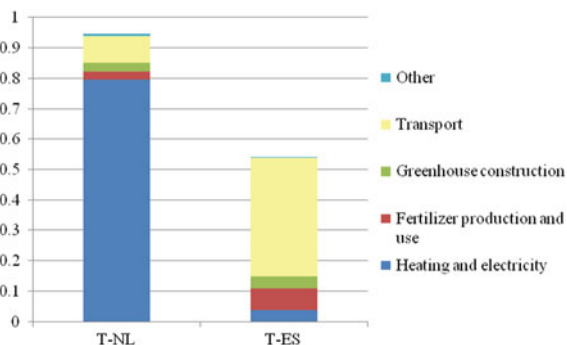


Fig. 10 Carbon footprint of 1 kg of tomatoes delivered to the Swedish market from the Netherlands (T-NL) and Spain (T-ES) (data from Rööös and Karlsson 2013)



Western diet (Weber and Matthews 2008; Garnett 2011). To achieve large reductions in GHG emissions from food consumption, reducing meat and dairy consumption is the most important mitigation option (Garnett 2011).

Another important insight that has come from estimating the GHG emissions associated with food production is that emissions from the food sector are strongly dominated by CH₄ and N₂O, at not CO₂ which is the dominant GHG in the transport and energy sector. Emissions of CO₂ from energy use in agriculture can be avoided by improved energy efficiency and the use of renewable energy sources; however, because energy-related emissions constitute a minor proportion of total emissions from agriculture (Fig. 2), this will not be sufficient to achieve substantial reductions in emissions. The emissions of CH₄ from enteric fermentation and N₂O from soil arise from natural biological processes that are difficult to control and the mitigation

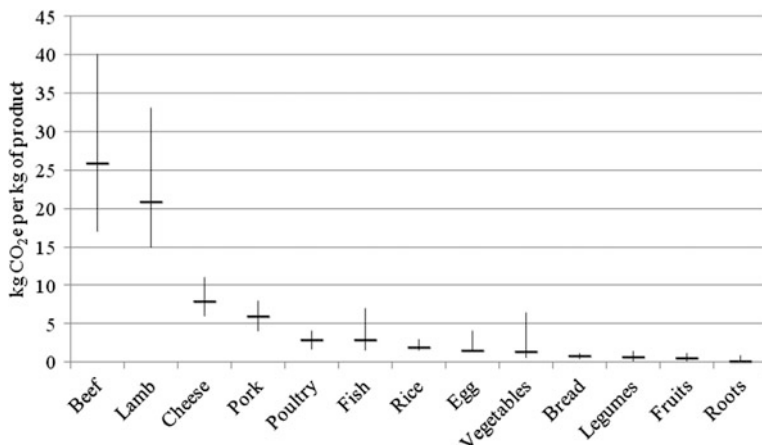


Fig. 11 Carbon footprint of different types of food products at retail. Average values estimated to be representative for food products sold on the Swedish market. Error bars show ranges of values found in the literature as a result of different production systems and methodological choices. Emissions from land use change and carbon stock changes in soils not included (Rööös 2012)

potential for reducing these gases is much less. CH₄ emissions can be reduced to some extent by altering the diet fed to ruminants (Beauchemin et al. 2008), but the risk of pollution swapping is great (Shibata and Terada 2010; Flysjö 2012). N₂O emissions from soils can be reduced by optimizing nitrogen use and by N₂O inhibitors (although these are banned in many countries), but major N₂O formation in soil is inevitable. Therefore, most studies looking at mitigation options for agriculture include changes in consumption patterns as one essential option in achieving major reductions in emissions from food consumption (Beddington et al. 2011; Foley et al. 2011; Foresight 2011; SBA 2012).

Because GHG emissions from food products are dominated by emissions arising on-farm (from feed cultivation, animals, and manure), numerous studies have looked at mitigating emissions in this phase of the life cycle. For example, Ahlgren (2009) used LCA to evaluate different systems for producing tractor fuel and mineral nitrogen fertilizers from biomass, thereby reducing the use of fossil fuels in food production, and found that 3–6 % of a farm's available land was needed to produce the tractor fuel used on the farm. The study also showed potential for reduced emissions of GHG from the reduced fossil fuel use in the system. However, there were potential trade-offs with other environmental impacts, such as eutrophication, and the use of limited resources such as water and phosphorus. This is another example of the risk of pollution swapping when only emissions of GHG are considered, as discussed in Sect. 2.5.

Dairy production and the CF of milk is one of the most thoroughly researched areas of food production (e.g., Thomassen et al. 2008; Flysjö 2012). Flysjö (2012) covered several methodological aspects in calculating the CF of milk and discussed different mitigation options based on results from calculating the CF of Swedish dairy products. Another area that has received relatively great attention is comparison of different diets in livestock production in order to identify feeding strategies that contribute to reduced emissions from livestock production (e.g., Strid Eriksson et al. 2005; Pelletier et al. 2010).

4.2 Consumer Communications

Labeling food products with their CF has been proposed as a way of enabling active choices by consumers. The British supermarket Tesco was a pioneer in this area, announcing a grand ambition in 2007 of putting CF labels on all its products (Boardman 2008). However, this labeling initiative was later dropped, as it proved very time-consuming and costly to calculate the CF and as others did not follow suit, so the labeling initiative lacked critical mass (Guardian 2012). However, the CF of hundreds of products was estimated and published in a report (Tesco 2012). In Sweden, the hamburger restaurant MAX has labeled its different meals with information on the CF. The labels are presented at the point of purchase in order to illustrate to consumers the impact of different meal alternatives (Fig. 12).

Fig. 12 Example of carbon footprint label of a food product. From the Swedish hamburger restaurant MAX



Although CF labeling or some other way of informing consumers about the CF of food products is necessary to enable active choices by consumers, it is questionable whether this is an effective policy instrument that can justify the time-consuming and costly process of calculating the CF of food items. Rööös and Tjärnemo (2011) point out that the attitude-behavioral gap identified as regards purchasing organic products is also applicable to carbon labeled products. In other words, although consumers have positive attitudes toward preserving the environment, sales of eco-labeled food products are still low for reasons such as perceived high price, strong habits governing food purchases, perceived low availability, lack of marketing and information, lack of trust in the labeling system, and low perceived customer effectiveness. Hence, CF information on food products might be more useful in business-to-business communication, for food professionals in the retail sector, and in public procurement. These actors have a large influence on which products are procured, marketed, displayed, and put on sale in a country. For example, in Sweden there is strong interest among different actors in the public sector in calculating the CF of total food purchases and meals in schools, hospitals, and retirement homes in order to identify hotspots and work with lowering the impact from food consumption. To facilitate these calculations, a list of average CF values representative of food items on the Swedish market has been compiled and is now in use in a number of companies, municipalities, and organizations in Sweden (Rööös 2012).

The CF value of food products and the magnitude of other environmental impacts is also valuable information for organizations and authorities concerned with formulating dietary advice. Including environmental concerns in the recommendations for nutritionally sound food consumption is becoming increasingly common; for example, the new Nordic Nutrition Recommendations include a chapter on sustainable food consumption in which different food products are categorized into one of three groups: low CF (<1 kg of CO₂ per kg), such as roots, bread, and local fruits; medium CF (between 1 and 4 kg CO₂ per kg), such as poultry, rice, and greenhouse vegetables; and high CF (more than 4 kg CO₂ per kg), such as beef, pork, cheese, and tropical fruits transported by air (NNR 5 2012). Studying food consumption from both a nutritional and environmental

perspective is also a rapidly growing field in research (e.g., Bere and Brug 2009; Macdiamid et al. 2012; Meier and Christen 2013).

5 Conclusions

In this chapter, the importance of the food system as a contributor to climate change, as well as the relevance and challenges of CF as a decision support tool, have been described. The main sources of GHG emissions in the life cycle of food products are N_2O from soils, CH_4 from enteric fermentation in animals, and CO_2 from LUC, such as deforestation. Emissions also arise from manure management, mineral fertilizer production, rice cultivation, and energy use on farms and from post-farm activities such as processing, packaging, storage, distribution, and waste management. With increasing awareness of climate change, calculating the CF of food products has become increasingly popular among researchers and companies wanting to determine the impact of their products on global warming and/or to communicate the CF of their products to consumers. Some issues are especially relevant when calculating the CF of food products, such as the choice of functional unit, which is challenging owing to the multi-functionality of food. Other issues concern how to include emissions arising from indirect land use change and removal of CO_2 from the atmosphere by carbon sequestration in soils into CF calculations. Causes of the large uncertainties associated with calculating the CF of food products and ways to handle this uncertainty have been discussed. Despite the large uncertainties, it is clear that the differences in CF between different types of food products are very large. In general, the CF of livestock-based products is much larger than those of plant-based products. Although informing consumers about the CF of food products is necessary to enable active choices by consumers, it is questionable whether labeling products with CF data is an effective policy instrument that can justify the time-consuming and costly process of calculating the CF of food items. CF information on food products may be more useful in business-to-business communication, for professionals in the retail sector, and in public procurement.

6 Future Challenges and Research Needs

Major changes to the food system are needed in order to sustainably feed the rising global population. The high CF of livestock-based products in relation to plant-based food products speaks for itself. Future diets must be heavily dominated by food products of vegetal origin in order to reduce emissions of GHG and other pollutants, and to protect water, land, and biodiversity. Implementation of improvements during the primary production of food, such as increased energy efficiency on farms and better nutrient management, needs to accelerate. Post-farm

stages in the food chain also need to be considered, as emissions can be substantial during these phases, especially for future diets that will (hopefully) be based more on plants. Calculation of the CF will continue to be a valuable tool in preventing sub-optimization and in identifying the most effective mitigation options. More research is needed in several areas regarding calculating the CF of food products. There is a need for better methods to assess emissions from biological processes and to assess, for example, emissions from land use change and changes in soil carbon balance. More food products from different production systems need to be investigated. As food patterns need to change, assessing the CF of complete diets and optimizing these based on local resource availability, nutritional status, effect on biodiversity, and other environmental impacts, as well as cost, must be given increased attention. Finally, communicating CF results, including their uncertainty, and developing and evaluating policy instruments based on these results are research areas that require a broad interdisciplinary approach to be successful.

References

- Ahlgren S (2009) Crop production without fossil fuel. Production systems for tractor fuel and mineral nitrogen based on biomass. Dissertation, Swedish University of Agricultural Sciences
- Audsley E, Brander M, Chatterton J et al (2009) How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. FCRN-WWF, UK
- Beauchemin K, Kreuzer M, O'Mara C, McAllister T (2008) Nutritional management for enteric methane abatement: a review. *Aust J Exp Agri* 48:21–27
- Beddington J, Asaduzzaman M, Fernandez A et al (2011) Achieving food security in the face of climate change: summary for policy makers from the commission on sustainable agriculture and climate change. CGIAR research program on climate change, Agriculture and Food Security (CCAFS), Copenhagen
- Bere E, Brug J (2009) Towards health-promoting and environmentally friendly regional diets: a Nordic example. *Public Health Nutr* 12(1):91–96
- Berglund Ö, Berglund K (2010) Distribution and cultivation intensity of agricultural peat and gyttja soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. *Geoderma* 154(3–4):173–180
- Björklund A (2002) Survey of approaches to improve reliability in LCA. *Int J LCA* 7:64–72
- Boardman B (2008) Carbon Labelling: too complex or will it transform our buying? *Significance* 5(4): 168–171
- Broch A, Kent Hoekman S, Unnasch S (2013) A review of variability in indirect land use change assessment and modeling in biofuel policy. *Environ Sci Pol* 29:147–157
- BSI (2011). PAS 2050:2011. Method for assessing the life cycle greenhouse gas (GHG) emissions of goods and services. British Standard Institution, London
- BSI (2012) PAS 2050-1:2012. Assessment of life cycle greenhouse gas emissions from horticultural products. British Standard Institution, London
- CCAFS (2013) Big facts: where agriculture and climate change meet. Site from the CGIAR research program on climate change, Agriculture and Food Security's (CCAFS). <http://ccafs.cgiar.org/bigfacts/global-agriculture-emissions/>. Accessed 16 May 2013
- Cederberg C, Darelius K (2001) Livscykelanalys (LCA) av griskött (Life cycle assessment of pork meat). Naturresursforum, Landstingen Halland

- Cederberg C, Nilsson B (2004) Livscykelanalys (LCA) av ekologisk nötköttsproduktion i ranchdrift (Life cycle assessment of organic beef production using ranch production system). SIK report 718. Swedish Institute for Food and Biotechnology, Gothenburg
- Cederberg C, Sonesson U, Henriksson M et al (2009) Greenhouse gas emissions from production of meat, milk and eggs in Sweden 1990 and 2005. SIK-Report 793. Swedish Institute for Food and Biotechnology, Gothenburg
- Cederberg C, Persson U, Neovius K et al (2011) Including carbon emissions from deforestation in the carbon footprint of Brazilian beef. *Environ Sci Technol* 45:1773–1779
- de Vries M, de Boer IJM (2010) Comparing environmental impacts for livestock products: a review of life cycle assessments. *Livestock Sci* 128:1–11
- Di Lucia L, Ahlgren S, Ericsson K (2012) The dilemma of indirect land-use changes in EU biofuel policy—an empirical study of policy-making in the context of scientific uncertainty. *Environ Sci Pol* 16:9–19
- Dutilh CE, Kramer KJ (2000) Energy consumption in the food chain: comparing alternative options in food production and consumption. *Ambio* 29(2):98–101
- EC (2006) Environmental impact of products (EIPRO): analysis of the life cycle environmental impacts related to the total final consumption of the EU 25. European commission technical report EUR 22284 EN
- Ellis J, Kebreab E, Odondo N et al (2007) Prediction of methane production from dairy and beef cattle. *J Dairy Sci* 90:3456–3467
- Ellis J, Bannink A, France J et al (2010) Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. *Glob Cha Biol* 16:3246–3256
- EPD (2013) The international EPD (Environmental product declaration) system—a communications tool for international markets. <http://www.environdec.com/sv/>. Accessed 15 May 2013
- Eurostat (2011) Food; from farm to fork statistics. Eurostat Pocketbooks. European Commission, Brussels
- FAOSTAT (2011) FAOSTAT database, livestock primary, cow milk, whole, fresh. <http://faostat.fao.org/>. Accessed 15 May 2013
- Flysjö A (2012) Greenhouse gas emissions in milk and dairy product chains—improving the carbon footprint of dairy products. Dissertation, Aarhus University
- Flysjö A, Cederberg C, Henriksson M, Ledgard S (2011) How does co-product handling affect the carbon footprint of milk? Case study of milk production in Sweden and New Zealand. *Int J of LCA* 16:420–430
- Foley J, Ramankutty N, Brauman KA et al (2011) Solutions for a cultivated planet. *Nature* 478:337–342
- FoodDrink Europe (2012) ENVIFOOD protocol. Environmental assessment of food and drink protocol. Draft version 0.1. European food sustainable consumption and production round table, Brussels
- Foresight (2011) The future of food and farming. Executive summary. The Government Office for Science, London
- Garnett T (2011) Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Pol* 36:23–32
- Gerber P, Vellinga T, Opio C (2010) Greenhouse gas emissions from the dairy sector: a life cycle assessment. FAO, Rome
- Global Carbon Project (2013) Global carbon budget highlights. <http://www.globalcarbonproject.org/carbonbudget/12/hl-full.htm>. Accessed 18 Feb 2013
- Guardian (2012) Tesco drops carbon-label pledge. <http://www.guardian.co.uk/environment/2012/jan/30/tesco-drops-carbon-labelling>. Accessed 11 May 2013
- Guthman J (2003) Fast food/Organic food: reflexive tastes and the making of ‘yuppie chow’. *Soc a Cult Geo* 4(1):45–58
- Henriksson M, Flysjö A, Cederberg C, Swensson C (2011) Variation in carbon footprint of milk due to management differences between Swedish dairy farms. *Animal* 5:1474–1484
- Houghton RA (2012) Carbon emission and the drivers of deforestation and forest degradation in the tropics. *Curr Opin Environ Sustain* 4:597–603

- International Dairy Federation (IDF) (2010) A common carbon footprint for dairy: the IDF guide to standard lifecycle assessment methodology for the dairy industry. International Dairy Federation
- IPCC (2006a) IPCC guidelines for national greenhouse gas inventories. Emissions from livestock and manure management, vol 4, chap 10. Intergovernmental Panel on Climate Change, Geneva
- IPCC (2006b) IPCC guidelines for national greenhouse gas inventories. N₂O emissions from managed soils, and CO₂ emissions from lime and urea application, vol 4, chap 11. Intergovernmental Panel on Climate Change, Geneva
- IPCC (2007) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Jansson P-E, Karlberg L (2004) Coupled heat and mass transfer model for soil-plant atmosphere systems TRITA-LWR report 3087. Royal Institute of Technology, Department of Land and Water Resources Engineering, Stockholm
- Johnson K, Johnson D (1995) Methane emissions from cattle. *J of Anim Sci* 73(8):2483–2492
- Kernebeek H, Oosting S, de Boer I (2012) Comparing the environmental impact of human diets varying in amount of animal-source food—the impact of accounting for nutritional quality. Proceedings from the 8th international conference on lifecycle assessment in the agri-food sector, St Malo, 1–4 Oct 2012
- Kirchgessner M, Windisch W, Müller H (1995) Nutritional factors for the quantification of methane production. In: von Engelhardt W, Leonhard-Marek S, Breves G, Giesecke D (eds) Ruminant physiology: digestion, metabolism, growth and reproduction, pp. 333–348
- Lantmännen (2013) Klimatdeklarationer. (Climate declarations). <http://lantmannen.se/omlantmannen/press-media/publikationer/klimatdeklarationer/>. Accessed 16 May 2013
- Leip A, Weiss F, Wassenaar T et al (2010) Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS)—final report. European Commission, Joint Research Centre, Rome
- Macdiamid JI, Kyle J, Horgan GH et al (2012) Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? *Am J Clin Nutr* 96:632–639
- MAX (2013) Klimatdeklaration (Climate declaration). <http://max.se/sv/Maten/Klimatdeklaration/>. Accessed 22 May 2013
- Meier T, Christen O (2013) Environmental impacts of dietary recommendations and dietary styles: Germany as an example. *Environ Sci Techn* 47(2):877–888
- Meul M, Ginneberge C, Van Middelaar C et al (2012) Carbon footprint of five pig diets using three land use change accounting methods. *Livestock Sci* 149:215–223
- Millennium Ecosystem Assessment (MEA) (2005) Ecosystems and human well-being: biodiversity synthesis. World Resources Institute, Washington DC
- Mills J, Kebreab E, Crompton L, France J (2003) The Mitscherlich equation: an alternative to linear models of methane emissions from cattle. In: Proceedings of the British society of animal science 2003
- Moe PW, Tyrrell HF (1979) Methane production in dairy cows. *J Dairy Sci* 62:1583–1586
- Munoz I, Milà i Canals L, Clift R (2008) Consider a spherical man—a simple model to include human excretion in life cycle assessment of food products. *J Ind Ecol* 12(4): 521–538
- Nemecek T, Gaillard G (2010) Challenges in assessing the environmental impacts of crop production and horticulture. In: Sonesson U, Berlin J, Ziegler F (eds) Environmental assessment and management in the food industry. Woodhead Publishing Limited, Cambridge
- Nijdam D, Rood T, Westhoek H (2012) The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Pol* 37:760–770
- NNR 5 (2012) Sustainable food consumption. What are the environmental issues concerning food consumption? How does food consumption connect to the environmental impact? Chapter in the draft proposal of the Nordic nutritional recommendations (NNR 5). <http://www.slv.se/en-gb/Startpage-NNR/>. Accessed 15 May 2013

- Nylinder J, Stenberg M, Janson P-E, Kasimir Klemedtsson Å, Weslien P, Klemedtsson L (2011) Modelling uncertainty for nitrate leaching and nitrous oxide emissions based on a Swedish field experiment with organic crop rotation. *Agric Ecos Environ* 141:167–183
- Pelletier N, Pirog R, Rasmussen R (2010) Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agri Syst* 103:380–389
- Ponsioen T, Blonk T (2012) Calculating land use change in carbon footprints of agricultural products as an impact of current land use. *J Clean Prod* 28:120–125
- Powlson D, Whitmore A, Goulding K (2011) Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *Euro J Soil Sci* 62:42–55
- Rockström J, Steffen W, Noone K et al (2009) A safe operating space for humanity. *Nature* 461:472–475
- Röös E (2011) The trade-off between animal welfare and lowered emissions of greenhouse gases from pork production. Presentation at the NJF conference in Uppsala, 15–16 June 2011
- Röös E (2012) Mat-klimat-listan version 1.0 (The food-climate-list version 1.0) report 2012:040. Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala
- Röös E, Karlsson H (2013) Swedish vegetal consumption—effect on the carbon footprint from eating seasonal. *J Clean Prod* 59:63–72
- Röös E, Nylinder J (2013) Carbon footprint of livestock products—variations and uncertainties. Report 2013:063. Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala
- Röös E, Tjärnemo H (2011) Challenges of carbon labelling of food products: a consumer research perspective. *Brit Food J* 113(8):982–996
- Röös E, Sundberg C, Hansson P-A (2011) Uncertainties in the carbon footprint of refined wheat products: a case study on Swedish pasta. *Int J of LCA* 16:338–350
- Röös E, Sundberg C, Tidåker P, Strid I, Hansson P-A (2013) Can carbon footprint serve as an indicator of the environmental impact of meat production? *Ecol Ind* 24:573–581
- Roy P, Nei D, Orikasa T et al (2009) A review of life cycle assessment (LCA) on some food products. *J Food Eng* 90:1–10
- Rubinstein R, Kroese D (2007) Simulation and the Monte Carlo method. Wiley-Interscience, ISBN 0470177942, 9780470177945
- Saarinen M (2012) Nutrition in LCA: are nutrition indexes worth using? In: Proceedings from the 8th international conference on lifecycle assessment in the agri-food sector, St Malo, 1–4 Oct 2012
- SBA (2012) Ett klimatvänligt jordbruk 2050 (Climate friendly agriculture 2050). Report 2050:35. Swedish Board of Agriculture, Jönköping
- Schau EM, Fet AM (2008) LCA studies of food products as background for environmental product declarations. *Int J LCA* 13(3):255–264
- Schmidt J, Reinhard J, Weidema B (2012) A model of indirect land use change. In: Proceedings from the 8th international conference on lifecycle assessment in the agri-food sector, St Malo, 1–4 Oct 2012
- SEPA (2008) Konsumtionens klimatpåverkan (The climate impact of consumption). Report no 5903. Swedish Environmental Protection Agency, Stockholm
- Shibata M, Terada F (2010) Factors affecting methane production and mitigation in ruminants. *Anim Sci J* 81:2–10
- Sjaunja L, Baevre L, Junkkarinen L et al (1990) A Nordic proposal for an energy corrected milk (ECM) formula. In: 27th session of the International Commission for Breeding and Productivity of Milk Animals, Paris
- Smedman A, Månsson H, Drewnowska A, Edman A (2010) Nutrient density of beverages in relation to climate impact. *Food Nutr Res* 54:5170 doi: [10.3402/fnr.v54i0.5170](https://doi.org/10.3402/fnr.v54i0.5170)
- Smith P (2012) Agricultural greenhouse gas mitigation potential globally, in Europe and the UK. Scientific review. *Glob Cha Biol* 18:35–43
- Smith P, Martino D, Cai Z et al (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) *Climate change 2007: mitigation. Contribution of working group III to the*

- fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, United Kingdom and New York
- Soussana J, Allard V, Pilegaard K et al (2007) Full accounting of the greenhouse gas budget of nine European grassland sites. *Agric Ecos Environ* 121:121–134
- Soussana J, Tallec T, Blanfort V (2010) Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* 4(3):334–350
- Strid Eriksson I, Elmquist H, Stern S, Nybrant T (2005) Environmental systems analysis of pig production. The impact of feed choice. *Int J LCA* 10:143–154
- LRF, Svensk Mjök, Swedish Meats et al (2002) Maten och miljön. Livscykelanalys av sju livsmedel (Food and environment. Life cycle assessment of seven food items). The Federation of Swedish farmers (LRF), Stockholm
- Tesco (2012) Product carbon footprint summary. [http://www.tescoplc.com/assets/files/cms/Tesco_Product_Carbon_Footprints_Summary\(1\).pdf](http://www.tescoplc.com/assets/files/cms/Tesco_Product_Carbon_Footprints_Summary(1).pdf). Accessed 22 May 2013
- Thomassen M, Dalgaard R, Heijungs R, de Boer I (2008) Attributional and consequential LCA of milk production. *Int J of LCA* 13:339–349
- Tillman AM (2010) Methodology for life cycle assessment. In: Sonesson U, Berlin J, Ziegler F (eds) *Environmental assessment and management in the food industry*. Woodhead Publishing Limited, Cambridge
- UCS (2011) The root of the problem—what is driving tropical deforestation today?. Union of Concerned Scientists, Cambridge
- van Middelaar CE, Cederberg C, Vellinga ThV et al (2013) Exploring variability in methods and data sensitivity in carbon footprints of feed ingredients. *Int J LCA* 18(4):768–782
- Veysset P, Lherm M, Bébin D (2011) Productive, environmental and economic performances assessments of organic and conventional suckler cattle farming systems. *Org Agr* 1:1–16
- Weber CL, Matthews HS (2008) Food-miles and the relative climate impacts of food choices in the United States. *Environ Sci Technol* 42:3508–3513
- Wilkerson VA, Casper DP (1995) The prediction of methane production from Holstein cows by several equations. *J Dairy Sci* 78:2402–2414
- WRI & WBCSD (2011) Greenhouse gas protocol. Product life cycle accounting and reporting standard. <http://www.ghgprotocol.org/standards/product-standard>. Accessed 16 May 2013