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Product carbon footprint of rye bread

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ABSTRACT

The primary purpose of this paper is to estimate the carbon footprint of conventional rye bread produced on an industrial scale and consumed in Denmark by identifying the stages that contribute significantly to the carbon footprint (hotspots) of production. The results are then interpreted by comparing and discussing the results of this study with the results of other studies identified in the extant body of literature. To estimate the carbon footprint, we considered an industrial bakery supply chain in a single in-depth quantitative case study. Using an attributional approach, we estimated the carbon footprint of 1 kg of rye bread to be 731 g CO_2 equivalents (CO_2eq). As in previous studies, the primary hotspot was found to be the raw material stage, especially agricultural production (cultivation), with processing and distribution stages as secondary hotspots. The waste management stage was determined to be an important and previously overlooked opportunity for improvement.

1. Introduction

Growing concern for climate change among company stakeholders has triggered increased interest in and relevance of estimating greenhouse gas (GHG) emissions of products (Cellura et al., 2012; Notarnicola et al., 2012; Seuring and Müller, 2008). For this reason, product carbon footprints (PCF) are of great interest as a central measure of environmental impact in supply chains (Čuček et al., 2012). By applying PCFs, companies can estimate the total GHG emissions emitted along the entire supply chain, from cradle to grave (Cappelletti et al., 2010). Numerous studies have assessed the environmental impact associated with consumption of food products, advancing the knowledge base about the environmental impact of food products (Tukker et al., 2006; Schau and Fet, 2008; Notarnicola et al., 2012). This research contributes to the course of research in two ways. First, although bread is among the food products with the lowest environmental impact, it remains a staple and important food product that is consumed in large amounts and in many countries (Braschkat et al., 2003; Roy et al., 2009; Espinoza-Orias et al., 2011; Kulak et al., 2012). For instance, in the Nordic countries, consumption of bread products has been linked to tradition and food culture, with Finland and Denmark having a strong tradition of baking sourdough rye bread (Nordic Ecolabelling, 2013). Second, interest in comparing the results between PCF studies is increasing from a research perspective, but has generally been fraught with difficulties (Schau and Fet, 2008; Udo de Haes and Heijungs, 2007; Pulkkinen et al., 2010). This paper contributes to research through a comprehensive review of life cycle assessment (LCA) and PCF studies of bread by comparing the results across the literature with the findings of this study. The next section provides an outline of the extant body of literature.

2. Product carbon footprints for bread products

Several researchers have studied the environmental impact of bread production. A search of the literature revealed 15 studies published since 1999 that support Pulkkinen et al.'s (2010) finding that many LCA or PCF studies have been carried out in the last 10 years. A brief summary of the studies is presented in Table 1.

2.1. Bread product

Various bread products have been studied, including white, wholemeal, and rye bread, as well as mixtures of these types. As shown in Table 1, studies tend to emphasize white or mixed bread (11 studies), with only three studies specifically assessing rye bread products (Nielsen et al., 2003; Grönroos et al., 2006; Saarinen, 2012). For instance, by estimating the GHG emissions along the supply chain until 1 kg each of white bread and rye bread reaches

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the retail market, Nielsen et al. (2003) found rye bread to be associated with slightly lower GHG emissions (790 g CO_2eq), as compared with white bread (840 g CO_2eq).

2.2. Production method

Similar to other studies of food products, a distinction is made between conventional and organic production methods, which basically refers to how the crop was cultivated and treated (Roy et al., 2009; Hokazono and Hayashi, 2012; Schäfer and Blanke, 2012). It is no surprise that previous studies have tended to emphasize conventionally produced bread (all 15 studies), although Braschkat et al. (2003) and Grönroos et al. (2006) also included an assessment of organically produced bread. According to Braschkat et al. (2003), organically produced bread has a lower carbon footprint (368 g CO_2eq, on average), as compared with conventionally produced bread (565 g CO_2eq, on average) and requires less energy use (see also Grönroos et al., 2006). This difference is explained as conventional cereal production requiring production of mineral fertilizers that are not, or only to a limited degree, used in organic cereal production (Nordic Ecolabelling, 2013). These results suggest that organically produced bread is a better option, from the perspective of GHG emissions, but organic production does not always result in lower environmental impacts (Department for Environment, Food and Rural Affairs [DEFRA], 2009b; Notarnicola et al., 2012; Salomone and Ioppolo, 2012). The same applies when comparing conventional and organic cereal production: it is difficult to decide which one is "better" due to large variations and uncertainties, especially when modeling highly complex organic production systems (Nordic Ecolabelling, 2013).

2.3. Production scale

Previous studies have compared emissions associated with bread produced on different scales, such as industrial production, local bakery or shop, and home baking. While most studies have focused on industrially produced bread (13 studies), Andersson and Ohlsson (1999), Braschkat et al. (2003), and Swedish Institute for Food and Biotechnology ([SIK] 2009) focused on comparing bread produced on different scales. For instance, Andersson and Ohlsson (1999) estimated the GHG emissions associated with bread manufactured on an industrial scale, a local bakery, and home baking. Their results indicate industrially produced bread as the option most likely to have the highest GHG emissions and home baking as the option with the lowest emissions. In contrast, Braschkat et al. (2003) identified industrially produced bread as resulting in the lowest GHG emissions, as compared with local bakeries and home baking. In addition, the more recent study by SIK (2009) identified that bread from local bakeries is associated with the lowest GHG emissions, as compared to industrially produced bread or home baking. This disparity indicates ambiguity in the results in terms of the GHG emissions associated with bread produced on different scales.

2.4. Geographical scope

A typical distinctive characteristic of bread production is the geographical region in which production occurs (Iriarte et al., 2010; Ruviaro et al., 2012). Bread has been studied in different national contexts, but the studies have all been conducted in Europe, with the only exception being Narayanas-Wamy et al. (2005), who studied bread production in Australia. The earliest study identified was performed in Sweden (Andersson and Ohlsson, 1999), while more recent studies were undertaken in the UK (Espinoza-Orias et al., 2011; Kingsmill, 2012; Sarrouy et al., 2012). The national context clearly has an impact on the PCF. For instance, Espinoza-Orias et al. (2011) studied how the origin of wheat (e.g., in the UK, Canada, France, Germany and USA) influences the PCF and identified that sourcing locally or nationally (i.e., in UK) produced wheat may be preferred, as compared to imported wheat, with respect to product quality.

2.5. Life cycle methodology and system boundary

By grouping the 15 studies based on publication date, it was noted that previous (pre-2006) studies are generally not explicit about their life cycle methodology and tend to define their system boundary "from cradle to retail/ready for consumption," thereby excluding the consumption and waste management stages. This exclusion can be explained, in part, because defining the system boundary as "from cradle to grave" requires estimating the actual (or average) use of the product, as well as subsequent recycling or disposal of the product after its useful life (McKinnon, 2010). This explanation is similar to Finkbeiner (2009), who argues that including the use phase might be controversial, both from a business-to-business (B2B) and business-to-consumer (B2C) perspective. However, given the increasing recognition of the importance of conducting integrated studies of the environmental performance of entire food production systems (Notarnicola et al., 2012), some of the more recent (post-2009) studies of bread products include environmental impact along the supply chain from cradle to grave.

2.6. Climate impact

Surprisingly large ranges exist for the PCF of bread, with results varying from 256 to 2300 g CO_2eq/kg bread. According to Pulkkinen et al. (2010), this difference is explained by methodological choices, type of energy used, and climate conditions. The carbon footprint is generally lower in earlier studies, as compared to more recent studies, with the only exception being Narayanaswamy et al. (2005). Specifically, studies targeting from cradle to retail/ready for consumption found that production of white bread on an industrial scale results in approximately 675 g CO_2eq/kg bread on average, while studies limited to from cradle to grave yielded results of approximately 1425 g CO_2eq/kg bread on average (see Table 1).

2.7. Hotspots

Studies generally identify cultivation of crop as the dominant in the PCF, and thus label it as the primary hotspot. Here, emissions of nitrous oxide (N_2O), a strong GHG, from agricultural land have a significant climate impact (Nordic Ecolabelling, 2013). Establishing sustainable agricultural systems, therefore, is an important aspect of the development of sustainable food supply chains (Notarnicola et al., 2012). In addition, the bread manufacturing and consumption stages are generally identified in studies as the second and third most significant contributing stages, with the only exception of Andersson and Ohlsson (1999), who identified transportation as the second largest contributor. However, this result is most likely due to Andersson and Ohlsson (1999) having included consumer transport to retail stores, which are excluded in later PAS-compliant PCF studies (Publicly Available Specification [PAS] 2050, 2011). Although transport is integral in the life cycle of many products, this is generally not the case in studies of fresh bread products (Nordic Ecolabelling, 2013).

Table 1
Studies of environmental impact of bread measured per 1 kg bread (missing values indicate that the information is not available).

Author and year	Bread product	Production method	Production scale	Geographical scope	Life cycle methodology	System boundary	g CO_2eq (low)	g CO_2eq (high)	MJ energy (low)	MJ energy (high)	Hotspot
Andersson and Ohlsson (1999)	White	Conventional	Industrial	Sweden	Not specified	Cradle to retailing	630	1000	14	22	Cultivation; transportation; processing
Andersson and Ohlsson (1999)	White	Conventional	Local bakery	Sweden	Not specified	Cradle to retailing	660	670	12	12	Cultivation: processing
Andersson and Ohlsson (1999)	White	Conventional	Home baking	Sweden	Not specified	Cradle to retailing	520	650	17	18	Cultivation; transportation; processing
Braschkat et al. (2003)	White	Conventional	Industrial	Germany	Not specified	Cradle to retailing	448	448	4.6	4.6	Cultivation; final product processing
Braschkat et al. (2003)	White	Conventional	Local bakery	Germany	Not specified	Cradle to retailing	576	576	6.2	6.2	Cultivation; final product processing
Braschkat et al. (2003)	White	Conventional	Home baking	Germany	Not specified	Cradle to retailing	672	672	8.2	8.2	Final product processing; cultivation
Braschkat et al. (2003)	White	Organic	Industrial	Germany	Not specified	Cradle to retailing	256	256	3.6	3.6	Final product processing
Braschkat et al. (2003)	White	Organic	Local bakery	Germany	Not specified	Cradle to retailing	384	384	5.4	5.4	Final product processing
Braschkat et al. (2003)	White	Organic	Home baking	Germany	Not specified	Cradle to retailing	464	464	7.4	7.4	Final product processing
Carlsson-Kanyama et al. (2003)	Not specified	Conventional	Local bakery	Sweden	Not specified	Cradle to retailing			8.9	8.9	
Carlsson-Kanyama et al. (2003)	Not specified	Conventional	Industrial	Sweden	Not specified	Cradle to retailing			9.7	9.7	
Nielsen et al. (2003)	White	Conventional	Industrial	Denmark	Consequential (marginal)	Cradle to retailing	840	840			
Nielsen et al. (2003)	Rye	Conventional	Industrial	Denmark	Consequential (marginal)	Cradle to retailing	790	790			
Holderbeke et al. (2003)	White	Conventional	Industrial	Belgium	Not specified	Cradle to retailing	620	620			Cultivation; final product processing
Narayanas-wamy et al. (2005)	White	Conventional	Industrial	Australia	Attributional (specific)	Cradle to consumption	2300	2300			Retailing and consumption; processing
Grönroos et al. (2006)	Rye	Conventional	Industrial	Finland	Attributional (average)	Cradle to final product processing			15.33	15.33	Final product processing
Grönroos et al. (2006)	Rye	Organic	Industrial	Finland	Attributional (average)	Cradle to final product processing			13.34	13.34	Final product processing
DEFRA (2009b)	White	Conventional	Industrial	UK	Attributional (specific)	Cradle to final product processing	730	730			
Kingsmill (2009)	White/mixed	Conventional	Industrial	UK	Attributional (specific)	Cradle to grave	1625	1625			Cultivation; consumption
Kingsmill (2009)	Wholemeal	Conventional	Industrial	UK	Attributional (specific)	Cradle to grave	1500	1500			Cultivation; consumption
SIK (2009)	White/mixed	Conventional	Home baking	Sweden	Not specified	Cradle to retailing	517	608	7.7	11.4	Cultivation; transportation; final product processing
SIK (2009)	White/mixed	Conventional	Local bakery	Sweden	Not specified	Cradle to retailing	448	459	8.1	8.2	Cultivation; transportation; final product processing
SIK (2009)	White/mixed	Conventional	Industrial	Sweden	Not specified	Cradle to retailing	505	826	8.1	12.6	Cultivation; transportation; final product processing
Espinoza-Orias et al. (2011)	White	Conventional	Industrial	UK	Attributional (specific)	Cradle to grave	1498	1555			Cultivation; consumption
Espinoza-Orias et al. (2011)	Wholemeal	Conventional	Industrial	UK	Attributional (specific)	Cradle to grave	1388	1445			Cultivation; consumption
Espinoza-Orias et al. (2011)	White	Conventional	Industrial	UK	Attributional (generic)	Cradle to grave	1309	1375			Cultivation; consumption
Espinoza-Orias et al. (2011)	Wholemeal	Conventional	Industrial	UK	Attributional (generic)	Cradle to grave	1221	1287			Cultivation; consumption
Kingsmill (2012)	White/mixed	Conventional	Industrial	UK	Attributional (specific)	Cradle to grave	1250	1250			Cultivation; consumption
Kingsmill (2012)	Wholemeal	Conventional	Industrial	UK	Attributional (specific)	Cradle to grave	1188	1188			Cultivation; consumption
Kulak et al. (2012)	Mixed	Conventional	Local bakery	France	Not specified	Cradle to retailing	610	1900	14.3	23.8	Cultivation; distribution; final product processing
Saarinen (2012)	Rye	Conventional	Industrial	Finland	Not specified	Cradle to final product processing	951	1616			
Sarrouy et al. (2012)	Not specified	Conventional	Not specified	UK	Not specified	Cradle to retailing			3.7	15.8	Cultivation

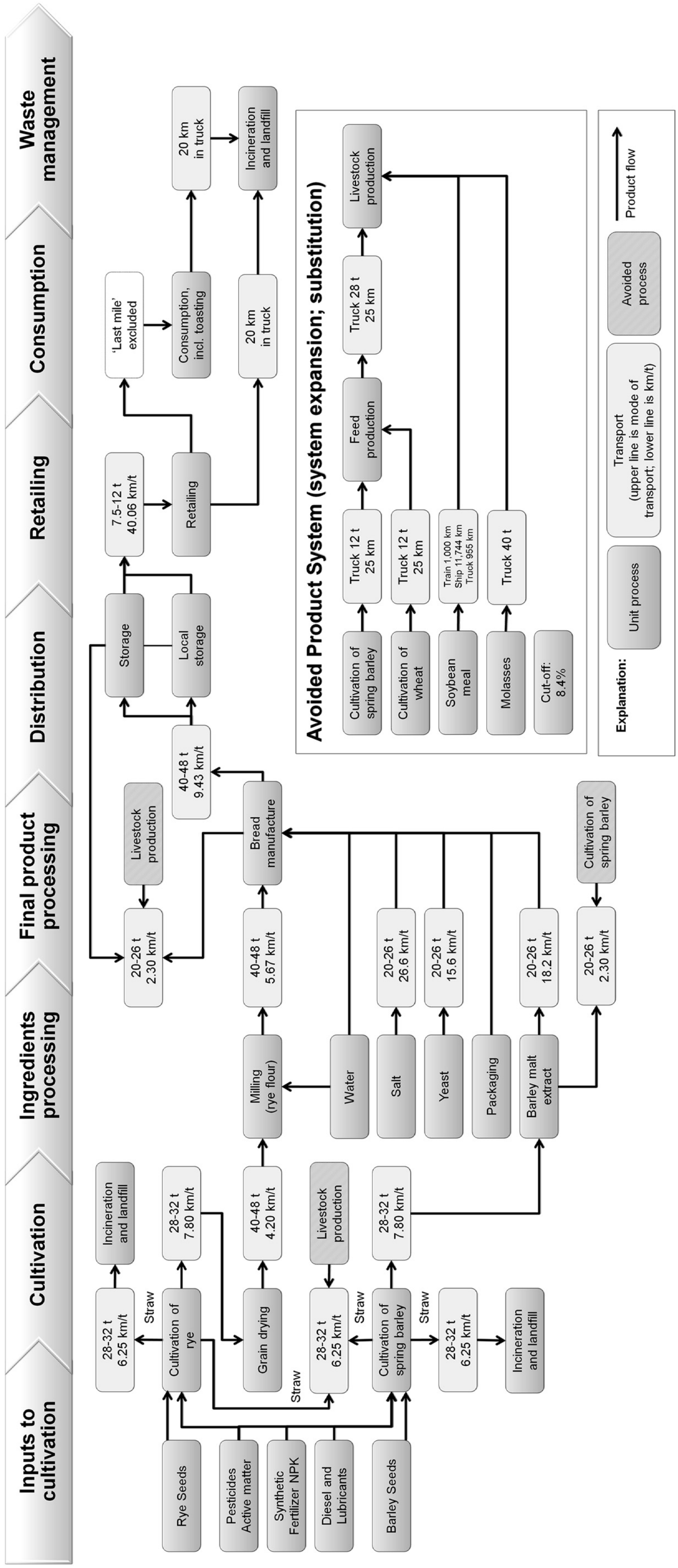

Fig. 1. System boundary.

3. Methodology

3.1. Goal of the study

The main purpose of this paper is to estimate the carbon footprint of a conventional rye bread produced on an industrial scale and consumed in Denmark and identify the stages that contribute significantly to the carbon footprint (hotspots). The results are then interpreted by comparing and discussing the results of this study with the results of previous studies found in the extant body of literature. For these purposes, this paper estimates the PCF based on the ISO 14044 methodology (ISO, 2006) as it is recognized as a solid and standardized method (Jensen, 2012). By applying PCF, this paper estimates the accumulated GHG emissions, recalculated according to their CO_2eq factors on a 100-year time horizon, as defined by the Intergovernmental Panel on Climate Change ([IPCC] 2007). Based on this estimate, the research questions can be summarized as follows:

1. What is the carbon footprint of a loaf of conventional rye bread produced on an industrial scale and consumed in Denmark?
2. What are the main hotspots associated with production and consumption of the rye bread?

3.2. Functional unit

Central to any PCF is the definition of the function unit provided by the system being studied (Heijungs and Suh, 2002; Schau and Fet, 2008; European Commission, 2010). In this paper, the functional unit is defined as 1 kg of conventional rye bread produced on an industrial scale, consumed at home in Denmark, and discarded after its useful life. The selected bread product is sold in Denmark in packages of 0.5 kg with 10 slices, 1 kg with 20 slices, 1.4 kg with 27 slices, and 1 kg with 17 extra-thick slices. The functional unit is defined in accordance with previous studies of bread products and includes the main aspects identified by the literature review (e.g., production method and scale, as well as geographical scope; see Table 1).

3.3. System boundary and cut-off criteria (completeness)

The scope of this study is from cradle to grave, which, in a food supply chain context, sometimes is referred to as “from seed to shelf,” “from farm to fork,” or “from field to the consumer's table” (Kulak et al., 2012). The reason behind this definition is that the life cycle of perishable food products typically ends when the food product is consumed, leaving behind only packaging materials and potential waste. To estimate the PCF, this paper considers an industrial bakery supply chain in Denmark in a single in-depth quantitative case study, which differentiates it from supply chains including local bakeries or home baking (Braschkat et al., 2003). An overview of the stages and unit processes that form part of the production system as well as their interrelationships (flows) is presented in Fig. 1.

In defining the production system, is it also necessary to specify the particular unit processes and/or flows that are excluded from the system (the cut-off criteria). For consistency with previous PAS-compliant studies (Kingsmill, 2009; Espinoza-Orias et al., 2011; Kingsmill, 2012), it was decided to exclude the production of capital goods from the system boundary, although ISO 14044 (ISO, 2006) does not explicitly exclude these items. Consumer transport to retail stores was excluded for the same reason (PAS 2050, 2011). Based on the recipe, the rye bread is modeled with a cut-off equaling 2% of the ingredients by weight. To correct for this cut-off, the included ingredients have been raised equally to account for the missing ingredients. A mass-balance was performed, based on the knowledge of the industrial bakery, in which it was assumed that approximately 10% of the weight vaporizes in the baking process. In addition, the product system excludes solid waste and wastewater from ingredients and final product processing. Given the majority of ingredients delivered to the industrial bakery arrive without packaging, it was considered reasonable to exclude the packaging materials from the remaining small amount of ingredients that are delivered with packaging. Production of barley malt extract excludes input of lactic acid, enzymes, and water for steam, and assumes an 80% efficiency for steam production for mashing, as well as use of spent grains from mash filtration, and heat and hops extracts from boiling. However, these inputs are considered to be inconsequential and only expected to affect the result to a minor degree.

4. Life cycle inventory analysis

This paper applies the process analysis (PA) approach for building a quantitative analytical model of the product system in which data are collected to represent each of the identified unit processes, and thus collected and combined “bottom-up” (Wiedmann and Minx, 2008). Although this method is considered as appropriate when modeling specific production systems (Finkbeiner, 2009), it has been criticized for its risk of excluding important flows, or even unit processes, leading to system incompleteness (Faruk et al., 2002). To ensure a correct scaling of all unit processes and provide a quantitative match with the reference flow, a matrix calculation approach fundamentally based on subsequent matrix inversions was used, in accordance with the procedures as explained by Heijungs and Suh (2002). In addition, the data were modeled using the attributional approach, because it is considered the most appropriate option when depicting environmental impacts from the existing supply chain (European Commission, 2010; PAS, 2050, 2011). In cases where a unit process provides more than one function, this paper applies the principle of system expansion to avoid allocation (ISO 14044, 2006; European Commission, 2010).

4.1. Data collection

The product system defines the unit processes from which it is necessary to collect and quantify data. This approach typically requires data from various sources. As a result, it was deemed necessary to collect and combine multiple datasets, including:

- Primary data from the initial case company
- Publicly available company documents
- Documents and national statistics published by public authorities
- Findings in the literature from previous conducted studies
- Emissions databases

First, interviews were conducted and recorded with the project and environmental manager at the industrial bakery company, the quality manager at a milling company, as well as a representative from a Danish retailer responsible for corporate social responsibility (CSR) and sustainability. In addition, an initial meeting was held with the managing director and the quality manager from the milling company to gain an understanding of the supplier structure further upstream the supply chain. The aim was to identify the unit processes of the analyzed system and the related material, byproducts, and waste flows. Next, a specific rye bread product was chosen and defined as the functional unit in

Table 2
Ingredients required for 1 kg of dough (missing values indicate that the information is not available).

Study		This study	Jespersen (2004)	Espinoza-Orias et al. (2011)	Cauvain and Young (1998)	Nielsen et al. (2003)	Narayanaswamy et al. (2005) [a]	Oxenbøll et al. (2010)
Bread product		Rye	Rye	Wholemeal	Wholemeal	Rye	White	White
Flour, grain and seeds	kg	542	524	561	617	700	690	700
Water (ingredient)	L	417		379	352	400	668	
Salt	kg	12	11	8	6			
Barley malt extract	kg	8	34	0	0			
Yeast	kg	<1	11	22	12			
Other ingredients	kg	0	6	20	12			
Cut-off	kg	20	0	10				14

[a] 1 loaf of bread in the study is assumed to equal 1 kg of bread.

collaboration with the industrial bakery, and the ingredients data were obtained from the quality department of the industrial bakery. The bread ingredients, as compared to previous studies, are shown in Table 2.

Based on this, site specific primary data were collected in the industrial bakery and three distribution warehouses. These data include production data as well as data from energy meters and bills from the Enterprise Resource Planning (ERP) system of the company. Environmental reports and LCA and PCF documents from suppliers were identified based on the supplier catalogue provided by the industrial bakery. In addition, it was deemed necessary to include findings from previous studies as well as datasets from emissions databases to model the complete product system, which is common practice in PCF and LCA. For an overview of the data sources, see Table 3.

4.2. Data quality

The overall data quality of a PCF or LCA starts from the quality of the individual dataset (European Commission, 2010) and can be evaluated according to its representativeness and appropriateness (technological, geographical, and time-related), completeness (impact category coverage and shared or included environmental flows), precision and uncertainty (variability of data values), and methodological appropriateness and consistency (whether the dataset fit the methodological choices; European Commission, 2010). Given that completeness has already been treated when defining the system boundary (see Section 3.3), this section will focus on the remaining quality criteria.

The primary collected data are considered to be of high quality because the data were collected from the specific unit processes,

Table 3
Overview of data sources.

Stage	Unit process	Type of data	Type of data source	Geographical scope	Reference Year[a]	Data source
Energy	Electricity	Secondary	Average	Denmark	2012	Energinet et al. (2012)
	District heating	Secondary	Estimate	Denmark	2012	Danish Energy Agency (2011)
	Diesel and heavy fuel oil	Secondary	Generic	Europe	2006	Fruergaard et al. (2009)
	Natural gas and lubricants	Secondary	Generic	Europe	2003 (valid until 2012)	Bertoldi et al. (2010)
Raw Material	Cultivation of rye	Secondary	Average	Denmark	2012	IPCC (2006), Ahlgren et al. (2009), Mogensen et al. (2011), Statistics Denmark (2013), Danish AgriFish Agency (2013)
	Cultivation of spring Barley	Secondary	Average	Denmark	2012	IPCC (2006), Dalgaard et al. (2008), Statistics Denmark (2012, 2013), Danish AgriFish Agency (2013)
	Grain drying	Secondary	Generic	Sweden (proxy)	2005	Jonsson (2006)
	Barley malt extract	Secondary	Specific	Denmark	2009	Kløverpris et al. (2009)
	Salt	Secondary	Generic	USA (proxy)	1999	Jiménez-Gonzáles and Overcash (2000)
	Yeast	Secondary	Specific	Europe	2011	COFALEC (2012)
	Packaging	Secondary	Generic	Sweden (proxy)	1998	Williams and Wikström (2011)
	Water	Primary	Specific	Denmark	2011	Local waterwork (this study)
Processing	Milling (rye flour)	Primary and secondary	Specific	Denmark	2012	Valsemøllen (2012)
	Bread manufacture	Primary	Specific	Denmark	2012	This study
	Depot storage	Primary	Specific	Denmark	2012	This study
Retail	Retail store	Primary and secondary	Average	Denmark and UK (proxy)	2007–2010	This study, DEFRA (2009), Mena et al. (2011)
Consumption	Ambient storage and toasting	Secondary	Estimate	Denmark	2008–2011	Estimated based on WRAP (2009), Saarinen et al. (2010), Espinoza-Orias et al. (2011) and Petersen et al. (2012)
Waste management	Incineration of bread	Secondary	Generic	Denmark	2008	Astrup et al. (2009), National Food Institute (2009), Reimann (2009)
	Straw used for heating	Secondary	Generic	Denmark	2002	Nielsen et al. (2003)
Transport	Primary bread supply chain	Primary and secondary	Specific and average	Denmark	2003–2012	This study, Nielsen et al. (2003), Jespersen (2004), Danish Ministry of Transport (2010)
	To incineration	Secondary	Generic	Denmark	2004–2008	Eisted et al. (2009)
System expansion	Livestock feed	Secondary	Generic	Denmark	2009	Mogensen et al. (2011), Nielsen et al. (2008)

[a] The year(s) the dataset represents has been determined by the age of the main contributing data (European Commission, 2010).

Table 4
Emissions factors (EF) for general inputs.

Input	Unit	Emission Factor (g CO_2eq)	Selected data source
Electricity	kWh	308	Energinet et al. (2012)
District heating	kWh	196	Danish Energy Agency (2011)
Diesel oil	kWh	311	Fruergaard et al. (2009)
Heavy fuel oil	kWh	327	Ibid
Natural gas	kWh	237	Bertoldi et al. (2010)
Lubricants	kWh	264	Ibid
Water	m^2	192	Local waterwork
Fertilizer N	kg	5917	BioGrace (2011)
Fertilizer P	kg	1014	Ibid
Fertilizer K	kg	579	Ibid
Pesticides	kg	11,026	Ibid
Rye seeds	kg	583	Olesen et al. (2004)
Barley seeds	kg	667	Ibid

Table 5
Composition of the Danish electricity grid (Energinet, 2013).

Input	%
Coal	27
Natural gas	12
Wind, water and sun	41
Biomass and biogas	1
Nuclear	5
Waste	14

ensuring technological and geographical representativeness and cover the exact time period (2012). In addition, data from the entire year are used to account for intra-annual variations. Similarly, secondary data collected from specific suppliers are considered to be technologically and geographically representative, but do not have precise time-related representativeness. In this context, data with good technological and geographical representativeness were considered to be more appropriate than using the most recent data, particularly because the age of the secondary data are considered to be within a reasonable range (see Table 3).

The secondary generic or average data naturally have a lower degree of technological and time-related representativeness. However, the secondary data generally represent the actual case in its geographical coverage (primarily Denmark, but also Europe). Here, the Swedish and UK datasets are considered to be reasonable proxies representing Danish conditions, whereas the dataset for salt was identified to have a negligible effect on the final result of the study (4 g). Methodological appropriateness and consistency are ensured by selecting datasets using an attributional approach. In the following section, data sources and assumptions are accounted for and clearly stated to increase the transparency and reproducibility of this study.

4.3. Inputs to the product system

Table 4 summarize the emission factors used. For provision and use of electricity, the composition of the Danish electricity grid mix from 2012 is applied (see Table 5). Normally, the emission factor from district heating depends on local conditions. However, given that this paper models an average use of district heating from retail stores across Denmark, it was decided to use a national emission factor, as estimated by the Danish Energy Agency (2011). The emission factor for provision and combustion of fuels is based on Fruergaard et al. (2009) and Bertoldi et al. (2010), who both rely on European conditions (see Table 3). Inputs to cultivation comprise mainly production of mineral fertilizers, seeds, and pesticide for cultivation purposes. For provision of fertilizer, it was considered appropriate to use the harmonized emission factor provided through the BioGrace (2011) project.

4.4. Cultivation

For cultivation of conventional crops, inputs are used such as seeds for sowing, fertilizers, and pesticides, but also diesel are required for field operations, such as plowing, harrowing, sowing, and harvesting, as shown in Table 6. After the crops are harvested, they must be post-processed or dried to reduce the moisture content to 14% to allow for storage (Rajaniemi et al., 2011). Given that the industrial bakery uses only Danish rye and sourced barley malt extract from Denmark, this paper models the cultivation of rye and spring barley in Denmark. It was assumed that all nutrients applied to the fields originate from the use of synthetic fertilizers. The cultivation of rye and barley result in co-production of straw, which is left in the field, as well as used as fodder and for heating purposes (see Table 6). Straw used as fodder was modeled as replacing a feed mix comprising the main fodder ingredients, based on Nielsen et al. (2008). Straw used for heating purposes was modeled as incinerated with electricity and heat recovery.

4.5. Ingredients processing

This stage includes processing of ingredients used in bread manufacturing such as wholemeal rye flour and cleaned rye grain, but also, to a lesser extent, malt extract, salt, and yeast. The milling

Table 6
Inventories for cultivation of 1 ha of rye and spring barley.

	Unit	Rye	Spring barley	Rye data source	Barley data sources
Dry matter	%	86	85	Ahlgren et al. (2009)	Dalgaard et al. (2008)
Yield	kg/ha	5881	5490	Statistics Denmark (2013)	Statistics Denmark (2013)
Electricity	kWh	17	32	Mogensen et al. (2011)	Dalgaard et al. (2008)
Diesel	kWh	1176	1273	Ibid and Jonsson (2006)	Ibid
Lubricant oil	kWh	176	138	Nielsen et al. (2003)	Ibid
Seeds	kg	170	235	Rajaniemi et al. (2011)	Rajaniemi et al. (2011)
Fertilizer N	kg	129	123	Danish AgriFish Agency (2013)	The Danish AgriFish Agency (2013)
Fertilizer P	kg	18	22	Ibid	Ibid
Fertilizer K	kg	55	43	Ibid	Ibid
Pesticides (active matter)	kg	1.2	1.8	Jespersen (2004)	Statistics Denmark (2012)
Direct and indirect N_2O emissions	kg	2.97	3.00	IPCC (2006), tier 1 approach	IPCC (2006), tier 1 approach
Straw of which	kg	4760	3019	Statistics Denmark (2013)	Statistics Denmark (2013)
- Left on field	kg	1688	848	Ibid	Ibid
- Used for fodder	kg	1582	1474	Ibid	Ibid
- Used for heating	kg	1490	697	Ibid	Ibid
Environmental impact					
Climate change (ex farm)	g CO_2eq/kg grain	223	298	Cradle-to-gate, calculated in model	Cradle-to-gate, calculated in model

Table 7
Inventory for milling.

Input	Unit	Valsemøllen (2012)	Cerealia Mills (2010)	Nielsen et al. (2003)
Rye grain	kg	1000	1000	1429
Water (process)	L	81.7	62.6	142.9
Water (wastewater)	L	7.0	15.4	
Electricity	kWh	74.4	89.5	114.3
District heating	kWh	4.3	0	0
Natural gas	kWh	0	37.6	142.9
Diesel	kWh	0	2.7	0
Output				
Rye flour	kg	1000 (wholemeal)	1000 (wholemeal)	1000 (bolted flour)
Bran	kg	0	0	429
Environmental impact				
Climate change (ex mill)	g CO_2eq/kg flour	253	not calculated	980

process includes cleaning the grain received, storage in silos, moistening with water, grinding at different rolls, controlling, and packaging. Because wholemeal rye flour is used in the bread recipe, no byproducts are produced during the milling process; the whole grain is used (see Table 7). The milling process was modeled using data from Valsemøllen (2012) because this represents the specific case conditions and was cross-checked with data from Cerealia Mills (2010), which according to Nielsen et al. (2003), represents approximately 60% of the flour and oat flakes produced in Denmark.

The malt extract production process is modeled using data from Harboes Bryggeri published in a comparative LCA (Kløverpris et al., 2009), because this represents the specific case conditions. The process includes production of the malt, hammer milling, mashing, mash filtration, and boiling. The processing of malt results in co-production of barley sharps and malt sprouts, which are used as animal feed (Kløverpris et al., 2009). The avoided environmental burden is modeled using the calculation by Kløverpris et al. (2009) that production of 1 ton of malt would result in 12.4 kg barley sharps and 43.9 kg malt sprouts, replacing 50.4 kg spring barley, based on the digestible energy content. The data sources for the remaining ingredients are indicated in Table 3.

4.6. Packaging

Packaging is fundamental to almost all food products (Pardo and Zufia, 2012; Roy et al., 2009) and can represent significant environmental impacts (Cellura et al., 2012). The primary role of packaging is to protect the quality of food products and minimize losses during storage and transportation, and hence should be "fit for purpose." Williams and Wikström (2011) examine the environmental impact of packaging for bread products, including the waste handling of the packaging after useful life of the bread. The packaging includes the primary packaging material, such as the plastic bags produced of low-density polyethylene with a plastic clips, as well as returnable plastic boxes as secondary packaging. Given their packaging system is in agreement with this study, the emission factor of 28 g CO_2eq/kg bread is used, as provided by Williams and Wikström (2011).

4.7. Final product processing

According to this study, energy use in bread manufacturing includes electricity for machinery and cooling, as well as natural gas for heating purposes. After the rye breads are packed, they are stored at a local depot or transferred to other depots, from where they then are distributed to retail stores. To validate the dataset, a cross-check was performed with data on bread manufacturing in the extant literature, which resulted in diverging results, as shown in Table 8. This discrepancy is similar to Andersson and Ohlsson (1999), who identified different results for their two industrial bakery cases. Processing of bread results in various bakery wastes that, according to the bakery respondent, is used as pig feed. As a result, it replaces conventional pig feed, which comprises wheat, spring barley, and soy bean meal as the three main ingredients, as well as molasses, covering approximately 91% of the total ingredients (Nielsen et al., 2008). The avoided environmental burden is calculated based on the digestible energy content to account for the differences in energy content of the bakery waste and the feed ingredients. For this purpose, the system is modeled using data from Mogensen et al. (2011).

4.8. Transport

Data on distances traveled from cultivation to ingredients processing are based on Nielsen et al. (2003). Data regarding transportation to and from the bakery were obtained from the industrial bakery and the milling company, and transportation from depots to retailers were based on Jespersen (2004). GHG emissions from transportation are calculated using the software TEMA 2010 (Danish Ministry of Transport, 2010), which take account general

Table 8
Inventory for final product processing (missing values indicate that the information is not available).

Study		This study	Espinoza-Orias et al. (2011)	Nielsen et al. (2003)	Oxenbøll et al. (2010)	Grönroos et al. (2006)
Bread product		Rye	Wholemeal	Rye	White	Rye
Ingredients	kg	1167				
Water (cleaning, etc.)	L	88		1500		
Energy (unspecified)	kWh	0	750	0	0	0
Electricity	kWh	187	0	20	170	770
Heating	kWh	358	0	278	175	1058
Output						
Bread	kg	1000	1000	1000	1000	1000
Water vapor	kg	100				
Organic waste	kg	67				
Environmental impact						
Climate change (ex bakery)	g CO_2eq/kg bread	340		720		
Sensitivity analysis (final)	g CO_2eq/kg bread	731	815[a]	615	653	1.294
Difference	%	0.0%	+11.5%	−15.9%	−10.7%	+39.0%

[a] Assumes same allocation between electricity and heating as in this study.

driving patterns, truck type and size, approval norm, type of fuel, distance, the allocation of km driven in cities, highway and motorway, including the average driving speed in each zone, as well as fill rate and empty return. For an overview, see Fig. 1 and Table 9.

4.9. Retailing

From the literature search, it became evident that limited data have been published on energy consumption in Danish food retailing. Consequently, it was decided to use data provided by DEFRA (2009a) for UK food retailing with the assumption that the energy consumption is similar to retailing in Denmark. According to DEFRA (2009a), bread products require ambient storage conditions, which require energy for lighting, heating, ventilation, and air conditioning (HVAC), as well as a plastic bag when sold. It was assumed that bread products are, on average stored, for one day, that district heating is used, and that bread waste equals 10% of the delivered bread to stores (Mena et al., 2011).

4.10. Consumption

There are no data available on how bread is consumed at home in Denmark. For this reason, it will be assumed that bread is stored in ambient conditions and that half of the bread consumed is toasted and the other half is consumed directly. The energy used for toasting was calculated according to Espinoza-Orias et al. (2011). The percentage of bread wasted was calculated by multiplying the average amount of bread waste per capita (Petersen et al., 2012) for the population in Denmark and dividing that figure by an approximate bread market of 360,000 tons (Saarinen et al., 2010). This calculation resulted in a proportion of bread waste equal to 29% of purchased bread, which is similar to the result by WRAP (2009), based on UK conditions. According to Katajajuuri et al. (2012), bread is mainly disposed of when it is moldy or otherwise undesirable due to drying out or becoming less appetizing.

4.11. Waste management

From the retail and consumption stages, bread waste is modeled as discarded and shipped for incineration. The waste management process was modeled according to Astrup et al. (2009), who explain how to account for GHG emissions from grate-fired incineration, which is the most commonly used technology for incineration (see Table 10). Based on both a survey (Reimann, 2009) and a case study (Fruergaard et al., 2010) of Danish incineration plants, it is reasonable to assume that waste is primarily used to produce both electricity and heat. Multiple studies have been conducted on the conversion efficiencies between energy in waste and electricity and/or heat produced (Astrup et al., 2009; Fruergaard et al., 2009). According to a survey, the weighted average gross conversion efficiency for cogeneration with heat recovery was found to be 14.2% for electricity production and 45.9% for heat recovery (Fruergaard et al., 2009; Reimann, 2009).

5. Results

The GHG emissions associated with 1 kg of rye bread consumed in Denmark were estimated to be 731 g CO_2eq. In accordance with the extant literature it was identified that the life cycle of bread is foremost dominated by GHG emissions from the raw material stage, which accounts for 412 g CO_2eq. At the agricultural stage, N_2O emissions is dominant in cultivation of crops (62%), but diesel for field operations also contributes significantly (34%). The secondary hotspot is processing, which, due to high energy use (nearly equally from electricity and natural gas), accounts for 279 g CO_2eq.

Table 9
Transportation data and assumptions (missing values indicate that the information is not available).

From	To	t truck EURO4-norm	Distance in km	km/t	kg CO_2eq/t
Cultivation (rye and spring barley)	Grain Drying	28–32	50	7.80	8.20
Grain Drying	Mill	40–48	70	4.20	5.55
Mill	Bakery	40–4	85	5.67	6.42
Cultivation	Malting	28–32	50	7.80	8.20
Malting	Bakery	20–2	204	18.18	13.79
Salt	Bakery	20–26	298	26.58	19.97
Yeast	Bakery (refrigerated)	20–26	226	24.20	22.40[a]
Bakery	Depots	40–48	201	9.43	9.84
Depots	Retail	7.5–12	175	40.06	21.33
Retail	Consumption	Excluded	0	0.00	0.00
Cultivation (barley and wheat)[b]	Feed production	12	25		9.00
Feed production[b]	Livestock production	28	25		6.00
Soybean meal (Argentina and Brazil)[b]	Denmark	Mixed			342.00
Molasses (Russia and Germany)[b]	Denmark	40			237.00
Soy Bean Meal and Molasses (Denmark)[b]	Livestock production	28	121		27.00
Cultivation (straw)	Livestock production	28–32	50	6.25	6.16
Bakery, Mill and Depot (waste)	Livestock production	20–26	12	2.30	1.91
Cultivation (straw)	Incineration	28–32	50	6.25	6.16
Retail[c]	Incineration	NA	20		13
Consumption[c]	Incineration	NA	20		13

[a] Includes an additional 19.5% to account for refrigeration fuel consumption (Tassou et al., 2009).
[b] Mogensen et al. (2011).
[c] Eisted et al. (2009).

Table 10
Inventory for incineration and production of heat.

Study		Masnedø Kraftvarmeværk (2010)	Astrup et al. (2009)
Input		Straw	Bread
Waste	kg	1000	1000
Fuel oil	kWh	0	10.5
Diesel oil	kWh	1.8[a]	0
Electricity (consumed)	kWh	110[a]	92.5
Natural gas (consumed)	kWh	0	38.5
District Heating (consumed)	kWh	11[a]	0
Water	L	75[a]	500
$CaCO_3$	kg	0	4
$Ca(OH)_2$	kg	0	6
NaOH	kg	0	3.5
NH_3	kg	4.0	2.5
Output			
N_2O emissions	kg	0.020[a]	0.013
Air pollution control residues	kg	0	25
Electricity (produced)	kWh	951[b]	327[c]
District heating (produced)	kWh	2,357[b]	1,058[c]
Ashes	kg	0.1	21[d]
Slag	kg	52	0

[a] Nielsen et al. (2003).
[b] Lower heating value (LHV) of straw is 14.5 GJ/t (Fruergaard et al., 2009).
[c] This study and Reimann (2009).
[d] National Food Institute (2009).

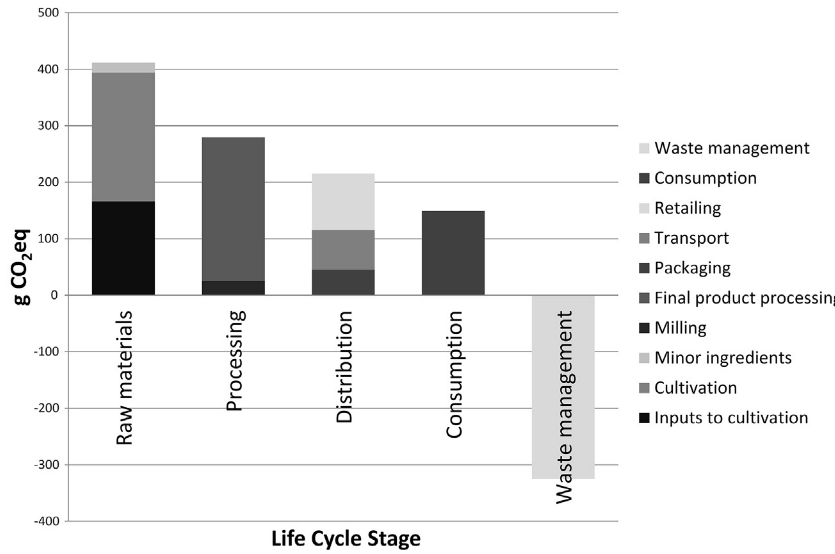

Fig. 2. Relative GHG emissions from different life cycle stages.

In addition, the waste management stage is identified to yield a net reduction equaling 325 g CO_2eq. The result is shown in Fig. 2.

There is uncertainty embedded in all LCA and PCF studies, including the model in this paper. Based on this uncertainty, three sensitivity analyses were performed to measure how emission factors and choice of datasets at different stages affects the result. The dominant role of N_2O emissions at the cultivation stage, combined with selection of the Intergovernmental Panel on Climate Change ([IPCC] 2006) Tier 1 approach to calculate N_2O emissions from managed soils, using the default emission factors, indicates the importance of performing sensitivity analysis using the related uncertainty values. Consequently, a second sensitivity analysis was performed to determine this effect. As shown in Tables 11 and 12, the uncertainty ranges are large for the default emission factors and have a significant impact on the final result. However, in light of new evidence, the first default emission factor was adjusted in the IPCC (2006) publication from 1.25% to 1% (see also Schäfer and Blanke, 2012), which indicates that the emission factor is most likely to be in the lower end of the uncertainty range, as in this study. Lastly, the prominent role of final product processing, in terms of the contribution to the PCF and the large variations identified in energy consumption between bakeries, indicates that this emission factor analysis ought to be tested as well using the different datasets. As shown in Table 12, using the different datasets for the final product processing provide an even larger range in the result, which further indicate the importance of collecting reliable data at this stage.

In addition, the “inputs to cultivation” stage, production of fertilizer N is identified to contribute significantly to the PCF (134 g CO_2eq). However, in the literature, large variations exist between emission factors for fertilizer N. In fact, Ahlgren et al. (2009) discuss this issue and point towards a European average of 6800 g CO_2eq/kg fertilizer N in 2003 to as low as 2900 g CO_2eq/kg fertilizer N for modern industries using catalytic cleaning of N_2O (see also Rajaniemi et al., 2011; Yara International ASA, 2014). However, emission factors as high as 7616 g CO_2eq/kg fertilizer N were identified. Therefore, the first sensitivity analysis determines the effects on the results if fertilizer N is produced with or without catalytic cleaning of N_2O. The result of the sensitivity analysis can be seen in Table 12.

6. Discussion

This study confirms the previous finding that it remains difficult to make comparisons (Pulkkinen et al., 2010), especially because a typical weakness in previous studies is their nontransparent nature regarding the use of data sources and limitations. As shown in Table 1, previous studies also differ in their life cycle methodology, including the definition of the product system boundary and the selected allocation method, as well as the circumstances of production such as the bread product (recipe), production method and geographical scope. Consequently, it is difficult to compare the results of this study with the results of other studies in the extant body of literature. To partially overcome this difficulty, the life cycle stages were categorized according to the stages defined by Espinoza-Orias et al. (2011), as shown in Table 13. A calculation using a redefined functional unit was performed to compare to previous studies excluding the consumption and waste management stages (see Table 14).

The comparison revealed that this and previous studies identify the raw material stage as the main contributor to the PCF (approximately 40%–56%). This and previous studies also point towards the processing stage as a prominent contributor, primarily based on the energy required for bread manufacturing. However, this study identified the processing and distribution stages as the second and third main hotspots, respectively, whereas previous

Table 11
Uncertainty range of default emission factor of IPCC tier 1 approach.

Parameters	Low	Default	High
EF_1 for N additions	0.003	0.01	0.03
EF_4 for volatilization and re-deposition	0.002	0.01	0.05
EF_5 from leaching and run-off	0.0005	0.0075	0.025

Table 12
Results of sensitivity analysis.

Parameters	Low	Default	High
Fertilizer N	661	731	770
IPCC tier 1 approach	605	731	1.098
Bakery dataset	615	731	1.294

Table 13
Relative contributions (%) of the life cycle stages to the carbon footprint of bread (missing values indicate that the information is not available).

Summary	This study	This study (excl. waste management)	Espinoza-Orias et al. (2011)	Espinoza-Orias et al. (2011)	Kingsmill (2012)	Low	High
Type of study	PCF	PCF	PAS 2050 PCF case study	PAS 2050 PCF generic data	PAS 2050 PCF case study		
Functional unit	1 kg of fresh rye bread	1 kg of fresh rye bread	1 kg of sliced bread	1 kg of sliced bread	1 kg of sliced bread		
Life Cycle Stages	consumed at home	consumed at home	consumed at home	consumed at home	purchased and consumed at home		
Raw materials	56.3	39.0	41	45	40.4	40.4	56.3
Inputs to cultivation	22.7	15.7				22.7	22.7
Cultivation	31.2	21.6	35	32	40.4	31.2	40.4
(Minor) ingredients	2.4	1.7	6	13		2.4	13.0
Processing	38.3	26.5	19	12	18.8	12.0	38.3
Milling	3.5	2.4	3	5		3.0	5.0
Bread manufacture	34.8	24.1	16	7		7.0	34.8
Distribution	29.4	20.3	9	11	7.3	7.3	29.4
Packaging	6.1	4.2	1	4	2.0	1.0	6.1
Transport	9.7	6.7	4	5	4.6	4.0	9.7
Retail	13.6	9.4	4	2	0.7	0.7	13.6
Consumption	20.5	14.2	25	26	29.8	20.5	29.8
Waste management	−44.5	0.0	6	6	3.7	−44.5	6.0
g CO_2eq/kg bread	**731**	**1056**	**From 1388 to 1555**+ 156 if 30% consumer waste	**From 1221 to 1375**	**From 1188 to 1250**	**1143**	**1555** (+156)

studies identified the consumption and processing stages as the second and third main hotspots, respectively. Interestingly, the main difference between this study and previous studies was identified in relation to the waste management stage, where this study provides a net savings in comparison to a net contribution in previous studies (Espinoza-Orias et al., 2011; Kingsmill, 2012). Espinoza-Orias et al. (2011) models waste bread as disposed in landfills, compared to incineration in this paper. The finding that incineration can result in a net saving to the PCF is not a new proposition, but has been confirmed by research specifically dealing with the waste management stage (Burnley et al., 2012; Jeswani et al., 2013; Manfredi and Pant, 2013).

7. Conclusion

The PCF of 1 kg of rye bread consumed in Denmark was estimated using an attribution approach to be 731 g CO_2eq. The main hotspot was identified, in agreement with previous studies, to be the raw material stage, which, in this paper, accounts for 412 g CO_2eq. The secondary hotspot was identified to be the processing stage, which, due to high energy use (nearly equally from electricity and natural gas), accounts for 279 g CO_2eq. The distribution and consumption stages were also identified as significant contributors and hence identified to be the third and fourth hotspots, respectively. In addition, this paper highlights the great potential that the waste management stage can have in reducing the carbon footprint, although it has been neglected as a hotspot in previous studies due a low environmental impact. Thus, this research indicates that hotspots should not exclusively be identified based on their contribution to the PCF, but also their improvement potential. This conclusion is similar to Sánchez et al. (2004), who argue that life cycle management should, to a large extent, be governed by an awareness of environmental improvement potential (Sánchez et al., 2004). Based on this finding, we encourage future research to

Table 14
Relative contributions (%) of the life cycle stages to the carbon footprint of bread (missing values indicate that the information is not available).

Summary	This study	This study (excl. waste management)	Andersson and Ohlsson (1999)	Braschkat et al. (2003)	Holderbeke et al. (2003)	Narayanas-wamy et al. (2005)	SIK (2009)	Kulak et al. (2012)	Low	High
Type of study	PCF	PCF	LCA of industrial bakeries	LCA of industrial bakery	LCA of industrial bakery	LCA of industrial bakery	LCA of industrial bakeries	LCA of local bakeries (average)		
Bread product	Rye	Rye	White	White	White	White	White/mixed	Mixed		
Raw materials	61.1	45.7	42.5	57.2	41.4	16.5	58.8	66.5	16.5	66.5
Inputs to cultivation	24.7	18.4							24.7	24.7
Cultivation	33.8	25.4	42.5	57.2	41.4			66.5	33.8	66.5
(Minor) ingredients	2.6	1.9							2.6	2.6
Processing	41.5	31.0	17.4	35.7	42,7	27.1	7.5	6.3	6.3	42.7
Milling	3.8	2.8		7.1	4.9			2.3	2.3	7.1
Bread manufacture	37.7	28.2		28.6	37.8			4.0	4.0	37.8
Distribution	31.2	23.3	38.5	7.1	15.9	24.0	33.7	27.2	7.1	38.5
Packaging	6.7	5.0	3.1				11.8		3.1	11.8
Transport	9.7	7.3	35.4	7.1	15.9	2.4	18.6	27.2	2.4	35.4
Retail	14.8	11.0				21.6[a]	3.3		3.3	21.6
Consumption	0.0	0.0	1.6			32.4[a]			0.0	32.4
Waste management	−33.8	0.0							−33.8	0.0
g CO_2eq/kg bread	**478**	**640**	**From 630 to 1000**	**448**	**620**	**2300**	**From 505 to 826**	**From 610 to 1900**	**448**	**2300**

[a] Impact allocated between retail and consumption stages based on this study.

investigate how hotspots can be identified based on their potential for change, rather than solely on their contribution to the PCF. In addition, through sensitivity analysis, this paper identifies that reducing uncertainty ranges when calculating N_2O emissions from managed soils, as well as high data quality in relation to industrial bakery datasets, is essential for achieving robust results. However, it is important to note that solely assessing GHG emissions potentially creates the risk of burden shifting, where reducing GHG emissions can result in increasing other environmental impacts. Therefore, future research should investigate other environmental impacts in the life cycle of bread.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.06.061.

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