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CARBON FOOTPRINTING

The carbon footprint of bread

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Abstract
Background, aim, and scope The aim of this study has been to estimate the carbon footprint of bread produced and consumed in the UK. Sliced white and wholemeal bread has been considered for these purposes and the functional unit is defined as "one loaf of sliced bread (800 g) consumed at home". The influence on the carbon footprint of several parameters has been analysed, including country of origin of wheat (UK, Canada, France, Germany, Spain and USA), type of flour (white, brown and wholemeal) and type of packaging (plastic and paper bags). The effect on the results of the type of data (primary and secondary) has also been considered.
Materials and methods The carbon footprint has been estimated in accordance with the PAS 2050 methodology. The results have also been calculated following the ISO 14044 methodology to identify any differences in the two approaches and the results. Primary data for the PAS 2050-compliant study have been collected from a UK bread supply chain. Secondary data have been sourced from the UK statistics, life cycle inventory databases and other published sources.
Results and discussion The carbon footprint results range from 977 to 1,244 g CO_2 eq. per loaf of bread. Wholemeal thick-sliced bread packaged in plastic bags has the lowest carbon footprint and white medium-sliced bread in paper bag the highest. The main hot spots are wheat cultivation and consumption of bread (refrigerated storage and toasting), contributing 35% and 25% to the total, respectively.
Conclusions The carbon footprint could be reduced on average by 25% by avoiding toasting and refrigerated storage of bread. Further reductions (5–10%) could be achieved by reducing the amount of waste bread discarded by consumers. The contribution of transport and packaging to the overall results is small. Similar trends in the results are also found in the study based on the secondary data and following the ISO 14044 methodology.

Keywords Bread · Carbon footprint · Global warming potential · ISO 14044 · LCA · PAS 2050

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1 Introduction

International agreements and scientific assessments call for a concerted action for substantial reductions of global greenhouse gas (GHG) emissions. A better understanding of where along the supply chains and the life cycle of products GHG emissions should be reduced can be gained by calculating the carbon footprint of products, the term now commonly used for the life cycle assessment (LCA) impact category global warming potential.

In October 2008, the British Standards Institution launched the Publicly Available Specification (PAS) 2050:2008 "Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services" (BSI 2008). PAS 2050 aims to provide a standardised guidance for calculating carbon footprints of products and services; the PAS 2050-compliant results can also be used for carbon labelling in the UK (subject to certification by a PAS 2050 accredited body).

An increasing number of organisations are calculating carbon footprints of their products and services using PAS 2050. Currently, most companies are using the information gained through carbon footprinting to identify opportunities for reducing the carbon footprint within their supply chain. A smaller number of companies, including retailers, are also disclosing the information on carbon footprints of their products to enable consumers to make more informed purchasing decisions on 'environmental' grounds.

As a result, the carbon footprints of products, and particularly of food, have become a topic of increasing interest. In an attempt to contribute to a more informed debate on the impacts of food on climate change, this study presents the results of the estimation of the carbon footprint of bread, a staple food product in many countries. In the UK, 99% of households buy bread and 12 million loaves are sold each day, 80% of which is sold sliced and wrapped (FAB 2011; FoB 2007; Mintel 2007). Thus, the focus of the study is on sliced packaged bread, produced and consumed in the UK.

The carbon footprint has been estimated according to the PAS 2050 methodology (BSI 2008). For comparison, the results have also been calculated following the ISO 14044 (ISO 2006a) methodology to identify the influence on the results of any differences in the two approaches. Where appropriate, the differences between the PAS 2050 and ISO 14044 are discussed; differences with the ISO 14025 standard on Environmental Product Declaration (ISO 2006b) and the related Product Category Rules (PCR) for bread (EPD 2010) are also highlighted as applicable.

2 Methodology

2.1 Goal and scope of the study

The main aim of this study has been to estimate the carbon footprint and identify the hot spots in the life cycle of white and wholemeal bread produced and consumed in the UK. The purpose of the study has been to provide information for carbon labelling to inform the consumer on the total carbon footprint of bread as well as to indicate how it could be reduced. The PAS 2050 methodology has been followed for these purposes.

The second aim of this study has been to study the influence of different parameters on the total results. This includes the origin of wheat (UK-grown and imported), type of flour (white, brown and wholemeal), thickness of bread slices (medium and thick) and packaging materials (plastic and paper bags).

Another aim of the study has been to find out if secondary (generic) data could be used as "proxies" for the primary (specific) data,[1] thus potentially reducing the data collection effort. This is because PAS 2050 has specific rules that favour primary over secondary data (see Section 2.3). ISO 14044, on the other hand, allows the use of secondary data. Therefore, the ISO methodology has been followed for the bread study based on generic data.

The final aim of the study has been to compare the methodological approaches between PAS 2050 and ISO 14044 to identify any influence on the results; a summary of the main methodological differences between the two standards can be found in Table 1.

Therefore, two types of study are presented and discussed: PAS 2050-compliant study, based on the primary data specific to the UK bread supply chain considered here, and generic study based on the secondary data and following the ISO 14044 methodology.

The analysis is based on the functional unit defined as a 'standard 800 g loaf of sliced bread' made of wheat flour at industrial scale and consumed at home. Two slice sizes are considered: thick (47 g per slice) and medium (40 g per slice). The scope of the study is from 'cradle to grave' as explained in more detail below. With reference to PAS 2050, this functional unit and scope of the study are appropriate for business-to-consumer communication and for carbon labelling.

2.2 System boundaries and system definition

As shown in Fig. 1, the following stages are included within the system boundary:

1. Raw materials:
   - Agricultural stage: cultivation of wheat, grain drying and storage
   - Manufacture and intermediate processing of ingredients and packaging materials
2. Processing:
   - Milling of wheat to produce wheat flour and the co-products (wheat germ and bran)
   - Storage of ingredients, mixing, proving, baking, slicing and bread packing

[1] In the context of this study, primary (specific) data are those collected directly from a player in the bread supply chain and secondary (generic) data are those sourced from literature, LCI databases or other sources. Primary data are compliant with PAS 2050. Wherever necessary and possible, the secondary data have been adapted for the UK bread supply chain considered in this study to reflect the UK situation (e.g., background energy mix etc.).

Table 1 Main methodological differences between PAS 2050 and ISO 14044

Methodological aspect	PAS 2050	ISO 14044
Life cycle methodology	Attributional	Attributional or consequential
System boundary	Cradle to gate (business to business) Cradle to grave (business to consumer)	Depending on the goal of the study
Primary data	For processes owned, operated or controlled by organisation implementing PAS 2050 and contributing 10% or more to the upstream emissions	Data quality depends on the goal and scope of the study. Data may be collected from production sites, or obtained or calculated from other sources. Data may include a mixture of measured, calculated or estimated data
Secondary data	Preferred data from peer reviewed publications and competent sources. For downstream emissions beyond organisation implementing PAS 2050 and for cases when collection of primary data is impractical or not possible	
Cut-off criteria	1% ("materiality threshold")	Not specified but must be based on mass, energy and environmental significance
Waste management	Included	Included if the emissions comply with cut-off criteria
Consumer transport	Excluded	Not specified
Capital goods	Excluded	Included
Biogenic carbon storage in products	Included for non-food, non-feed; more than 50% of the mass of carbon of biogenic origin in the product remains removed from the atmosphere for 1 year or longer	Not specified
Release of carbon from use and final disposal	Included after the first year of formation of product	Not specified
Land-use change	Included if within the last 20 years	Not specified
Allocation	System subdivision; system expansion; economic allocation	System subdivision; system expansion; mass allocation; economic allocation

3. Retail: storage of products at ambient temperature in retail shops
4. Consumption:
   - Storage of bread at home at room temperature and under refrigerated conditions (chilled and frozen)
   - Consumption of bread at home (as it is and toasted)
5. Waste management: disposal of bread and packaging waste by landfilling
6. Transport of ingredients, packaging materials, products and waste along the life cycle.

Given the aim of the study, this system boundary is compliant with both the PAS 2050 and ISO 14044 standards.

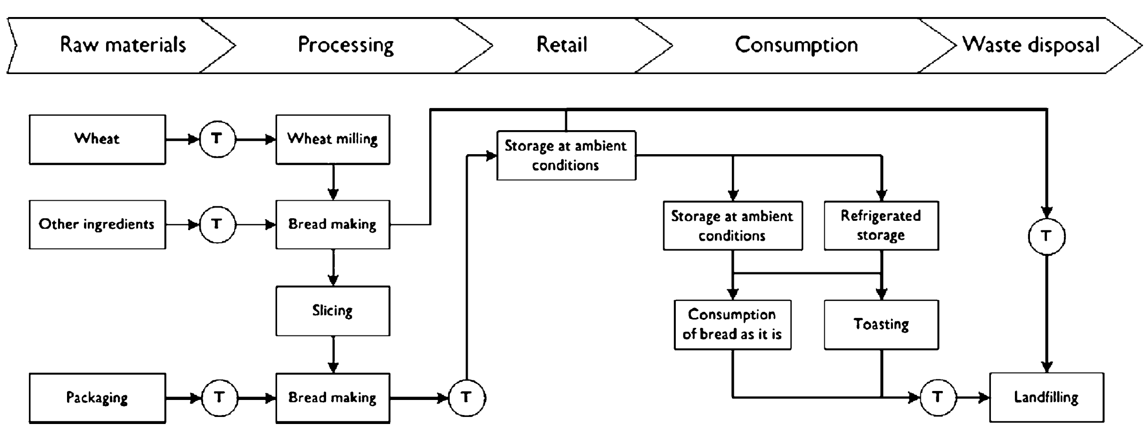

Fig. 1 Bread system boundary (T=transport)

2.2.1 Raw materials

The agricultural stage includes wheat cultivation and post-harvest operations such as grain drying and grain storage. As shown in Fig. 2, wheat used in the UK is both home-grown and imported. Due to the relatively high yields of wheat in the UK, around 80% of the wheat used in the UK flour milling industry is home-grown (NABIM 2008). The remaining wheat is imported because it has different quality parameters required to produce strong flours used in mixtures for breadmaking and specialty flours. Wheat is imported from Canada, France, Germany, Spain and USA—all these sources have been considered in the study, as discussed later. It has also been assumed throughout that wheat is cultivated on land which has been used for agricultural purposes for longer than 20 years (PAS 2050 Clause 5.5); therefore, the GHG emissions arising from land use change are not considered.

In addition to wheat, other ingredients used to make bread considered here are yeast and salt. Furthermore, in the UK the law requires iron, thiamin and niacin to be added to brown and white flour to compensate for nutrient losses during milling (BNF 2004). Calcium is also added to some flours. Although minor, these ingredients have been considered in the analysis (see the next section for further detail).

2.2.2 Processing

In the processing stage, wheat is first milled to produce flour (see Fig. 1). Depending on the wheat components included, three basic flour types can be produced: white, brown or wholemeal. White flour contains typically 75% of the grain, brown flour 85% of the grain and wholemeal flour is made from the whole grain. In the UK, on average, bread wheat milling produces 86.7% of white flour, 8.7% wholemeal flour and 4.6% brown flour (Defra 2009a). All three types of flour have been considered in this study. As indicated in Fig. 2, flour is sold to bakeries, food processors and retailers. The majority (62%) of the flour produced in the UK is destined for breadmaking (Defra 2009a).

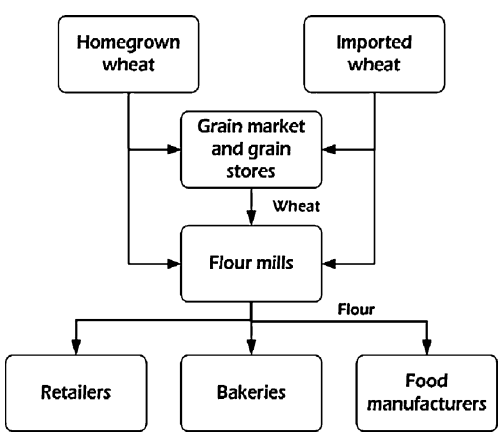

Fig. 2 Flour supply chain in the UK (adapted from NABIM 2008)

Breadmaking comprises dough preparation, proving, baking, slicing and finally packing using either polyethylene or wax-coated paper bags. The typical loaf of bread produced in the UK weighs 800 g and is sliced as extra-thick (57.5 g per slice), thick (47 g), medium (40 g) and thin slices (28.8 g). In this study, only thick and medium slices are considered.

2.2.3 Retail

Due to a high throughput and a short shelf life, bread is distributed from bakeries directly to the retail shops, bypassing central distribution centres. For the purposes of this study, retail storage time of one day at ambient conditions has been assumed.

2.2.4 Consumption

The ‘completeness’ principle in PAS 2050 requires the inclusion of the consumption stage, considering all possible consumption modes—in the case of bread, this includes toasting as well as chilled and frozen storage (Carbon 2009). These requirements are in agreement with the PCR for bread (EPD 2010). ISO 14044, on the other hand, does not have such specific requirements.

There is no reliable information on how bread is consumed at home. In the absence of real data, the PCR recommended by the Carbon Trust (2009) have been used here, assuming that 39% of bread is toasted and the rest is eaten as it is; 20% of bread is frozen over 10 days and 8% is chilled for 4 days, with the rest kept at ambient conditions.

2.2.5 Waste management and transport

The final stage considered is post-consumer bread waste. There are no specific data on how much bread is wasted by consumer, but WRAP (2008) estimate that 30% of food in the UK is landfilled together with packaging. In this study, it has been assumed that 10% of bread is discarded, in accordance with the PCR for bread recommended by the Carbon Trust (2009). To gauge the impact of waste bread on the total carbon footprint, a sensitivity analysis has been carried out using the value of 30% of waste; this is discussed further below.

Inclusion of post-consumer waste is one methodological difference between the PAS 2050 and the other standards. While ISO 14044 allows for the use of cut-off criteria based

Table 2 Overview of data sources used in the PAS 2050-compliant and generic studies [NB: primary data used only in the PAS 2050-compliant study]

	Data set	Type of data	Source	Type of study the data used in:
Raw materials	Cultivation of wheat in the UK (2007)	Secondary	This study, based on data from Defra (2007; 2008a, b) & IPCC (2006)	PAS 2050-compliant and generic
	Cultivation of spring wheat in Canada (2007)	Secondary	Pelletier (2008)	Generic
	Cultivation of wheat in France	Secondary	Ecoinvent (2007)	Generic
	Cultivation of wheat in Germany	Secondary	Ecoinvent (2007)	Generic
	Cultivation of wheat in USA	Secondary	Ecoinvent (2007)	Generic
	Grain drying and storage	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Production of flour additives	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Production of skimmed milk powder	Secondary	PROBAS	PAS 2050-compliant and generic
	Production of yeast	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Production of salt	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Production of paper packaging	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Production of plastic (PE) packaging	Secondary	Plastics Europe (2005)	PAS 2050-compliant and generic
Processing	Wheat milling	Primary	UK bakery	PAS 2050-compliant
		Secondary	Nielsen et al. (2003)	Generic
	Bread making	Primary	UK bakery	PAS 2050-compliant
		Secondary	Nielsen et al. (2003)	Generic
Retail	Ambient storage at retail shop and store air conditioning	Primary	UK retailer	PAS 2050-compliant
		Secondary	Defra (2009b)	Generic
Consu-mption	Ambient, chilled and frozen storage; toasting	Secondary	Carbon Trust (2009)	PAS 2050-compliant and generic
Waste management	Landfilling of plastics (PE)	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Landfilling of paper	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
	Landfilling of bread (as municipal waste)	Secondary	Ecoinvent (2007)	PAS 2050-compliant and generic
Trans-port	Road and rail transport	Secondary	EU JRC (2007)	PAS 2050-compliant and generic
	Bulk sea carrier		EU JRC (2007)	
	Refrigerated transport		Carbon Trust (2008)	

on mass, energy or environmental significance to decide whether such waste should be considered (see Table 1), this consideration is not part of the ISO 14025 (ISO 2006b) or PCR for bread (EPD 2010).

Waste generated in the other life cycle stages has also been considered (manufacture, distribution and retail) as has the transport (see Fig. 1). The only exception to the latter is consumer transport to and from the retail shop, which is excluded by both the PAS 2050 methodology (see Clause 6.5) and the PCR for bread (EPD 2010). By comparison, ISO 14044 does not make a specific reference to consumer transport.

2.2.6 Exclusions from the system boundary

Excluded from the system boundary is the production of capital goods (machinery, equipment and energy wares), as stipulated by PAS 2050 and the PCR for bread (EPD 2010). This represents another methodological difference with ISO 14044 which does not explicitly exclude these items.

Table 3 Bread ingredients

Ingredient	PAS 2050-compliant study		Generic study	
	White bread (%)	Wholemeal bread (%)	White/Brown bread (%)	Wholemeal bread (%)
Flour	59.07	56.66	61.72	61.73
Water	36.00	38.24	35.18	35.19
Yeast	2.21	2.26	1.23	1.23
Salt	0.82	0.82	0.62	0.62
Skimmed milk	–	–	1.23	1.23
Flour additives	–	–	0.02	–
Minor ingredients[a]	1.90	2.02	–	–

[a] Includes dough improvers, emulsifiers and preservatives, individually not present in proportions larger than 1%

Table 4 Nutrients added to wheat flour (HMSO 1998)

Nutrient	Quantity (g/kg flour)
Calcium carbonate	2.35–3.9
Iron	0.0165
Thiamin	0.0024
Nicotinic acid or nicotinamide	0.016

2.3 Data sources

PAS 2050 requires the use of primary data for all activities that the organisation implementing the standard owns, operates or controls (Clause 7.3). Where the organisation implementing the PAS does not contribute 10% or more to the upstream GHG emissions, the primary activity data requirement applies to the first upstream supplier that contributes 10% or more to the upstream GHG emissions. Secondary data can be used where the primary data are not required. In this study, in compliance with PAS 2050, primary data have been used for wheat milling, bread manufacture, distribution and retail. Sources of both primary and secondary data used in this study are summarised in Table 2. The data correspond to a bread supply chain representing a share of 22% of the bread market in the UK (Mintel 2011); to preserve confidentiality, the specific sources of the primary data are not identified.

It should be noted that, currently, secondary data fully compliant with PAS 2050 are almost non-existent. The Carbon Trust has developed a set of such data, modifying the Ecoinvent database to remove the GHG emissions related to infrastructure (capital goods); these data are available on a commercial basis.[2] The original data from the Ecoinvent database that have been used in this study are treated as secondary data and are currently not PAS 2050-compliant. In an attempt to make the PAS 2050-compliant data more widely available and free of charge, Defra have published carbon footprints for some food products (ADAS 2009). PAS 2050-compliant primary data are being collected as studies are being carried out, but it is going to be long before such databases are widely available (after all, it took more than 15 years to build the current LCI databases).

2.4 Assumptions

The following sections discuss in more detail the assumptions for different life cycle stages, for both the PAS 2050-compliant and the generic studies.

2.4.1 Raw materials

In the PAS 2050-compliant study, wheat is sourced entirely from the UK. In the generic study, in addition to the UK, wheat is assumed to be sourced from Canada, France, Germany, Spain and USA, to study the influence on the results of the source of wheat. The other bread ingredients are listed in Table 3. While the recipes in the PAS 2050-compliant study reflect the current practice in the bakery from which the primary data have been sourced (in accordance with Clause 6.4.1), the recipes in the generic study have been adapted from Cauvain and Young (1998) to reflect an average bread composition. In accordance with PAS 2050 (Clause 6.3), the ingredients making a material contribution (to ≥1%) the total carbon footprint of bread have been included in the analysis; However, ingredients with a contribution <1% have been included if the respective data have been available, as has been the case for salt and the flour additives. In order to account for the omitted ‘non-material’ ingredients in the PAS 2050-compliant study, the final carbon footprint values have been scaled up using correction factors equal to 1/98.1 and 1/97.98, representing the percentage mass contribution of the missing components in the white and wholemeal bread, respectively (Clause 6.3).

By law, wheat mills in the UK are required to add thiamine, niacin, iron and calcium to all types of flour other than wholemeal so as to restore and fortify its nutritional content (HMSO 1998). Table 4 details the quantities of each nutrient added to the flour.

Agricultural GHG emissions associated with the cultivation of wheat in all countries considered in this study include the production of fertilisers and pesticides, N_2O emissions from crop residues, the application of nitrogen fertilisers to managed soils, atmospheric deposition of nitrogen volatilised from managed soils, CO_2 emissions from the application of urea, lime and dolomite, and fuel used in field work. The GHG emissions arising from the application of fertilisers to managed soils in the case of UK wheat cultivation have been calculated in accordance with IPCC guidelines (2006) and in conformity with PAS 2050 (Clause 7.8), using the “highest tier approach” in the UK, which is tier 2.[3] The GHG emissions associated with the production of fertilisers and pesticides have been taken from the Ecoinvent database (2007). Table 5 compares the fertiliser input for wheat production in the countries considered in this study.

[2] However, it should be noted that, typically, the contribution of infrastructure to the overall results is insignificant and this is likely to be true for the bread system given the high volumes of production and a long life of equipment.

[3] The highest tier approach set out in the IPCC Guidelines for National Greenhouse Gas Inventories for non-CO_2 emissions from livestock and soils (IPCC 2006).

Table 5 Fertiliser input for wheat cultivation in different countries

Fertiliser and yield	UK (Defra 2008a, b)	Canada (Pelletier et al. 2008)	Germany (Ecoinvent 2007)	France (Ecoinvent 2007)	Spain (Ecoinvent 2007)	US (Ecoinvent 2007)
N-fertiliser (kg/ha)	190.0	65.6	162.1	198.8	94.2	30.0
P-fertiliser (kg/ha)	31.0	75.6	54.2	73.8	81.3	41.7
K-fertiliser (kg/ha)	39.5		45.8	44.5	588.7	53.4
Lime (kg/ha)	279.0	–	–	12.6	–	–
Dolomite (kg/ha)	15.2	–	–	–	–	–
Yield (kg wheat/ha)	8,000	2,690	7,567	6,753	3,050	2,253

2.4.2 Energy

Table 6 summarises the data used to calculate the GHG emissions of energy-using processes in the life cycle of bread. Whereas the data used in the PAS 2050-compliant study correspond to a UK bakery and a UK retail chain, the data used in the generic study correspond to average publicly available data (Nielsen et al. 2003; Defra 2009b; Frigidaire 2010). The UK electricity mix is detailed in Table 7. The GHG emission factors for electricity and fuels have been calculated using the emission factors from the Carbon Trust (2008) for the PAS 2050-compliant study and from Ecoinvent (2007) for the generic study.

2.4.3 Transport

Table 8 gives an overview of the transport distances and transportation conditions (ambient or chilled) assumed in this study. The GHG emission factors associated with the transport stage are sourced from the Carbon Trust (2008) and Defra (2008a,b). The data are based on the distance travelled and load of the truck (tonne–km) and include the return trip for an empty truck. The same transport assumptions have been used for both the PAS 2050 and generic studies. More detail on transport requirements in PAS 2050 can be found in Clause 6.4.6.

2.4.4 Refrigerant losses

Refrigerant losses in the life cycle of bread take place during the refrigerated transport of yeast to the bakery, refrigerated storage of yeast at the bakery, at the retail stores due to air conditioning and at the refrigerated storage of bread at home. In the absence of measured data, an up-lift of 1% of the final value of the carbon footprint of bread has been added to account for all refrigerant emissions (Carbon 2009). This is in compliance with the requirement of PAS 2050 (Clause 6.3) for the cases where less than 99% of life cycle GHG emissions have been determined.

2.4.5 Final disposal

The sources of waste considered in the life cycle as well as the disposal method for each waste stream are summarised

Table 6 Energy consumption in different bread life cycle stages

Process	PAS 2050-compliant study		Generic study
	White bread	Wholemeal bread	All bread types
Wheat milling (kWh/loaf)	0.059[a]	0.048[a]	0.107
Bread manufacture (kWh/loaf)	0.600[a]	0.600[a]	0.239
Retail (kWh/loaf)	0.090[b]	0.090[b]	0.031
Refrigerated storage at home (kWh/loaf)	0.134[c]	0.134[c]	0.035
Bread toasting (kWh/slice of bread)	0.047[d]	0.047[d]	0.047

[a] PAS 2050 Clause 6.4.2

[b] PAS 2050, Clause 6.4.5

[c] PAS 2050, Clause 6.4.7

[d] PAS 2050, Clause 6.4.8

Table 7 Breakdown of the UK grid by data source

Electricity source	Carbon Trust (2008 (%))	Electricity source	Ecoinvent (2007 (%))
Gas	36.4	Fossil	71.9
Coal	37.6	Nuclear	20.9
Nuclear	18.2	Hydro	1.3
Biofuels/non-biodegradable wastes	2.4	Pumped storage	0.7
Hydro-Natural flow	1.2	New renewable	1.4
Oil	1.1	Imports	3.8
Other thermal, e.g. coke oven/blast furnace gas	0.9		
Wind/wave/solar	1.1		
Hydro-pumped storage	1.0		

Table 8 Distances travelled to or within the UK by the bread ingredients

Material		Average distance and transport mode	Transport conditions
Wheat	UK	100 km by road	Ambient
	Canada	1,500 km by road, 1,500 km by train, 4,620 km by sea	
	USA	1,500 km by road, 1,500 km by train, 5,760 km by sea	
	Spain	250 km by road, 250 km by road, 1370 km by sea	
	France	250 km by road, 250 km by train, 41 km by sea	
	Germany	250 km by road, 250 km by train, 713 km by sea	
Flour, skimmed milk, fat, plastic bags, plastic trays		100 km by road	Ambient
Yeast		95 km by road	Chilled
Salt		90 km by road	Ambient
Bread		50 km by road (from bakery to retail shop)	Ambient

in Table 9. Note that it is assumed that all the post-consumer waste is landfilled, including packaging, as currently this is not recycled in the UK. The GHG emissions from final disposal of waste have been calculated using the emission factors and methods provided by the Carbon Trust (2008).

Table 9 summarises the data sources for different waste disposal methods. More detail on waste disposal requirements can be found in Clause 6.4.9 of the PAS 2050 standard.

2.4.6 Allocation

The allocation issue with respect to the primary data arises in the wheat milling stage which co-produces flour, wheat germ and bran (see Section 2.2). In the absence of data to perform system expansion, allocation based on economic value has been applied, as stipulated by PAS 2050 (Clause 8.1.1); this is also in compliance with ISO 14044. Therefore, economic allocation has been used in both studies considered here, allocating 88% of the GHG emissions from the wheat milling stage to white flour, 92.5% to wholemeal flour and 90% to brown flour.

2.4.7 Biogenic carbon storage in products and release from final disposal

According to PAS 2050 (Clause 5.4), biogenic carbon stored in bread (and paper packaging) should not be considered, as products containing biogenic carbon with a short life span (less than 1 year) and intended for human or animal consumption are exempted from this requirement. ISO 14044 has no specific provision for carbon storage in products. Therefore, carbon storage has not been considered.

The GHG emissions arising from final disposal (e.g. waste disposed by landfill) must also be included (Clause 6.4.9) and has therefore been considered in this study.

Table 9 Waste disposal in the life cycle of bread

Waste stream	Disposal method
Waste from bread manufacture	Used as animal feed
Waste bread from retail	Landfilling
Post-consumer bread waste	
Bread waste packaging	

2.4.8 Inclusion and treatment of land use change

PAS 2050 requires inclusion of any land use change that occurred over the last 20 years relative to the base year of the study (Clause 5.5). In this study, this would be referring to the land use change for wheat cultivation that occurred after 1990. Given the countries from which the wheat is sourced in the UK (Canada, France, Germany, Spain, UK and USA), it has been assumed that no land change occurred after this date.

2.4.9 Use of recycled materials and recycling

PAS 2050 (Clause 8.5) requires the calculation of GHG emissions associated with the use of recyclable material inputs. Within the bread system, the packaging materials (plastic and paper bags) could contain recycled material. In the case of the bread system considered here, no recycled material is used in the manufacture of packaging. It has also been assumed that no further recycling takes place and that all the packaging is landfilled (see Table 9).

3 Results

The results are first presented for the bread made from UK wheat, for both the PAS 2050-compliant and the generic studies, to identify any differences in the results. This is followed by an analysis of the influence of the other

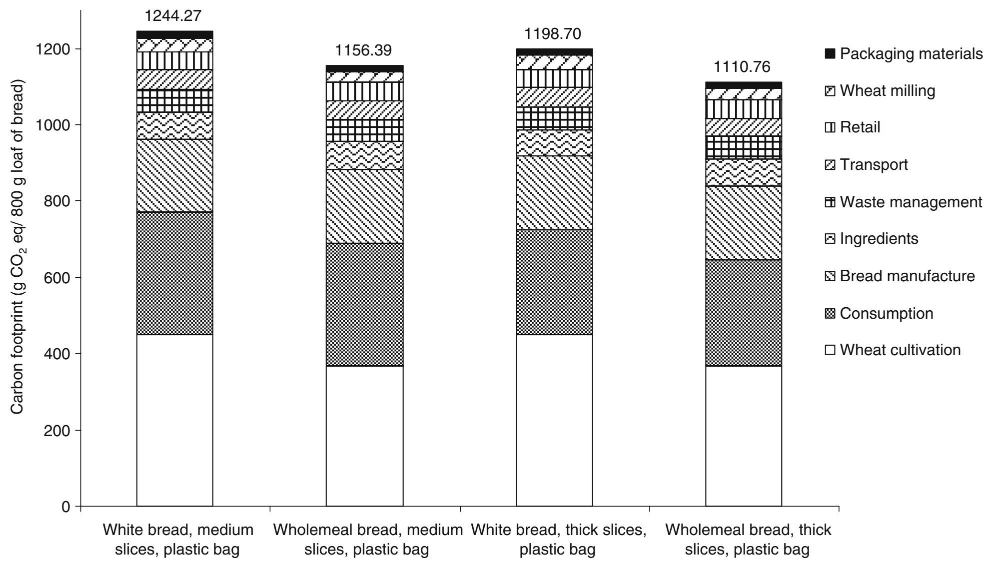

Fig. 3 Carbon footprints of white and wholemeal bread (thick and medium slices) produced from UK wheat and packaged in plastic bags (PAS 2050-compliant study) [thick slices, 47 g/slice; medium slices, 40 g/slice; consumption stage, 20% of bread is frozen over 10 days, 8% is chilled over 4 days, 39% of bread is toasted]

parameters on the results, including the types of flour and packaging as well as the origin of wheat.

3.1 Carbon footprint of bread from UK wheat

The carbon footprints of white and wholemeal bread packaged in plastic bags for the PAS 2050-compliant study are shown in Fig. 3. For comparison, Figs. 4 and 5 show the results of the generic study for white, wholemeal and brown bread packaged in plastic and paper bags, respectively. In all three figures, the relative contribution of different life cycle stages is also shown.

The results from the PAS 2050-compliant study (see Fig. 3) show that that the carbon footprint ranges from 1,111 g CO_2 eq./loaf for wholemeal bread cut into thick slices to 1,244 g CO_2 eq./loaf for white bread cut into medium slices. The main reason for the difference in the results is the type of flour and post-consumer waste. Wholemeal bread has a lower carbon footprint due to a more efficient utilisation of the wheat grain. Furthermore, toasting thick-sliced bread uses less energy per loaf of bread as there are slightly fewer slices to toast compared to the medium-sliced bread; resulting in lower GHG emissions. Overall, the type of flour influences the results more than the thickens of bread slices, so that

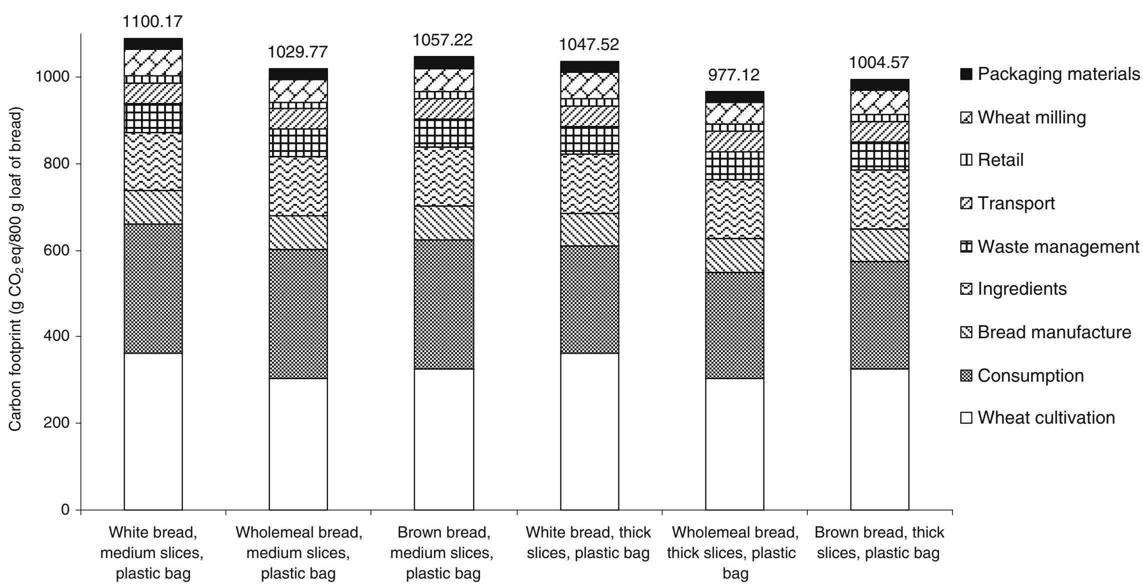

Fig. 4 Carbon footprints of white, wholemeal and brown bread produced from UK wheat and packaged in plastic bags (generic study) [thick slices, 47 g/slice; medium slices, 40 g/ slice; consumption stage, 20% of bread is frozen over 10 days, 8% is chilled over 4 days, 39% of bread is toasted]

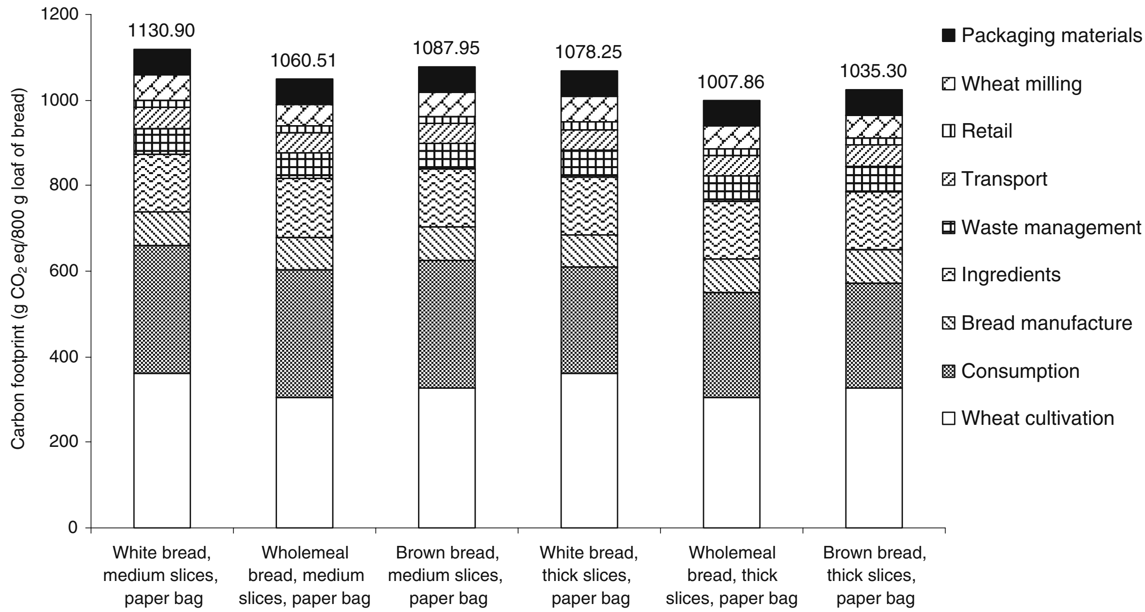

Fig. 5 Carbon footprints of white, wholemeal and brown bread made from UK wheat and packaged in paper bags (generic study) [thick slices, 47 g/slice; medium slices, 40 g/slice; Consumption stage: 20% of bread is frozen over 10 days, 8% is chilled over 4 days, 39% of bread is toasted]

white bread has a higher carbon footprint than wholemeal bread regardless of the slice thickness.

The carbon footprints calculated in the generic study show the same trend as in the PAS 2050-compliant study with the wholemeal having the lowest carbon footprint, followed by brown bread. However, the overall results are lower for the same types of bread compared to the PAS 2050-compliant study. For the bread packaged in plastic bags (see Fig. 4), the results range from 977 g CO_2 eq./loaf for the thick-sliced wholemeal bread to 1,100 g CO_2 eq./loaf for the medium-sliced white bread. This represents an average relative difference of 12% compared to the results obtained in the PAS 2050-compliant study (Table 10).

The use of paper bags leads to a higher carbon footprint compared to the use of plastic bags (see Fig. 5); the results range from 1,008 to 1,131 g CO_2 eq./loaf for the thick-sliced wholemeal and medium-sliced white bread, respectively. The difference between the bread packaged in the plastic and paper bags is around 3% in favour of plastic bags (see Table 10). This is mainly due to the emissions of methane from the landfilled paper bags.

In both studies, the largest contributor to the total carbon footprint of bread is the wheat cultivation stage, contributing on average 35% in the PAS 2050-compliant study and 32% in the generic study (Table 11). The second largest contributor is consumption of bread (25% in the PAS 2050 and 26% in the generic study), due to the refrigerated storage of bread and toasting. In the PAS 2050-compliant study, the third significant contributor is the bread manufacturing stage (16%) while in the generic study it is the production of other ingredients (13%). This is because the average recipe assumed in this study includes more ingredients than in the PAS 2050-compliant study (see Table 3). The contribution of other stages is less significant, notably waste, packaging and transport, each contributing less than 5% to the total carbon footprint.

The carbon footprints of bread calculated in this study are comparable to those of similar bread products that have

Table 10 Relative differences in the carbon footprints of bread in the PAS 2050-compliant and generic studies

Product	Carbon footprint (g CO_2 eq./800 g loaf of bread)		Relative difference (%)
	PAS 2050-compliant study	Generic study	
White bread, medium slices, plastic bag	1,244.27	1,100.17	11.58
White bread, thick slices, plastic bag	1,198.70	1,047.52	12.61
Wholemeal bread, medium slices, plastic bag	1,156.39	1,029.77	10.95
Wholemeal bread, thick slices, plastic bag	1,110.76	977.12	12.03

Table 11 Relative contributions of the life cycle stages to the carbon footprint of bread

Average contribution for all bread types (%)			
Life cycle stages	PAS 2050-compliant study	Generic study	Kingsmill bread (Allied 2009)
Raw materials	41	45	45
Wheat	35	32	
Ingredients	6	13	
Processing	19	12	21
Wheat milling	3	5	
Bread manufacturing	16	7	
Packaging	1	4	2
Transport	4	5	4
Retail	4	2	2
Consumption	25	26	23
Waste management	6	6	3

been carbon labelled in the UK according to PAS 2050; for example, three products from Allied Bakeries: Kingsmill Great Everyday White, Kingsmill Tasty Wholemeal and Kingsmill 50/50 (Allied 2009). As shown in Tables 11 and 12, there is a relatively good agreement between the respective values.

3.2 Influence of wheat sourcing on the carbon footprint

Given that wheat is the main hot spot in the system, it is relevant to analyse the influence of wheat sourcing on the carbon footprint. As already mentioned, 80% of wheat is UK-grown and the remaining 20% is imported from Europe and North America. Therefore, five further sources of wheat have been considered here: Canada, France, Germany, Spain and USA. In all cases, the mixture of UK and imported wheat is taken to be 80% and 20%, respectively. Wheat cultivation in each country of origin and transport to the UK has been considered, as detailed in Tables 5 and 8, respectively. Data sources for the different types of wheat are listed in Table 1; since these data are generic, the ISO 14044 methodology has been used (generic study).

As an illustration, the carbon footprint of a loaf of white medium-sliced bread produced using a mixture of 80% UK and 20% imported wheat is shown in Fig. 6, for comparison, bread made from the UK wheat only is also shown (the results previously shown in Figs. 4 and 5). As can be seen, the bread made from UK wheat and packaged in a plastic bag has the lowest carbon footprint (1,100 g CO_2 eq./loaf of bread) while the bread made with a mixture of wheat from the UK and Spain has the highest (1,131 g CO_2 eq./loaf of bread). These differences can be attributed to the different field productivities and fertiliser application rates in different countries. As shown in Table 5, the highest field productivity appears to be in the UK (8 tonnes of wheat ha^{-1}) at 260.5 kg of fertiliser ha^{-1}; in Spain, these figures are 3.05 tonnes of wheat ha^{-1} at 764.2 kg of fertiliser ha^{-1}, respectively. Therefore, as shown in Fig. 7, wheat from the UK appears to have the lowest carbon footprint (518 kg CO_2 eq./t) while the mix of 80% UK and 20% Spanish wheat has the highest carbon footprint (577 kg CO_2 eq./t).

As also shown in Fig. 7, the relative contribution of transport to the total carbon footprint of imported wheat is minor in all cases (between 1.6% for the European and 5.5% for the Canadian and US wheat).

Table 12 Comparison of the average carbon footprints of different bread types in different studies

Product	Carbon footprint (kg CO_2 eq./800 g loaf of bread, plastic bag)		
	PAS 2050-compliant study	Generic study	Kingsmill bread (Allied 2009)
White bread	1.20	1.07	1.30
Wholemeal bread	1.16	1.00	1.30
Brown bread	–	1.03	1.20

4 Discussion

4.1 Primary vs. secondary data

In general, it is desirable to collect as many primary data as possible. However, in reality, this will be constrained by data, time and resource availability. To overcome this ubiquitous problem in LCA, it is important to understand when it is appropriate to substitute primary (specific) with secondary (generic) data. In the first instance, this will depend on the purpose of the study and secondly, on the contribution to the total results of a particular data set (i.e. on the hot spots in the system). With respect to the purpose of the study, clearly, specific data have to be used if the intention is to carbon label products—carbon labelling is all about specific supply chains, so in most cases it will be inappropriate to substitute primary by secondary data. However, the majority of applications of carbon footprinting are for purposes other than carbon labelling, most notably for internal decision making by companies and for identification of improvement opportunities along a supply chain. In these cases, it may be appropriate to substitute primary with secondary data. However, this must be guided

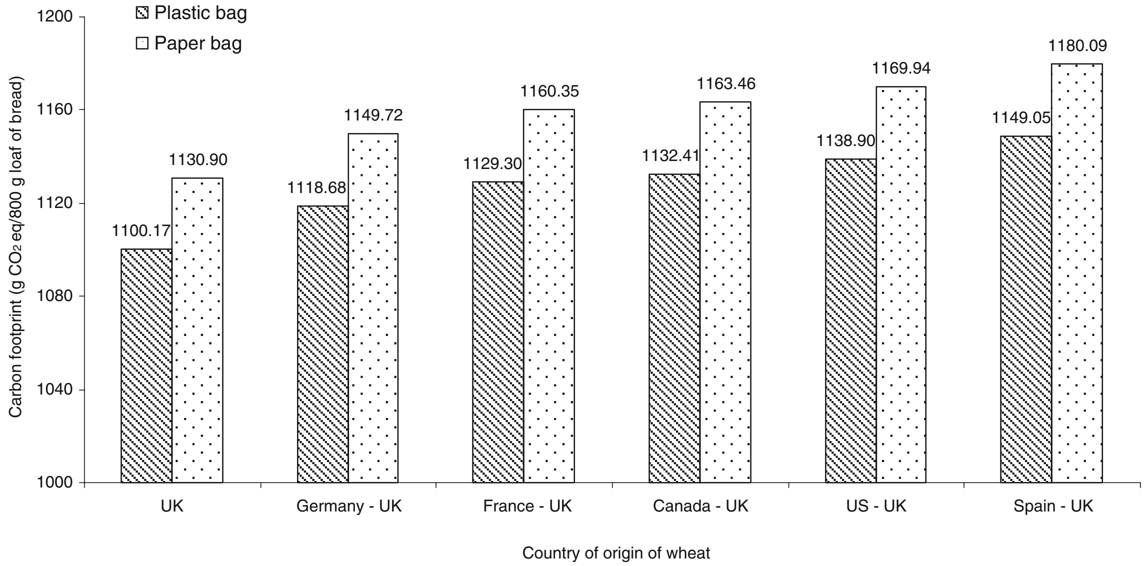

Fig. 6 Carbon footprint of a white medium-sliced bread made from wheat sourced from different countries (80% UK wheat, 20% imported wheat)

by the understanding of the hot spots in the system and the impact that a particular data set may have on the overall results (Milà i Canals et al. 2011).

In this study, the difference in the total carbon footprint between the studies based on the primary data (as required by PAS 2050) and secondary data is on average 12%. Clearly, for the carbon labelling purposes, this is significant. However, a similar although slightly smaller difference is observed between the results of the PAS 2050-compliant study carried out in this work and the results for the Kingsmill bread, also PAS 2050 compliant. Although both studies have used primary data as prescribed by PAS 2050, the difference of 8% is still relatively significant (see Table 12), regardless of the fact that the types of bread are roughly the same. Therefore, while primary data are desirable, the effort needed for data collection has to be compared against the potential gains. Arguably, for internal decision making and for identifying opportunities for reducing carbon footprints, the "80/20" rule can be applied—80% of the result at 20% of effort. Many organisations apply this rule in everyday business decision making, so carbon footprinting should be no exception. This study demonstrates that applying such an approach (i.e. by using secondary data), still yields the results better than 80% and identifies the same major hot spots as the PAS 2050-compliant study. Hence, the value of reliable generic data should not be underestimated nor should these data necessarily be discarded in favour of primary, PAS 2050-compliant data.

Another type of application where secondary data could be valuable is in extrapolating the carbon footprints of specific products into impacts at a national level. For example, extrapolating the results from this study for the individual loaf of sliced and packaged bread for the whole of UK, the carbon footprint of this staple food item at the national level would be equivalent to around 4 million tonnes CO_2 eq. year$-^1$.[4] Further applications could be for estimation of the impact of the average diet of the population in a region or a country (e.g. in Sweden (Carlsson-Kanyama et al. 2003) and Spain (Muñoz et al. 2010)) or for setting the carbon 'budgets' and 'allowances', should such concepts become more than just an "interesting theoretical exercise" (HC EFRAC 2007). PAS 2050 is not suitable for setting budgets for carbon emissions—however, extending specific carbon footprinting exercises into generic studies at national levels using secondary rather than primary data, in a way demonstrated here, illustrates how similar studies could be used to set budgets for GHG emissions.

Further discussion on the implications of using secondary data can be found elsewhere (e.g. in Milà i Canals et al. 2011). Here, we turn our attention to identifying opportunities for reducing the carbon footprint of bread.

4.2 Opportunities for reducing the carbon footprint of bread

The results of both the PAS 2050-compliant and generic studies reveal two major hot spots in the life cycle of bread:

[4] Twelve million loaves are sold each day, 80% of which is sliced and packaged; assuming the average carbon footprint of 1.18 kg CO_2 eq./loaf (obtained in this study) gives: 12 x 10^6 x 0.8 x 1; 18 x 10^{-3} x 365= 4.1 million t CO_2 eq.year$-^1$.

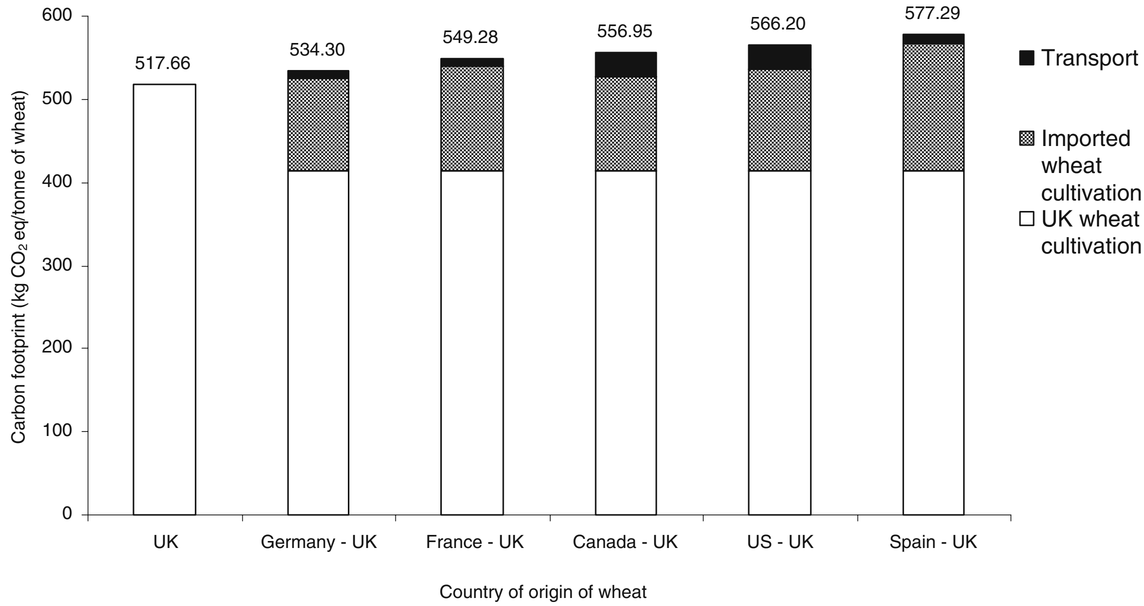

Fig. 7 Carbon footprint of wheat used for bread production in the UK (80% UK and 20% imported wheat)

agriculture (wheat cultivation) and consumption of bread (see Figs. 3, 4 and 5). Therefore, these hot spots could be targeted for reducing the carbon footprint of bread.

In particular, sourcing of UK wheat may be preferred as the option with the lowest carbon footprint, compared to the other origins of wheat examined in this study. If additional wheat has to be imported, then wheat from Germany appears to be the next best option with only 7.6% higher carbon footprint per tonne than UK wheat (see Fig. 7). The least preferred option appears to be wheat imported from Spain with the carbon footprint 49% higher than that of the UK wheat.

Wheat sourcing depends, among other factors, on the quality, availability and price of the grain. The quality of breadmaking flour is determined by a number of characteristics, such as the quality and quantity of protein, the fermentable sugar content and the diastatic power[5] (Calvel et al. 2001). Therefore, these parameters would need to be considered alongside the carbon footprint to ensure that the quality of flour and bread products is not compromised in an effort to reduce the GHG emissions.

The type of flour has a more significant contribution to the carbon footprint than the provenance of wheat: the carbon footprint of wholemeal bread is between 6% and 7% lower than that of white bread; by comparison, the source of wheat in the worst case increases the carbon footprint of bread only by 4%. Incidentally, wholemeal bread is recommended by health authorities as a healthier choice over white bread (FSA 2009). Therefore, wholemeal bread appears to be favoured on both health and carbon-footprint grounds.

Consumption patterns of bread also have a significant impact upon its carbon footprint (see Figs. 3, 4 and 5). If kept in dry conditions, bread can be stored at ambient temperatures for at least 3 days without affecting its quality. Refrigerated storage and toasting can therefore be deemed unnecessary and their avoidance could reduce the carbon footprint on average by 25% (based on the assumptions on UK consumption patterns made in this study).

Size of bread loaf also plays a role, particularly with respect to waste—the larger the bread, the less likely it is that it will be eaten before it is spoiled, thus leading to an estimated 30% wastage (WRAP 2008). In this study, a 10% waste of bread has been assumed. If, on the other hand, the value of 30% is used, then the carbon footprint for all types of bread would increase by 125 g CO_2 eq./loaf or by 10–12%. Needless to say, these emissions could be avoided if all bread purchased was consumed and one way to achieve this would be for consumers to buy smaller bread sizes.

Until 2007, the only available size of a loaf of bread was 800 g. As a result of the European Directive 2007/45/EC (EC 2007), which deregulates the specified quantities of pre-packaged goods, smaller bread loaf sizes (600 and 400 g) have been introduced in the EU market. This can help not only to reduce the amount of waste but also to satisfy more efficiently a reducing demand for bread in the

[5] Diastatic power of a grain refers to the grain's ability to break down starches into sugars.

UK as well as to cater for an increasing number of smaller households.

However, the production of smaller loaves results in an increased use of packaging per unit of bread. For instance, 800 g of bread can be packaged as a single 800 g loaf in an 8 g plastic bag or as two 400 g loaves in plastic bags weighing 6 g each, totalling 12 g of plastic bags.[6] This means that the same amount of bread requires 50% more packaging. Nevertheless, reducing food waste that could potentially be achieved through smaller bread sizes would still lead to a net reduction in the carbon footprint, regardless of the increased packaging requirements.

5 Conclusions

The carbon footprint of bread estimated in this study following the PAS 2050 methodology ranges from 1,111 to 1,244 g CO_2 eq./800 g loaf of bread. Wholemeal thick-sliced bread packaged in plastic bags has the lowest carbon footprint and white medium-sliced bread in paper bag the highest. The main hot spots are wheat cultivation and consumption (toasting and refrigeration) of bread, contributing 35% and 25% to the total, respectively. The latter indicates that the carbon footprint could be reduced on average by 25% by avoiding toasting and refrigerated storage of bread. Further reductions (5–10%) could be achieved by reducing the amount of waste bread discarded by consumers. The contribution of transport and packaging to the overall results is small.

Similar trends are also found in the generic study that followed the ISO 14044 methodology and used secondary data only. However, the difference in the results is on average 12%. Depending on the purpose of the study, it can be decided whether such a difference in the results can be traded off against the effort needed for collection of primary data. If the results of the study are intended for carbon labelling, then it is appropriate to use primary data. The use of secondary data may be more appropriate for internal decision making by companies and for identifying hot spots and related improvement opportunities. Secondary data may also be useful in extrapolating the results of specific studies to national levels—e.g. from the carbon footprint of a single loaf of bread to the national carbon footprint of consumption of bread. Therefore, the value of reliable secondary data should not be underestimated nor should these data necessarily be discarded in favour of primary, PAS 2050-compliant data.

[6] Based on own measurements of products available on the market.

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