Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food

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1 SUMMARY

1.1 Introduction

The Carbon Trust and Defra co-sponsored the development of Publicly Available Specification 2050 (Specification for the assessment of life cycle greenhouse gas emissions of goods and services), which was published by the British Standards Institution (BSI) in October 2009. This document is hereafter referred to as PAS 2050.

The main purpose of this project was to explore the validity and suitability of the methods described in PAS 2050 for food products. This report presents summaries of assessments of the life cycle greenhouse gas (GHG) emissions of food commodities and products, assessed within Defra project FO0404.

The work reported covers all major stages of the food chain from farm production (including transport from the farm to first purchaser), through to manufacturing, ending at the factory outlet. The distribution/retail, in-use, and disposal stages are not included.

1.2 Methods

1.2.1 PAS 2050

The assessments of global warming potential (also known as assessments of carbon footprint) presented in this report were done using the method given in PAS 2050:2008. This document, Publicly Available Specification 2050 (Specification for the assessment of life cycle greenhouse gas emissions of goods and services), is hereafter referred to as PAS 2050.

This report provides summaries of assessments done to test PAS 2050 for a variety of foods, and comment on drafts of PAS 2050 was provided to Defra during the project, before PAS 2050 was published.

PAS 2050 is available as a pdf document from BSI (http://www.bsi-global.com).

1.2.2 Data sourcing

Many of the assessments were for real businesses, made with the help of those businesses. Confidentiality of process information and data was another factor that has limited disclosure of information in some cases.

Some assessments were made for model businesses defined by the project team. In these cases, activity data came from a variety of sources, often weighted for the size of the model processes, and in some cases relying on expert knowledge for process information. These assessments were valuable for testing early drafts of PAS 2050, and were updated to use the final version of PAS 2050 that was published in October 2008.

Difficulties in obtaining data were severe for some assessments, and in these cases many assumptions were made. This occurred in cases where process information and data were not made available by the owners of those processes.

1.2.3 Assessment of co-products

Greenhouse gas emissions were allocated to co-products in proportion to the economic value of the co-products. This is the method specified by PAS 2050 where (a) the process cannot be divided into distinct sub-processes, and (b) the product system cannot be expanded to include additional functions allowing identification of a product that is displaced by a co-product so the avoided emissions of the displaced product can be calculated.

Values for livestock and crop products were obtained from Farmer's Weekly magazine (June 2008)[1]. Values for manures were based on the available N content of the manure[2], and its equivalent value in artificial N fertiliser. Values for skins and hides were obtained from EBLEX.[3]

1.2.4 Soil and animal emissions

The Intergovernmental Panel on Climate Change (IPCC) provide standard international guidelines on the methods to account for annual GHG emissions from agriculture. The method may be one of three, *viz*; Tier 1, Tier 2 or Tier 3, which increase in their complexity, but also in their accuracy[4 5]. The standard IPCC Tier 1 methodology is simple and generalised, due to its intended initial wide scope of application and uses IPCC equations and IPCC default parameter values (e.g.

emission factors). The Tier 2 methodology can use the same methodological approach as Tier 1, but applies default parameter values that are based on country or region specific data. Tier 3 provides emission estimates of a greater accuracy than from the two lower Tiers through the use of higher order methods, including models and inventory management systems tailored to address national circumstances.

The PAS 2050 rules require that agricultural N_2O and CH_4 emission should be calculated with the highest tier approach set out in the IPCC (2006) Guidelines for National Greenhouse gas Inventories or the highest tier approach employed by the country in which the emissions were produced. For UK products the 2006 IPCC method was followed using the same tier approach, and UK data specific to those used to calculate the latest published UK agricultural greenhouse gas inventory for 2006.

1.3 Results of greenhouse gas emissions assessments

Tables 1 to 4 give greenhouse gas emissions values in units of kg CO_2e per functional unit(FU) for the commodities and products assessed in this project. All values are given to an accuracy of two significant figures, which is the level of accuracy that the project team considered necessary to minimise misleading comparisons. Because of this rounding, where values are presented in tables together with a total (sum), the total may not be exactly the sum of the component values.

Table 1 – Summary of livestock GHG emissions per functional unit (FU; typically 1 kg hung carcass, unless otherwise stated)

Livestock Product	kg CO_2e / FU	FU
Intensive – Dairy beef	10	kg
Extensive – Suckler beef	30	kg
Organic – Suckler Beef	32	kg
Overseas – Brazilian Suckler beef	40	kg
Intensive – Lowland lamb	28	kg
Extensive – Upland lamb	39	kg
Organic – Lowland lamb	27	kg
Overseas – New Zealand lamb	33	kg
Intensive – Indoor pig meat	5.5	kg
Extensive – Outdoor pig meat	8.9	kg
Organic – Outdoor pig meat	9.9	kg
Intensive – Indoor chicken	3.1	kg
Extensive – Outdoor chicken	3.7	kg
Organic – Outdoor chicken	4.1	kg
Intensive – High yielding milk	1.2	L
Extensive – Low yielding milk	1.4	L
Organic – Milk	1.3	L
Egg	1.8	dozen
Duck meat	4.1	kg

Table 2 Summary of animal feed crop GHG emissions per kg product.

Crop Product	kg CO_2e / kg
Intensive winter feed wheat	0.55
Extensive spring feed wheat	0.39
Organic feed wheat	0.74
Winter feed barley	0.46
Conventional winter beans	0.096
Organic winter beans	0.12
Conventional OSR meal	0.70
Organic OSR meal	0.64
Intensive – 5 year ley (grass) (DM)	0.22
Extensive – permanent (grass) (DM)	0.16
Organic – permanent (grass) (DM)	0.067
Overseas – New Zealand permanent (grass) (DM)	0.030
Maize silage	0.18
Intensive – 5 year ley silage	0.25
Extensive – 10 year ley silage	0.25
Organic – 3 year ley silage	0.12
Organic -stubble turnips	0.0043

Table 3 Summary of food crop GHG emissions per kg product

Crop Product	kg CO_2e / kg
Conventional winter bread wheat	0.64
Extensive spring bread wheat	0.40
Organic bread wheat	0.75
Pre-pack potatoes	0.16
Processing potatoes	0.13
Organic pre-pack potatoes	0.12
UK Conventional oil heated tomatoes	2.3
UK Conventional waste heated tomatoes	0.39
Spanish conventional tomatoes	1.8
Intensive - Cox	0.066
Extensive - Cox	0.078
Organic - Cox.	0.10
Conventional UK Onions	0.42
Organic UK Onions	0.59
Spring onion	0.23
Carrot	0.35
Garlic	0.57
Maize	0.34
Coffee – cherries (Kenya)	1.5
Tea – green leaves (Kenya)	0.87

Crop Product	kg CO_2e / kg
Cocoa – beans (Ghana)	42
Sugarcane (Zambia)	0.050
Pineapple (Ghana)	1.3

Table 4 Summary of manufactured food products GHG emissions per kg product and per functional unit (FU).

Food product	kg CO_2e / kg or L	kg CO_2e / FU	FU
Instant coffee	33	3.3	100 g glass jar
Tea bags	4.1	4.1	1 kg BLT (320 tea bags) in a carton
Cocoa powder	210	21	100 g glass jar
Granulated sugar (from cane)	0.87	0.87	1 kg paper bag
Fresh pineapple	1.3	1.8	Whole pineapple 1.35 kg
Beef cottage pie	7.6	3.3	Single chilled ready meal – 434.9 g
White loaf of bread	0.73	0.60	827 g loaf in plastic bag
Packed mild cheddar cheese	9.8	4.9	500 g
Cox's apple juice	1.6	1.2	75 cL bottle
Jaffa cakes	2.5	0.42	165 g packet

Food product	kg CO_2e / kg or L	kg CO_2e / FU	FU
Duck in Hoisin Sauce	2.0	0.88	Single chilled ready meal (430 g inc packaging)
Lamb shanks and roasted potatoes	19	25	Single chilled ready meal (1,300 g inc packaging)
Thai chicken pizza	3.5	1.6	1 pizza (460 g inc packaging)

Values for GHG emissions (kg CO_2e per kg or L) covered a very wide range, from 0.0043 kg CO_2e/kg (stubble turnips) to 210 kg CO_2e/kg (cocoa powder in a glass jar).

Food commodities with low emissions (less than 1 kg CO_2e/kg or L) tended to be crop commodities with high yields and low inputs, such as apples (0.066-0.10 kg CO_2e/kg), potatoes (0.12-0.16 kg CO_2e/kg), spring onions (0.23 kg CO_2e/kg), animal feed crops (0.0043 to 0.74 kg CO_2e/kg), carrots (0.35 kg CO_2e/kg), UK conventional tomatoes grown using 'waste' heat (0.39 kg CO_2e/kg), wheat (0.40-0.74 kg CO_2e/kg), and onions (0.42-0.59 kg CO_2e/kg).

Two manufactured products also had GHG emissions less than 1 kg CO_2e/kg: white loaf of bread (0.73 kg CO_2e/kg) and granulated sugar from cane (0.87 kg CO_2e/kg; granulated sugar from beet was not assessed).

Food commodities with medium emissions (between 1 and 5 kg CO_2e/kg or L) tended to be high yielding livestock products such as milk (1.2-1.4 kg CO_2e/L), or manufactured products such as apple juice (1.6 kg CO_2e/L), duck in Hoisin sauce ready meal (2.0 kg CO_2e/kg), jaffa cakes (2.5 kg CO_2e/kg), Thai chicken pizza (3.5 kg CO_2e/kg), chicken meat (3.1-4.4 kg CO_2e/kg), duck meat (4.1 kg CO_2e/kg), and tea bags (4.1 kg CO_2e/kg).

Food commodities with high emissions (over 5 kg CO_2e/kg or L) tended to be livestock products and highly manufactured foods such as pig meat (5.5-9.9 kg CO_2e/kg), beef cottage pie ready meal (7.6 kg CO_2e/kg), packed mild cheddar cheese (9.8 kg CO_2e/kg), beef (10-40 kg CO_2e/kg), lamb shanks and roasted potatoes ready meal (19 kg CO_2e/kg), lamb (27-39 kg CO_2e/kg), instant coffee (33 kg CO_2e/kg), and cocoa powder (210 kg CO_2e/kg).

The cocoa assessment was the only assessment for which land use change was relevant, and this was the major source of emissions (98%). This dominated the emissions for the processed product, as well as for the agricultural commodity (Table 5).

Table 5 Emissions of GHGs (kg CO_2e) for the functional unit (FU; a 100g jar of cocoa powder) and for production of cocoa powder in a glass jar, expressed per kg of cocoa beans used.

Category	**GHG emissions (kg CO_2e/FU)**	**GHG emissions (kg CO_2e/kg cocoa beans)**	**Comments**
Beans (production and export)	20	42	
Packaging	0.29	0.62	Assumed glass jar holding 100g powder
Manufacture	0.21	0.42	Energy, water
Transportation	0.020	0.042	Cocoa beans transported from Southampton docks to Midlands factory
Total	**21**	**43**	

Coffee emissions from agricultural production were dominated by raw materials (mostly fertilisers) and soil emissions (Table 6). Red coffee cherries had a yield of 1.6 t/ha which is a low value compared with many crops (e.g. wheat often yields 10 t/ha, and potatoes 50 t/ha). Therefore, the emissions were allocated to a small quantity of product, resulting in a high value per unit mass, and a high contribution of the agricultural emissions to total emissions of a manufactured product (Table 7).

Table 6 GHG emissions (kg CO_2e) for 1 tonne coffee cherries (pre-processing).

Category	**GHG emissions (kg CO_2e/tonne cherries)**
Raw Materials	870
Processes	
Energy	<0.1
waste	<0.1
Soil emissions	580
(Processes total)	**(580)**
Transport	46
Total	**1,500**

Table 7 Summary of GHG emissions across life cycle of freeze dried instant coffee for the functional unit (FU; 100 g pack of freeze-dried instant coffee in a glass jar) and per kg of coffee cherries.

Category	GHG emissions (kg CO_2e/FU)	GHG emissions (kg CO_2e/kg coffee cherries)
Raw mat. - fresh cherries production	2.4	1.5
Raw mat. – production of green coffee beans from cherries	0.060	0.038
Raw mat. - water	0.0017	0.0011
Raw mat. - packaging	0.32	0.20
Transport - green coffee beans	0.12	0.076
Transport - packaging	0.020	0.013
Manufacture - energy consumption	0.46	0.29
Waste - effluent treatment	0.0005	0.00031
Waste - spent solids*	-0.14	-0.085
Transport - of finished product	0.0072	0.0045
Total	**3.3**	**2.1**

*This waste was used as an energy source, decreasing the amount of energy used, as calculated two rows above; thus this item has a negative value.

Tomato was the food commodity with the largest differences between production systems. Spanish tomatoes (1.8 kg CO_2e/kg) had lower emissions than conventional UK crop with a traditional heating method (2.3 kg CO_2e/kg), but conventional UK crop that utilised waste heat from another process had emissions (0.39 kg CO_2e/kg), that were only 23% of those from Spanish production (Table 8). Although the inputs for Spanish tomatoes were lower than for UK tomatoes, the yields were also lower, so the proportion of emissions from raw materials allocated per tonne of tomatoes was larger for Spanish production than for UK production.

Table 8 GHG emissions (kg CO_2e) per functional unit (FU; 1 t tomatoes delivered to UK distributer).

Category	GHG emissions (kg CO_2e/FU)		
	UK Conventional oil heated tomatoes	UK Conventional waste heated tomatoes	Spanish conventional tomatoes.
Raw Materials	**220**	**220**	**320**
Processes			
energy	1,900	4.7	4.7
waste	<0.01	<0.01	<1
Soil emissions	1.5	1.5	1.5
refrigeration (inc. energy & leakage)	140	140	420
(Total processes)	**(2,000)**	**(150)**	**(430)**
Transport	**21**	**21**	**1,000**
Total	**2,300**	**390**	**1,800**

Lamb is an example of a food commodity with high emissions and this was a common feature of livestock commodities, especially from ruminant animals (Table 1). Despite widely differing degrees of intensity and yield, the systems assessed had emissions that were within a similar range (27-39 kg CO_2e/kg; Table9). Large GHG emissions values were associated with raw materials (Table 9), which in turn were dominated by emissions from production of feed crops. Another important hotspot was emissions from soil and animals (Table 9), which included methane from enteric fermentation and manures, and nitrous oxide from soil and manures, including from soil during production of feed crops.

Table 9 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass).

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – Lowland lamb	Extensive – Upland lamb	Organic – Lowland lamb	Overseas – New Zealand lamb
Raw Materials	**11**	**8.3**	**7.9**	**1.3**
Processes				
Energy	0.87	0.85	0.98	0.12
Waste	3.3	2.7	2.6	2.8
Animal & soil emissions	11	26	13	19
Refrigeration (energy & leakage)	1.4	1.0	1.4	10
(Total Processes)	**(16)**	**(30)**	**(18)**	**(31)**
Transport	**0.22**	**0.27**	**0.22**	**0.56**
Total	**27**	**39**	**26**	**33**

Emissions of GHGs from manufactured foods tended to be dominated by emissions from agriculture. For example, approximately 70% of GHG emissions from a beef cottage were from raw materials (Table 10), and of these raw materials, approximately 75% were from agriculture. An exception to this was apple juice, for which the emissions associated with apple production contributed only 16% of the total emissions for a 75 cL bottle of apple juice (Table 11).

Table 10 Breakdown of GHG emissions per chilled beef cottage pie (400 g).

Category	**kg CO_2e/FU**
Raw Materials	2.4
Packaging	0.38
Transport	0.018
Processing	0.42
Waste	0.0032
Resources	0.0024
Total	**3.3**

Table 11 Breakdown of GHG emissions per 75 cL bottle of apple juice.

Category	**kg CO_2e/FU**
Apples	0.082
Glass bottle	0.24
Other raw materials	0.12
Total raw materials – inc. transport	0.44
Total processing	0.061
Total for 75 cl bottle of apple juice	0.50

1.4 Analysis of uncertainties

The aim of PAS 2050 is to standardise the procedures used when calculating all GHG emissions in the delivery of a product, in order to promote quality and comparability of the results. However, the values used within an analysis are 'best estimates', for many reasons, and having worked through the PAS, "users" should appreciate that the final result falls within a band of possible results and thus should be accompanied by an estimate of its uncertainty. This ensures comparisons between products or systems of production are made on an appropriate basis.

In its simplest form, the estimate of GHG emissions per unit product (*g*) is the sum of products of technical coefficients, *c*, (e.g. litres of diesel), emission factors, *e*, (e.g. x kg CO_2/l) and for gases other than CO_2, an additional factors (*w*) to convert the mass of gas to Global Warming Potential (GWP). These are then divided by the yield, *y*. For n components this becomes:

$$g = \sum_1^n c_j \; e_j \; w_f \big/ y$$

Each value of *c, e, w* and *y* has its own uncertainty. Broadly speaking, the technical coefficients are associated with measurement errors (*alpha* uncertainties) and model-based errors of emission factors and GWP factors (*beta* uncertainties). The latter are further divided into beta type 1 and type 2 uncertainties (beta1 and beta2). Beta2 are those uncertainties due to widely different climatic regions, e.g. factors for N_2O emissions from soils.

The process to estimate the uncertainty in an estimate under PAS 2050 was developed as follows:

1. Identify uncertainty for each input parameter and factor depending on source of information.
2. Define a probability distribution for each input parameter and factor that satisfy constraints on these parameters.
3. Estimate probability distribution of resulting total greenhouse gas emissions using Monte Carlo simulation software.

Monte Carlo simulation software is readily available, allows the allocation of a probability distribution function (PDF) to parameters and emission factors and enables large numbers of simulations to be run, thereby producing a probability distribution for the total GHG emissions. This can be characterised by a mean and coefficient of variation (CV). (For this study the software package @*Risk*, a commercial add-on to *Microsoft Excel*, was used, although there are several open source/freeware packages listed at: http://www.mathtools.net/Excel/Simulation/, other commercial Excel packages and some LCA packages support simulations.)

When describing the uncertainty of a result, PAS2050 analysts should provide three measures of uncertainty, representing the inclusion of alpha, beta1 and beta2 uncertainties respectively, to permit other analysts to be compare their results with them.

When comparing two results, the distributions can be assumed to be normal, and standard statistical tests for the difference between two means can be used. The exact procedure depends on the amount of information available to the analysts. For example, if all information comes from the same organisation, then the distribution of the difference in means can be explicitly calculated. If the *beta* values of the results being compared are sufficiently comparable (e.g. the systems are within the same country or same farm), only *alpha* uncertainties need be included in the comparison. Guidance is offered on appropriate procedures to be used in different cases.

Case studies illustrate the application of the framework to the calculation of uncertainties and the comparison of products and systems. These examples investigate the effects of sub-metering estimation and processing allocation, a shift in the proportion electricity generated from renewable energy, and the impacts of land use change.

The report also provides guideline estimates of uncertainties that can be used in the application of the framework where measured data are unavailable, these assessments were carried out on the numerical values before rounding.

1.5 Discussion

1.5.1 Crop and livestock commodities

1.5.1.1 Use of model systems

Some assessments were made for model businesses defined by the project team. In these cases, activity data came from a variety of sources, often weighted for the size of the model processes, and in some cases relying on expert knowledge for process information. This work was done to test PAS 2050, not to produce values that represent an average for UK production. Therefore, results should not be interpreted as benchmarks.

1.5.1.2 Hotspots

For livestock commodities, large GHG emissions values were associated with raw materials, which in turn were dominated by emissions from production of feed crops. Another important hotspot was emissions from soil and animals, which included methane from enteric fermentation (ruminant animals) and manures, and nitrous oxide from soil and manures, including from soil during production of feed crops.

Soil emissions and emissions from fertiliser manufacture dominated emissions from crop production (including feed crops for animals). For crops that were stored using refigeration, such as potato, onion and apple, emissions from energy consumption were geater than form other crops (e.g. 36% of the total for pre-pack potatoes, but 6% of the total for conventional winter bread wheat).

1.5.1.3 Comparisons between production systems

The assessment of differing production systems for some livestock and crop commodities (specifically: beef, lamb, pig meat, chicken, milk, bread wheat, potato, tomato, apple, onion) showed that in general, emissions of GHGs were of the same order for production systems that differed in level of intensification. Compared with intensive production systems, more extensive sytems have lower emissions associated with inputs and processes per area of land, but also have lower yields per area of land, with the result that emissions per FU are often similar. For example, organic production systems generally had emissions that were of the same order as more intensive conventional systems. In some cases, emissions values for organic systems were higher than for conventional (chicken, pig meat, wheat, onion, apple) and in other cases emissions values for organic systems were lower than for conventional (beef and potato).

Tomato stands out as a commodity with widely differing emissions values between production systems. Spanish tomatoes (1.8 kg CO_2e/kg) had lower emissions than conventional UK crop with a traditional heating method (2.3 kg CO_2e/kg), but conventional UK crop that utilised waste heat from another process had emissions (0.39 kg CO_2e/kg), that were only 23% of those from Spanish production.

1.5.1.4 Soil emissions

The calculation of N_2O emissions from soil following the incorporation of crop residues from many products originating in the UK or overseas was highly problematic. The IPCC 2006 method using the tier 1 approach is complicated and uses many default values for specific crops or crop group e.g. grains. A large number of products (even common UK crops such as oilseed rape) were not represented in the IPCC method and therefore default data were not available. None of the residues produced by the horticultural crops were represented.

1.5.1.5 Availability of emission factors and primary data

Availability of emission factors and values for GHG emissions is limited for minor raw processes and raw materials. Many secondary data values that are available have not been calculated using the PAS 2050 method. In many cases the workings are not clear as to what is or is not included so these values are subject to change.

1.5.2 Overseas products

The assessments of coffee, tea, cocoa, cane sugar and pineapple were included in this project to test the application of PAS 2050 for commodities from developing countries. These products were assessed with varying success. Because of budget constraints the assessments of the agricultural component for coffee, tea, cocoa and cane sugar, were made without visiting production sites. A visit was made to a pineapple producer in Ghana, and the same visit was used to meet experts in cocoa production.

1.5.2.1 Engagement of producers

Engagement of producers is essential for collection of complete process information and primary activity data. This is less likely to be a difficulty in application of PAS 2050 by the food industry, compared with the situation faced by the researchers in this project. In applications of PAS 2050 by the food industry the producers will have reasons for doing the work, otherwise they would not be doing it. In the work reported here the researchers relied on the goodwill of the producers, and in developing countries there was some suspicion of the motives for the work. Comparative assessments involving different producers are likely to be difficult because engagement of the producers is not likely to be equally enthusiastic.

Our experience of working with producers is that engagement is easier to obtain if the practitioner shows to the producer the likely benefits to their business. Such benefits could include marketing advantage, protection of existing markets, identification of cost saving or efficiency improvement opportunities, or more radical industry restructuring to improve business and environmental performance.

1.5.2.2 Confidentiality

Confidentiality can be an obstacle to assessments. If the producers are not fully engaged in the assessment then confidentiality can make a PAS 2050 compliant assessment impossible. As noted above, engagement is less likely to be a difficulty in application of PAS 2050 by the food industry, compared with the situation faced by the researchers in this project. However, in some cases confidentiality is still likely to be a difficulty for communication of results outside of the producing organisation. Our experience of the pineapple assessment suggests that confidentiality may be attached to parts of processes that the practitioner would not expect. It is possible that there will be a greater tendency for this problem to occur in developing countries, where details of production processes are not well known to European consumers.

1.5.2.3 Data availability

The cocoa assessment illustrates the difficulty that in some cases it will be difficult to obtain accurate process information and primary data.

1.5.2.4 Logistical challenges

Visits to producers in developing countries are likely to improve completeness of assessments, but would make such assessments expensive if they are not done by local practitioners. Completeness of a PAS 2050 assessment is more likely if practitioners have knowledge of the assessment method and production processes.

1.5.2.5 Interaction with other environmental impact categories

Our discussions with producers identified a concern about other environmental impact categories in addition to global warming potential. Life cycle assessment of a wider range of environmental impacts can help give assurance that recommendations for decreasing greenhouse gas emissions will not increase some other environmental impact.

1.5.2.6 Hotspots

For all of the overseas products assessed, emissions were dominated by agricultural emissions. For coffee tea and sugar, emissions from fertiliser manufacture and from soil were the major hotspots. For sugar, processing and transport emissions were also important. Hotspots for these products were similar to UK-produced crop products.

Cocoa was the only product that had a land use change component to the GHG emissions and this was the major source of emissions (98%).

Pineapple had significant emissions associated with refrigeration (47%), around 20% each for soil emissions and transport.

1.5.3 Complex manufactured food products

The value of a carbon footprint has been questioned by some companies. There are suspicions that this will lead to a means of taxation. Much of the criticism has come from companies not involved with this study.

Consistency is required in how assumptions are made for finding raw material GHG values, estimating utilities etc is seen as critical. There is still a view from some companies that a carbon footprint can be reduced by using different raw material data sources. In some ways this is true because certain materials, e.g. glass, have reported GHG values that differ widely. This concern lends itself to the development of a centrally held database of input values that is available to all companies who need to calculate a carbon footprint.

Using carbon footprints for carbon labelling is not liked by companies – the issues are with consistency in how the calculations are made (see above point). Factory and business footprinting is seen to have more merit.

There does seem to be a feeling that the PAS 2050 approach providing a useful tool for analysing GHG emissions, with the process of doing the calculations being more important that the final calculated GHG number.

In general PAS 2050 is seen as a useful approach, but it does require the GHG data for raw materials to be more available to companies.

1.5.4 Comparisons of the application of PAS 2050 with LCA

The calculation of carbon footprints following the method of PAS 2050 is an example of the application of life cycle assessment (LCA). Comparisons were made in the project between the approaches, requirements, allocation methods and boundaries using the two methods. This was fed back to Defra and the PAS 2050 steering group while the drafting progressed and most of this is reported in the Technical Annex, along with the analysis of uncertainties.

PAS 2050 is an application of LCA that has been adapted to calculate one environmental criterion: the aggregated GHG emissions of a product, quantified in CO2e, otherwise known as a C footprint. LCA normally includes other environmental criteria, such as energy use, eutrophication potential, acidification potential or ozone depletion potential. While much of the information needed to calculate these would pass through the hands of a PAS 2050 analysis, the standard includes no expectation of reporting them explicitly.

The C footprints calculated by both approaches are likely to be generally similar. However, despite the progress made in standardising the calculation method with the release of PAS 2050, comparing carbon footprint values for different products (or the same product from different sources) is still not at all straightforward. Data and model uncertainties, system boundary decisions and the treatment of product-system functions in calculations all influence the extent to which two declared values can be compared. Comparing carbon footprints calculated following PAS 2050 with GWP values derived from LCAs need particular care: for example, capital items are completely excluded under PAS 2050, but may be included in LCA.

Despite the progress made in standardising the calculation method for C footprints with the release of PAS 2050, comparing values for different products (or the same product from different sources) calculated using it is not straightforward. Data and model uncertainties, system boundary decisions and the treatment of product-system functions in calculations all influence the extent to which two declared values can be compared. The following changes to PAS 2050 could limit the scope for false comparisons:

- requirement for the inclusion of a statement of the FU on all carbon footprint declarations;
- a recommendation to develop product category rules (PCR) to improve comparability of declared values within product groups;
- inclusion of a formal estimate of uncertainty.

2 INTRODUCTION

The Carbon Trust and Defra co-sponsored the development of Publicly Available Specification 2050 (Specification for the assessment of life cycle greenhouse gas emissions of goods and services), which was published by the British Standards Institution (BSI) in October 2009. This document is hereafter referred to as PAS 2050.

Assessment of lifecycle GHG emissions is sometimes described as ‘carbon footprinting’ and is a sub-set of Life Cycle Assessment (LCA), which is both more rigorous and encompassing in the scope of analysis and includes a wider range of environmental impacts.

PAS 2050 is broadly based and not designed specifically for food production or manufacture. The main Purpose of this project was to explore the validity and suitability of the methods described in PAS 2050 for food products. This report presents summaries of assessments of the life cycle greenhouse gas (GHG) emissions of food commodities and products, assessed within Defra project FO0404.

The work reported covers all major stages of the food chain from farm production (including transport from the farm to first Purchaser), through to manufacturing, ending at the factory outlet. The distribution/retail, in-use, and disposal stages are not included.

Food commodities and products included:

- livestock commodities,
- livestock feed crops,
- arable and horticultural crops,
- some food products made from commodities produced in developing countries,
- manufactured food products of varying complexity, together with major ingredients.

For many of the food commodities, assessments were made of up to four production systems, to provide indicators of the relative merits of different food supply systems.

The values presented are not representative of the commodities or foods in general, but are specific to the actual processes or model processes that were assessed.

3 GREENHOUSE GAS EMISSION ASSESSMENTS

3.1 Methods

3.1.1 PAS 2050

The assessments of global warming potential (also known as assessments of carbon footprint) presented in this report were done using the method given in PAS 2050:2008. This document, hereafter referred to as PAS 2050, is a Publicly Available Specification (PAS) with the title: "Specification for the assessment of the life cycle greenhouse gas emissions of goods and services."

However, the assessments as presented in this report deviate from PAS 2050 in that the results of the assessments are not communicated in sufficient detail to give complete transparency (see PAS 2050 section 4.2). This report provides summaries of each assessment, rather than a full and transparent communication of the assessment, including GHG emissions-related information such as activity data for processes.

The assessments reported were done to test PAS 2050 for a variety of foods, and comment on drafts of PAS 2050 was provided to Defra during the project, before PAS 2050 was published.

PAS 2050 is available as a pdf document from:

http://www.bsi-global.com/en/Standards-and-Publications/Industry-Sectors/Energy/PAS-2050/

3.1.2 Data sourcing

Many of the assessments were for real businesses, made with the help of those businesses. Confidentiality of process information and data was another factor that has limited disclosure of information in some cases.

Some assessments were made for model businesses defined by the project team. In these cases, activity data came from a variety of sources, often weighted for the size of the model processes, and in some cases relying on expert knowledge for process information. These assessments were valuable for testing early drafts of PAS 2050, and were updated to use the final version of PAS 2050 that was published in October 2008.

Difficulties in obtaining data were severe for some assessments, and in these cases many assumptions were made. This occurred in cases where process information and data were not made available by the owners of those processes.

3.1.3 Assessment of co-products

GHG emissions were allocated to co-products in proportion to the economic value of the co-products. This is the method specified by PAS 2050 where (a) the process cannot be divided into distinct sub-processes, and (b) the product system cannot be expanded to include additional functions allowing identification of a product that is displaced by a co-product so the avoided emissions of the displaced product can be calculated.

Values for livestock and crop products were obtained from Farmer's Weekly magazine (June 2008)[6]. Values for manures were based on the available N content of the manure[2], and its equivalent value in artificial N fertiliser. Values for skins and hides were obtained from EBLEX.[7] In this assessment it was considered that bone, blood and fat were 'waste' products, i.e. had no economic value. Therefore, there were emissions associated with their disposal, but these emissions were allocated across the products with economic value, rather than to the waste products themselves.

3.1.4 Soil and animal emissions

The Intergovernmental Panel on Climate Change (IPCC) provide standard international guidelines on the methods to account for annual GHG emissions from agriculture. The method may be one of three, *viz*; Tier 1, Tier 2 or Tier 3, which increase in their complexity, but also in their accuracy[4 5]. The standard IPCC Tier 1 methodology is simple and generalised, due to its intended initial wide scope of application and uses IPCC equations and IPCC default parameter values (e.g. emission factors). The Tier 2 methodology can use the same methodological approach as Tier 1, but applies default parameter values that are based on country or region specific data. Tier 3 provides emission estimates of a greater accuracy than from the two lower Tiers through the use of higher order methods, including models and inventory management systems tailored to address national circumstances.

In the case of nitrous oxide (N_2O), the current UK GHG emissions inventory[8] estimates that 66% of N_2O is produced from agriculture, amounting to 82,010 t N_2O (25,423,100 t CO_2e). Approximately 61% of the N_2O produced from agriculture is *directly* emitted from agricultural soils e.g. following the application of manufactured fertiliser nitrogen & livestock manures, the incorporation of crop residues etc. About 35% of agricultural N_2O is emitted *indirectly* from soils from two mechanisms, *viz*:

- following nitrogen loss via ammonia (NH_3) volatilisation/NO_x emission (*c.*20%),
- nitrate (NO_3^-) leaching (*c.*80%).

Nitrogen directly lost from agricultural soils, either by NO_3^- leaching or NH_3 emissions to the atmosphere, may subsequently become potentially available for loss as N_2O. In the UK, both *direct* and *indirect* soil N_2O emissions are estimated using the standard IPCC Tier 1 methodology. The Tier 1 method involves applying IPCC default emission factors (EFs) to UK activity data and so, for example, all EFs used to calculate *direct* N_2O emissions from soil are the same (except for losses from nitrogen deposited by grazing animals). The default EF for *direct* soil emissions, which is used in the current UK GHG inventory, assumes that 1.25% of the total N source value after allowing for NH_3 loss (10% of total manufactured N applied or 20% of livestock N applied) is emitted as N_2O-N[4].

As a result of new global research and scientific understanding, the revised 1996 IPCC inventory methodology has recently been updated, such that the default value for *direct* soil emissions has been reduced to 1.0% of total N applied lost as N_2O-N and no longer takes account of NH_3 loss before the N_2O EF is applied[5]. Furthermore, the EF used to calculate *indirect* N_2O losses following NO_3^- leaching has also been reduced from 2.5% to 0.75% of leached N is lost as N_2O-N [5]. It is this method (i.e. IPCC 2006) which is used in PAS2050. Defra, however, has no immediate plans to use the IPCC 2006 methodology to calculate N_2O emissions from agricultural soils in the UK GHG inventory (Personal Communication, L. Cardenas, 2008).

The PAS 2050 rules require that agricultural N_2O and CH_4 emission should be calculated with the highest tier approach set out in the IPCC (2006) Guidelines for National Greenhouse gas Inventories or the highest tier approach employed by the country in which the emissions were produced. For UK products the 2006 IPCC method was followed using the same tier approach, and UK data specific to those used to calculate the latest published UK agricultural greenhouse gas inventory for 2006[8], although this inventory was calculated using the revised 1996 IPCC method and not the IPCC 2006 method.

The 2006 IPCC tier 1 method does not include calculations to estimate the N_2O emissions from soil arising from residues as a result of either pruning (i.e. where the crop remains in the soil still growing) or from vegetable/fruit out grades (i.e. just the vegetable/fruit and not any associated roots or foliage). Emissions from pruning and out grades were calculated using the simpler tier 1 method in the revised 1996 method.

For mineralisation in association with loss of soil carbon, the 2006 IPCC method includes a new term in the agricultural direct soil N_2O emissions calculations, where emissions are calculated from N mineralised in mineral soils as a result of loss of soil C through change in land use or management. This is not a term included in the revised 1996 IPCC agricultural method and hence the UK agricultural greenhouse gas inventory, although it has been addressed within the 'land-use, land use change and forestry' sector of the inventory. However, within the UK inventory no N_2O emissions have been calculated in this sector as it is believed that the IPCC method i.e. to take the CO_2 emission due to a specific change and then use the C:N ratio for the soils being disturbed to estimate the N lost due to the mineralisation of organic matter, is not scientifically sound[1]. It has been decided therefore to await an alternative approach to estimating N_2O emissions due to land use change before including any data in the inventory. The 2006 IPCC method is also based on the C:N ratio. On this basis N_2O emissions have not been included from this potential loss pathway, although it is part of the Tier 1, 2006 IPCC approach.

For most overseas products examined (especially from developing countries), it was not possible to find a published report of the relevant greenhouse gas inventory in order to establish the tier and country specific data to use. It was assumed that this was because countries which are not classed within Kyoto as 'Annex 1' countries do not have to compile and publish a national inventory. For these products the IPCC tier 1 and IPCC default data were followed and used. It was found that even from the published report of the New Zealand (an 'Annex 1' country) agricultural greenhouse gas inventory, not all the necessary information was provided in order to fully calculate emissions from rearing lamb using the New Zealand tier 2/3 methods. Where data was missing, UK values were substituted.

For the calculation of indirect soil N_2O emissions from nitrate leaching/runoff, the 2006 IPCC method only applies for regions where rain minus potential evaporation is greater than the water holding capacity or where irrigation is applied. In absence of climate and soil data for the relevant countries and regions, we have assumed that nitrate leaching occurs. This may not be the case for all products, but it will give the worse case scenario.

No guidance is given in the 2006 IPCC method for glasshouse farming. The revised 1996 IPCC method states that 'N_2O emissions from glasshouse agriculture should be included only in the total fertiliser nitrogen consumed within each country', Nitrogen use in glasshouses and the subsequent N_2O emissions are, however, not included in the current UK agricultural GHG inventory (Pers. Comm. Laura Cardenas, compiler of UK agricultural GHG inventory). Tomatoes grown in glasshouses are grown on rock wool and not soil. The rock wool would not be expected to contain all the nutrients, micro-organisms etc. that are present in soil and therefore it is assumed that there are no direct or indirect soil N_2O emissions form the growth of tomatoes in glasshouses. Tomato plants are composted after use and thereafter form compost sold in garden centres. Emissions of N_2O and CH_4 from the composting of tomatoes were estimated using the 2006 IPCC method in chapter 5: waste. Tier 1 emission factors (EFs) for composting on a wet weight basis were used. Various assumptions on the composition are assumed and how relevant these are to waste tomato plants is unknown.

3.1.5 Presentation of emissions values

All emissions values, in units of mass of CO_2e per functional unit (FU) are given to an accuracy of two significant figures, which is the level of accuracy that the project team considered necessary to minimise misleading comparisons. Because of this rounding, where values are presented in tables together with a total (sum), the total may not be exactly the sum of the component values.

3.2 Results

3.2.1 Livestock commodities

3.2.1.1 Summary of inclusions

For livestock commodities raw materials included all feed: concentrates (with ingredients such as wheat, beans and barley), conserved forage (such as silage) and grazing (such as grass and fodder crops). These values were calculated by ADAS using PAS 2050 – see later assessments. Other raw materials were bedding (either straw or wood shavings), veterinary medications[9] (antibiotics, wormers, disinfectants) and replacement stock brought into the system. Emissions for replacement stock brought in to the system were calculated using PAS2050, by ADAS (e.g. pedigree Texel flock for lowland tups, broiler breeder flocks to produce indoor and outdoor broilers for chicken meat production) these assessments are not described in this report.

Transport[10] included transport of feed, bedding and veterinary medications to the farm, the movement of livestock within the system (e.g. from housing to field), the removal of waste (dead stock, plastics and manures) and the transport of the animals to the abattoir. It was assumed that all vehicles returned empty, and therefore emissions from transport were doubled.

Processes included all aspects of production, from the production of parents and grandparents, the rearing of commodity animals and the eventual disposal of that animal. In certain systems. such as pig meat production, the parents are specifically produced from a nucleus herd. These parents are then specifically bred to produce the meat animals. Each level of production is different and has different emissions associated with it. The nucleus herd is there specifically to produce the parent animals for pigmeat production, therefore they are considered to be within the assessment boundary. All electricity[11], and fossil fuels[10] used for heat, light, stock feeding, compound feed manufacture[12], watering, refrigeration, etc. were included (Refrigeration was all based on an Ammonia system cooling 100m^2 having CO_2e emissions of 2016 kg CO2e/day – Prof Savvas Tassou pers. comm.).

Waste included incineration of dead stock and slaughter house waste and landfill of plastic waste as a result of feeding and medications[13]. Values for the amount of fuel required for the incineration of animal waste were calculated using figures supplied by Martyn Wharmby (pers comm. Techtrol Ltd www.techtrol.co.uk). The breakdown of animal carcasses into waste and co-products was calculated using information provided by Dr Alan Fisher of Bristol University (pers. comm.). All plastic waste was transported to land-fill[14].

Soil and animal emissions included nitrous oxide (N_2O) emissions associated with manure produced by the animal (at grass, stored and then spread on subsequent crops) and Methane (CH_4) emissions from enteric fermentation in ruminant animals, and emissions associated with manures. Refrigerant losses and energy use (in refrigeration) was included in this section where appropriate.

3.2.1.2 Beef

Product description

Four beef production systems were assessed.

1. Intensive dairy beef – calves produced from dairy herd, raised intensively on predominantly cereal diet (housed 100% of the year).

2. Extensive suckler beef – calves produced by beef suckler cows and raised with mother on a predominantly grass and forage based diet (housed 50% of the year).

3. Organic suckler beef – calves produced by organic beef suckler cows and raised with the mother on a predominantly organic grass based diet, using organic management techniques and stocking densities (housed 45% of the year).

4. South American beef – calves produced by Zebu / Nelore suckler cows and grown on extensive pasture in Brazil (housed 0% of the year).

In each case the FU was 1 kg hung carcass, slaughtered, gutted and hung, but not processed further.

Process description

Intensive dairy beef

This system was based on 100 calves that were produced as a co-product of a dairy system. At ten days of age they were transported to a rearing farm where they were housed for 13 months and fed a predominantly cereal based diet[15]. All calves that entered this system were destined for meat production. It took about 13 months for cattle to reach the required live weight (600 kg), when the cattle were transported to the abattoir and slaughtered (carcass weight 300 kg). No further butchering was included. From the abattoir there were other products of low value as well as the meat, including skins and offal for pet food. Housed animals produced farmyard manure as a co-product (see Table 15 for details).

Extensive suckler beef

This system was based on a core herd of 100 female suckler cows that were bred every year to produce calves (90% of cows produce live calves). The herd spent 50% of their time grazing grass and 50% housed over winter, when they were fed silage and some cereals. Of the live calves, about 16% were kept to become replacements in the suckler herd, replacing females that were either culled, or that died. The remaining calves were reared for meat (21 months), producing similar co-products to intensive dairy beef (farmyard manure, pet food and hides) plus additional low value meat from the culling of older females (see Table 16 for details). Live weight of meat animals was 600 kg, with a carcass weight of 330 kg.

Organic suckler beef

This system was based on a 100 cow herd that was produced in a similar manner to extensive suckler beef, except that feed came from organic sources and the cattle were given less medications. Co-products were the same as for extensive suckler beef (see Table 17 for details). Live weight (600 kg) was reached after 24 months, with a carcass weight of 330 kg.

South American beef

South American beef was produced on grass land that was converted from its primary vegetation prior to 1990, in Brazil. The production was similar to UK suckler beef in that a core herd of females (500) was bred once a year to produce calves, some of which became replacements and went for meat (see Table 18 for details). Cattle were grazed for their entire life with just some additional vitamin and mineral supplements fed[16]. For the purposes of this study values for UK permanent grazing were used as insufficient information was found to calculate South American grass production. Meat animals were slaughtered at 36 months at a carcass weight of 270 kg. Breeding cows were culled at 7 years (after 5 calves) and the meat from these was also used for export. The export meat tended to be the cheaper front end cuts, therefore it has been assumed that 50% of the meat produced from the cycle was exported. It was transported in refrigerated shipping containers from Rio de Janeiro to Southampton, a journey which took 15 days.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 12. The intensive dairy beef system had the lowest emissions. Raw materials were more important in the intensive dairy beef system than in the other three systems for which animal and soil emissions were the greatest component (due to parent animal emissions being included). Lower yields and slower growth rates in the South American system meant that there were increased levels of animal and soil emissions allocated per kg of meat compared to UK systems.

Table 12 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass).

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – Dairy beef	Extensive – Suckler beef	Organic – Suckler Beef	Overseas – Brazilian Suckler beef
Raw Materials	**4.9**	**10**	**5.9**	**0.048**
Processes				
Energy (exc. Refrigeration)	0.66	0.53	0.60	0.13
waste	2.8	2.8	2.6	3.7
Animal & soil emissions	2.1	18	21	34
Refrigeration (energy & leakage)	0.21	0.19	0.20	2.1
(Processes total)	**(5.5)**	**(22)**	**(26)**	**(40)**
Transport	**0.11**	**0.037**	**0.057**	**0.59**
Total	**10**	**30**	**32**	**40**

Raw materials

In all systems, feed[17] was the major contributor to the GHG emissions of raw materials (Table 13).

Table 13 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – Dairy beef	Extensive – Suckler beef	Organic – Suckler Beef	Overseas – Brazilian Suckler beef
Wheat	2.9	1.5	0.95	none
Rape meal	0.97	0.48	0.41	none
Grass	none	2.6	0.49	0.047
Silage	none	5.4	3.2	none
Vitamins & Minerals	<0.001	<0.001	<0.001	<0.001
Straw	0.16	0.45	1.0	none
Calf milk replacer	0.080	None	None	none
(Total feed and bedding)	**(4.2)**	**(9.9)**	**(5.8)**	**(0.047)**
Replacements from outside cycle	0.70	None	none	none
Veterinary medications	<0.001	<0.001	<0.001	<0.001
Total	**4.9**	**10**	**5.9**	**0.048**

Processes

In all systems, animal and soil emissions (N_2O and CH_4) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 14).

Table 14 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass) from processes.

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – Dairy beef	Extensive – Suckler beef	Organic – Suckler Beef	Overseas – Brazilian Suckler beef
Electricity	0.15	0.22	0.22	0.13
Other	0.51	0.31	0.38	<0.01
(Total energy)	**(0.66)**	**(0.53)**	**(0.60)**	**(0.13)**
Plastics (land-filled)	0.01	0.02	0.02	0.001
Animal waste (incineration of dead stock & slaughter house waste)	2.5	2.9	2.5	3.7
Other waste disposal	0.21	0.23	0.23	<0.01
(Total waste)	**(2.8)**	**(3.0)**	**(2.8)**	**(3.7)**
N_2O emissions	1.5	5.5	4.8	11
CH_4 emissions	0.57	13	16	23
(Total animal and soil emissions)	**(2.1)**	**(18)**	**(21)**	**(34)**
Refrigeration (inc. electricity)	0.21	0.19	0.20	2.1
Total	**5.5**	**22**	**26**	**40**

Land use change

It has been assumed that the beef produced in the South American system was produced on land that was converted to pasture prior to 1990. The majority of pasture in Brazil is over 20 years old, although there is a small proportion of pasture that has been converted from primary forest in recent years. If land use change was included for South American beef and calculated using default land use change values from table E.1 in PAS 2050 it could add up to 290 kg CO_2e / kg of meat to the footprint (if meat was used from 100% land use change land). This assumed the conversion of forest land into perennial crop released 26 t CO_2e/ha/year. Based on a stocking density of 450 kg cattle/ha this meant that a 500 cow breeding herd plus replacements and meat animals required 975 ha of land.

Co-products and yields

In Table 15 to Table 18 details of co-products are given for each system, to show how GHG emissions were allocated (for the allocation method see section 1.2.3), by percentage of emissions and by emissions per FU. In all systems, emissions allocated to meat dominated.

Table 15 Intensive dairy beef – co-products. FU = functional unit.

Co-product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	27,900	kg	£2.80	96.3	9.7
FYM	970	t	£0.48	0.6	1.7
Hides	93	skin	£21.00	2.4	73
Pet food	8,300	kg	£0.07	0.7	0.24

Table 16 Extensive suckler beef – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	24,200	kg	£2.80	85	28
Cull meat	5,000	kg	£1.80	11	18
FYM	1,500	t	£0.48	0.89	4.8
Skins	87	skin	£21.00	2.3	211
Pet food	7.74	kg	£0.07	0.67	0.70
Replacements	15	animals	Not applicable (returned to beginning of cycle)	Not applicable	Not applicable

Table 17 Organic suckler beef – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	24,800	kg	£3.00	87	23
Cull meat	4,300	kg	£0.66	3.5	5.7
FYM	1600	t	£0.48	0.88	3.8
Skins	88	skin	£21.00	2.2	160
Pet food	7.8	kg	£0.07	0.64	0.55
Replacements	15	animals	Not applicable (returned to beginning of cycle)	Not applicable	Not applicable

Table 18 South American beef – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	61,000	kg	£2.17	70	330
Cull meat	28,000	kg	£2.10	30	320
FYM	0	t	Not applicable	Not applicable	Not applicable
Skins	335	skin	£0.00	Not applicable	Not applicable
Pet food	38,000	kg	£0.00	Not applicable	Not applicable
Replacements	125	animals	Not applicable (returned to beginning of cycle)	Not applicable	Not applicable

Acknowledgements

We would like to thank Matheus Zanella of CNA - Confederação da Agricultura e Pecuária do Brasil - www.cna.org.br, for his assistance with information on Brazillian Beef production systems.

3.2.1.3 Lamb

Product description

Four lamb production systems were assessed.

1. Intensive – Lowland lamb – used cross bred ewes produced in the uplands crossed with Texel tups to produce lowland lambs, all lambs went meat. Raised on a predominantly grass based system, with some additional feeding.

2. Extensive – Upland Lamb – used purebred upland ewes to produce a mixture of replacement Purebred ewes, cross bred ewes for lowland replacements and Pure and cross bred male lambs for meat. Raised on a grass based system with a small amount of additional feed.

3. Organic – Lowland lamb – raised in a similar system to the lowland lamb, but at organic stocking densities and under organic management. All lambs went meat.

4. Overseas – New Zealand lamb – raised in an extensive grass based system with low fed and fertiliser inputs.

In each case the FU was 1 kg hung carcass, slaughtered, gutted and hung, but not processed further.

Process description

Intensive lowland lamb – This flock consisted of 500 cross-bred ewes bought in from upland flocks. These ewes were then bred to Pure-bred Texel tups. The entire flock was reared at grass with supplementary feeding for ewes at lambing and some creep feeding of lambs during winter for fattening. Some ewes were brought in briefly at lambing if conditions were bad or there are difficulties with the birth (12% of time housed). The flock was treated with veterinary medications as per standard practice (pers. comm. Harriet Fuller, vet). All live lambs (150% lambing rate) were sent for meat at 5 months of age. Live weights were 35kg with a carcass weight of 19kg. Co-products included a small amount of FYM from the brief housing period, wool from the ewes, lower grade mutton from the cull ewes, sheep hides and offal that goes for pet food. I

Extensive upland lamb – This flock consisted of 750 Pure-bred Swaledale ewes that were bred to a mixture of Swaledale and lowland tups with a lambing rate of 140%. Of the lambs produced 49% (majority of males) went meat, whilst the remaining 51% (all females and a few replacement tups) were used as replacements in the upland flock or were sold as replacements for the lowland flock. All animals were raised outside on grass, except for occasional ewes at lambing (4% of time housed). A small amount of supplementary feed was given, but not as much as for lowland flocks. Lambs reached a suitable live weight of 35kg after 6.5 months and carcass weights were 17.5 kg. Co-products included upland and lowland replacements, a small amount of FYM, wool, mutton from cull ewes, sheep hides and offal that went for pet food.

Organic lowland lamb – This flock consisted of 500 cross-bred ewes that were bought in from an organic upland flock. These ewes were then reared in a similar way to the intensive lowland flocks but pastures and feed were organic and medications are reduced. Lambing rates were 140%, with lambs reaching suitable live weights of 35kg after 6 months, carcass weights were 19kg after slaughter. Co-products are the same as intensive lowland flocks.

New-Zealand lamb[18 19 20] – This flock consisted of 2,500 ewes that were bred on farm. There was a lambing percentage of 130%. Of the live lambs produced 15% were used as replacements and the remaining 85% were reared for meat. New Zealand lambs were given very little in the way of additional feed and pastures were managed with very low inputs. New Zealand lambs reached live weights of 35kg in 5 months, with a carcass weight of 17kg. The calculations for New Zealand lamb included the freezing and shipping of whole carcasses to a UK port. Co-products from New Zealand lamb included mutton from cull ewes, offal going for pet-food and sheep hides.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 19. The lowland systems had the lowest emissions. Animal and soil emissions were the greatest component of all systems.

Table 19 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass).

Category	GHG emissions (kg CO_2e/FU)			
	Intensive – Lowland lamb	Extensive – Upland lamb	Organic – Lowland lamb	Overseas – New Zealand lamb
Raw Materials	**12**	**8.3**	**8.8**	**1.3**
Processes				
Energy	0.87	0.85	0.98	0.12
Waste	3.3	2.7	2.6	2.8
Animal & soil emissions	11	26	13	19
Refrigeration (energy & leakage)	1.4	1.0	1.4	10
(Total Processes)	**(16)**	**(30)**	**(18)**	**(31)**
Transport	**0.22**	**0.27**	**0.22**	**0.56**
Total	**28**	**39**	**27**	**33**

Raw materials

In all systems, feed was a major contributor to the GHG emissions of raw materials (Table 20). In the lowland systems the introduction of replacement ewes (from the upland system) also made a large contribution to the raw materials emissions.

Table 20 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – Lowland lamb	Extensive – Upland lamb	Organic – Lowland lamb	Overseas – New Zealand lamb
Wheat	0.98	1.3	0.41	Not fed
Rape	0.51	0.30	0.37	Not fed
Grass	3.3	5.1	1.5	0.66
Silage	1.0	1.6	0.36	0.55
Vitamins & Minerals	<0.01	<0.01	<0.01	<0.01
Straw	0.015	0.013	0.078	Not fed
Stubble Turnips	Not fed	0.008	Not fed	0.019
(Total feed & bedding)	**(5.8)**	**(8.2)**	**(2.7)**	**(1.2)**
Replacements from outside cycle	6.1	Bred in cycle	6.6	Bred in cycle
Veterinary medications	0.07	0.09	0.09	0.09
Total	**12**	**8.3**	**8.8**	**1.3**

Processes

In all systems, animal and soil emissions (N_2O and CH_4) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 21).

Table 21 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass) from processes.

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – Lowland lamb	Extensive – Upland lamb	Organic – Lowland lamb	Overseas – New Zealand lamb
Electricity	0.75	0.76	0.89	0.10
Other	0.11	0.09	0.09	0.02
(Total energy)	**(0.86)**	**(0.85)**	**(0.98)**	**(0.12)**
Plastics (land-filled)	0.02	<0.01	0.02	<0.01
Animal waste (incineration of dead stock & slaughter house waste)	0.74	0.57	0.72	0.62
Other waste disposal	<0.01	<0.01	<0.01	<0.01
(Total waste)	**(3.3)**	**(2.6)**	**(3.1)**	**(2.7)**
N_2O emissions	2.3	6.2	2.8	4.5
CH_4 emissions	8.2	20	9.8	14
(Total animal and soil emissions)	**(11)**	**(26)**	**(13)**	**(19)**
Refrigeration (inc. electricity)	1.4	1.0	1.4	10
Total for processes	**16**	**31**	**18**	**31**

Co-products and yields

Table 22 Intensive lowland lamb – co-products. FU = functional unit.

Co-Product	**Yield / cycle**	**FU**	**Value (£/FU)**	**% allocation of CO_2e emissions**	**kg CO_2e / FU**
Meat	14,000	kg	£3.70	91	27
Cull meat	2,300	kg	£1.40	5.6	10
FYM	99	t	£0.47	0.08	3.5
Skins	830	skin	£1.25	1.8	9.2
Pet food	3,700	kg	£0.07	0.44	0.51
Wool	1,400	kg	£0.45	1.2	3.6
Replacements	0	animals			

Table 23 Extensive upland lamb – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	8,900	kg	£3.70	52	39
Cull meat	2,600	kg	£1.40	5.8	15
FYM	103	t	£0.47	0.08	5.0
Skins	640	skin	£1.25	1.3	13
Pet food	2,800	kg	£0.07	0.31	0.74
Wool	2,600	kg	£0.45	1.32	4.3
Lowland Replacements	315	animals	£80.00	44.1	670
Upland Replacements	220	animals	-	-	-

Table 24 Organic lowland lamb – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	11,000	kg	£3.80	88	26
Cull meat	2,600	kg	£1.50	8.0	10
FYM	99	t	£0.47	0.09	3.3
Skins	690	skin	£1.25	1.8	8.7
Pet food	3,000	kg	£0.07	0.43	0.49
Wool	1,400	kg	£0.45	1.4	3.4

Table 25 New Zealand lamb – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	51,000	kg	£3.70	91	33
Cull meat	8,100	kg	£1.40	5.5	13
FYM	0	t	£0.47		
Skins	3,000	skin	£1.25	1.8	11
Pet food	14,000	kg	£0.07	0.45	0.62
Wool	690	kg	£0.45	1.5	4.0
Replacements	500	animals	NA – animals return to beginning of cycle		

Acknowledgements

Peter Shepherd, NZ sheep farmer.

Harriet Fuller, vet.

3.2.1.4 Pig meat

Product description

Three pig meat production systems were assessed.

1. Intensive - Indoor pig meat – Pigs spent entire life inside, fed on predominantly cereal based diet.

2. Extensive – Outdoor pig meat – Pigs spent entire life outside, fed on a predominantly cereal based diet.

3. Organic – Outdoor pig meat – Pigs spent entire life outdoors, at organic stocking densities and fed on an organic cereal based diet.

In each case the FU was 1 kg hung carcass, slaughtered, gutted and hung, but not processed further.

Process description

Intensive indoor pig meat – This system was made up of a 600 sow herd, brought in from a nucleus herd. These animals were kept indoors at all times and fed a predominantly cereal-based diet. They were inseminated using AI and produced a total of 14,280 live meat animals per year long cycle, all piglets went for meat. Meat pigs were fattened inside on predominantly cereal-based diets. Animals were slaughtered at a live weight of 100kg, at 5.9 months, carcass weight was 77kg. Co-products from this system included FYM, lower grade meat from cull sows, offal that went for pet food and skins.

Extensive outdoor pig meat – This system is made up of a 600 sow herd, bought in from a nucleus herd. These animals are kept in an outdoor system 100% of the time and fed a predominantly cereal based diet. They are inseminated using AI and produce a total of 13,440 live meat animals per year long cycle, all piglets go for meat. Meat pigs are fattened outside on a predominantly cereal based diet. Animals were slaughtered at a live weight of 100kg, at 6 months, carcass weight was 77kg Co-products from this system were similar to the indoor pig meat system.

Organic pig meat – This system was made up of a 250 sow herd, brought in from a nucleus herd. These animals were kept in an outdoor system 100% of the time and fed a predominantly organic cereal based diet. They were inseminated naturally using a boar and produced a total of 5,600 live meat animals per year long cycle. Animals were slaughtered at a live weight of 100kg, at 6.25 months, carcass weight was 77kg. Co-products from this system were similar to the indoor pig meat system.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 26. The intensive system had the lowest emissions. Animal and soil emissions were the greatest component of all systems.

Table 26 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass).

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive – Indoor pig meat	Extensive – Outdoor pig meat	Organic – Outdoor pig meat
Raw Materials	**2.4**	**2.1**	**2.8**
Processes			
Energy (exc. refrigeration)	0.22	0.20	0.26
waste	1.5	2.2	1.1
Animal & soil emissions	1.0	4.0	5.0
Refrigeration (inc. electricity & leakage)	0.09	0.08	0.08
(Total processes)	**(2.8)**	**(6.5)**	**(7.0)**
Transport	**0.36**	**0.29**	**0.09**
Total	**5.5**	**8.9**	**9.9**

Raw materials

In all systems, feed was the major contributor to the GHG emissions of raw materials (Table 27).

Table 27 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive – Indoor pig meat	Extensive – Outdoor pig meat	Organic – Outdoor pig meat
Wheat	0.89	0.87	0.90
Wheat feed	0.014	0.014	-
Soya meal	0.76	0.53	1.2
Barley	0.43	0.42	0.58
Beans	0.009	0.009	-
Rape meal	0.12	0.11	
Vitamins & Minerals	<0.001	<0.001	<0.001
Straw	<0.001	<0.001	0.002
(Total feed & bedding)	**(2.2)**	**(2.0)**	**(2.7)**
Replacements from outside cycle	0.15	0.13	0.67
Veterinary medications	<0.01	<0.01	<0.01
Total	**2.4**	**2.1**	**2.8**

Processes

In all systems, animal and soil emissions (N_2O and CH_4) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 28).

Table 28 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg hung carcass) from processes for.

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive – Indoor pig meat	Extensive – Outdoor pig meat	Organic – Outdoor pig meat
Electricity	0.08	0.06	0.06
Other	0.14	0.13	0.11
(Total energy)	**(0.22)**	**(0.20)**	**(0.24)**
Plastics (land-filled)	<0.01	<0.01	<0.01
Animal waste (incineration of dead stock & slaughter house waste)	0.34	0.48	0.24
Other waste disposal	<0.01	<0.01	<0.01
(Total waste)	**(0.34)**	**(0.48)**	**(0.24)**
N_2O emissions	0.58	1.1	2.4
CH_4 emissions	0.36	2.9	2.6
(Total animal and soil emissions)	**(1.0)**	**(4.0)**	**(5.0)**
Refrigeration (inc. electricity & leakage)	0.09	0.08	0.08
Total for processes	**2.8**	**6.5**	**7.0**

Co-products and yields

Table 29 Intensive indoor pig meat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	1,100,000	kg	£1.33	93.6	5.5
Cull meat	18,000	kg	£0.20	0.22	0.83
Slurry	10,000	t	£5.06	3.4	21
Skins	15,000	skin	£2.50	2.3	10
Pet food	100,000	kg	£0.07	0.46	0.29

Table 30 Extensive outdoor pig meat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	1,000,000	kg	£1.33	90.0	8.9
Cull meat	19,000	kg	£0.20	0.24	1.3
FYM	11,000	t	£9.67	7.1	64
Skins	14,000	skin	£2.50	2.2	17
Pet food	97,000	kg	£0.07	0.44	0.47

Table 31 Organic pig meat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	430,000	kg	£1.50	83	9.0
Cull meat	8,000	kg	£0.20	0.21	1.2
FYM	9,600	t	£9.67	12	58
Skins	13,544	skin	£2.50	4.3	6.6
Pet food	41,000	kg	£0.07	0.36	0.42

Acknowledgements

Helen Browning – Organic production - largest/longest running outdoor herd in UK.

Jonothan Cooper – Outdoor production- outdoor producer for 20 years.

Garth vets – Indoor production systems - East Yorkshire.

3.2.1.5 Chicken

Product description

Three chicken meat production systems were assessed.

1. Intensive - Indoor chicken meat – Chickens spent entire life inside, fed on predominantly cereal based diet.
2. Extensive – Outdoor chicken meat – Chickens have access to outdoors for 6% of life based on an initial housed period followed by limited access to the outdoors, fed on a predominantly cereal based diet.

3. Organic – Outdoor chicken meat – Chickens have access to outdoors for 12% of life based on an initial housed period followed by some restriction to access to outdoors, at organic stocking densities and fed on an organic cereal based diet.

In each case the FU was 1 kg oven ready chicken carcasses, slaughtered, gutted and hung, but not processed further.

Process description

Intensive indoor chicken meat – This system was based on a 200,000 bird flock, housed in standard chicken houses, with 98% of birds making it to slaughter. Eggs were produced by a broiler breeding flock, transported to a hatchery, hatched there and then the day old chicks were transported to the houses where they spent their entire lives. Birds were fed on a predominantly cereal-based diet. Birds reach slaughter weights of 2.46 kg dead weight in 40 days. The only co-product in this system was broiler litter.

Extensive outdoor chicken meat – This system was based on a 30,000 bird flock, housed in standard chicken houses, but with access to the outside for 6% of their life. The survival rate was 96%. Eggs were produced and hatched in a similar manner to those in the indoor flock. Birds were fed on a predominantly cereal based diet. Birds were slaughtered at 56 days with a dead weight of 2.2kg. The main co-product from this system was broiler litter.

Organic chicken meat – This system was based on a 2,000 bird flock, housed in small mobile chicken sheds. The survival rate was 94%. Eggs were assumed to be produced and hatched in a similar system to the indoor and outdoor flocks. Birds were fed on a predominantly organic cereal based diet, and had access to the outdoors for 12% of their lives. Birds were slaughtered at 81 days, with a dead weight of 2.2kg. The main co-product was broiler litter.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 26. The intensive system had the lowest emissions. Raw materials were the greatest component of all systems.

Table 32 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg oven ready bird)

	Category		
	Intensive – Indoor chicken	Extensive – Outdoor chicken	Organic – Outdoor chicken
Raw Materials	**1.8**	**2.2**	**2.4**
Processes			
energy	0.17	0.20	0.20
waste	0.83	0.90	0.95
Animal & soil emissions	0.14	0.24	0.35
Refrigeration (inc. electricity & leakage)	0.09	0.10	0.10
(Total processing)	**(1.2)**	**(1.4)**	**(1.6)**
Transport	**0.016**	**0.053**	**0.082**
Total	**3.1**	**3.7**	**4.1**

Raw materials

In all systems, feed was the major contributor to the GHG emissions of raw materials (Table 33).

Table 33 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg oven ready bird) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive – Indoor chicken	Extensive – Outdoor chicken	Organic – Outdoor chicken
Wheat	0.60	0.73	0.84
Barley	0.10	0.12	0.14
Soya meal	0.39	0.47	0.55
Beans	0.012	0.015	0.018
Vitamins & Minerals	<0.001	<0.001	<0.001
Grass	-	0.039	0.019
Straw (wood shavings for indoor)	<0.001	0.002	0.005
(Total feed & bedding)	**(1.1)**	**(1.4)**	**(1.6)**
Replacements from outside cycle	0.74	0.86	0.87
Veterinary medications	<0.01	<0.01	<0.01
Total	**1.8**	**2.2**	**2.4**

Processes

In all systems, animal and soil emissions (N_2O and CH_4) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 34).

Table 34 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg oven ready bird) from processes.

Category	GHG emissions (kg CO_2e/FU)		
	Intensive – Indoor chicken	Extensive – Outdoor chicken	Organic – Outdoor chicken
Electricity	0.016	0.020	0.005
Diesel	0.003	0.003	0.002
LPG	0.076	0.092	0.089
Other (feed manufacture)	0.076	0.090	0.11
(Total energy)	**(0.17)**	**(0.20)**	**(0.20)**
Plastics (land-filled)	<0.001	<0.001	<0.001
Animal waste (incineration of dead stock & slaughter house waste)	0.65	0.71	0.74
Other waste disposal	<0.001	<0.001	<0.001
(Total waste)	**(0.65)**	**(0.71)**	**(0.74)**
N_2O emissions	0.12	0.20	0.30
CH_4 emissions	0.022	0.035	0.051
(Total animal and soil emissions)	**(0.14)**	**(0.24)**	**(0.35)**
Refrigeration (inc. electricity)	0.09	0.10	0.10
Total for processes	**1.2**	**1.4**	**1.6**

Co-products and yields

Table 35 Intensive indoor chicken meat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	480,000	kg	£0.65	95	3.0
Broiler litter	1,800	t	£8.92	4.9	41

Table 36 Extensive outdoor chicken meat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	63,000	kg	£0.65	97	3.9
Broiler litter	160	t	£8.92	3.4	53

Table 37 Organic chicken meat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Meat	4,100	kg	£0.80	96.0	6.3
Broiler litter	16	t	£8.92	4.1	70

Acknowledgements

'Petersime' personal communication – energy usage in hatchery

3.2.1.6 Milk

Product description

Three milk production systems were assessed.

1. Intensive – High yielding milk – Dairy herd with high inputs of feed, spending 48% of time grazing, fed maize and grass silage and cereals.

2. Extensive – Low yielding milk – Dairy herd with low inputs of feed, spending 48% of time grazing, fed maize and grass silage and cereals.

3. Organic – Milk – Dairy herd raised to organic standards on organic feed. Spend 53% of time grazing, fed grass silage and cereals.

In each case the FU was 1 L of fresh milk.

Process description

Intensive high yielding milk – This system was based on a 140 cow Friesian herd, with each cow yielding on average 8,000L milk per year. Cows were artificially inseminated, some with pure-bred Friesian semen, whilst others were crossed with beef semen, once per year and produce one calf. 89% of dairy cows produced a live calf that went on to become either meat or a replacement dairy cow. The beef cross calves and male Pure-bred calves (64% of live calves) were reared for 10 days on milk replacer before being sold into an intensive dairy beef system. The remaining Pure-bred female calves were raised up to become replacement dairy cows. Dairy cows were given high inputs to enable them to yield well, but this shortens their productive life (20% of herd was replaced each year). Co-products included dairy beef calves, replacement dairy calves, slurry, low value cull meat, offal going for pet food and skins.

Extensive low yielding milk – This system was based on a 140 cow Friesian herd, with each cow yielding 5,500L milk per year. Cows were artificially inseminated, some with Pure-bred Friesian semen, whilst others were crossed with beef semen, once per year and produce one calf (89% of cows produced live calves that went on to become either meat or replacement animals). The beef cross calves and male Pure-bred calves (70% of live calves) were reared for 10 days on milk replacer before being sold into an intensive dairy beef system. The remaining Pure-bred female calves were raised up to become replacement dairy cows. Dairy cows were given lower inputs (compared to intensive systems) reducing milk yields, but increasing cow life (14% herd replaced per year). Co-products included dairy beef calves, replacement dairy calves, slurry, low value cull meat, offal going for pet food and skins.

Organic milk - This system was based on a 140 cow Friesian herd, with each cow yielding 6,000L milk per year. Cows were naturally covered, some with Pure-bred Friesian bulls, whilst others were crossed with beef bulls, once per year and produced one calf (89% of cows produced live calves that went on to become either meat or replacement animals). The beef cross calves and male Pure-bred calves (70% of live calves) were reared on the cow for 10 days before being sold. The remaining Pure-bred female calves were raised up to become replacement dairy cows. Dairy cows were given organic inputs. Co-products included dairy beef calves, replacement dairy calves, slurry, low value cull meat, offal going for pet food and skins.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 26. The intensive system had the lowest emissions. Animal and soil emissions were the greatest component of all systems.

Table 38 GHG emissions (kg CO_2e) per functional unit (FU; 1 L milk)

Category	GHG emissions (kg CO_2e/FU)		
	Intensive – High yielding milk	Extensive – Low yielding milk	Organic – Milk
Raw Materials	**0.36**	**0.41**	**0.33**
Processes			
Energy (inc milk cooling)	0.035	0.036	0.033
waste	0.089	0.024	0.096
Animal & soil emissions	0.74	0.95	0.86
Refrigeration of cull meat (inc. electricity & leakage)	0.001	0.001	0.002
(Total processes)	**(0.86)**	**(1.0)**	**(0.99)**
Transport	**0.017**	**0.013**	**0.017**
Total	**1.2**	**1.4**	**1.3**

Raw materials

In all systems, feed was the major contributor to the GHG emissions of raw materials (Table 39).

Table 39 GHG emissions (kg CO_2e) per functional unit (FU; 1 L milk) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive – High yielding milk	Extensive – Low yielding milk	Organic – Milk
Wheat	0.13	0.11	0.077
Rape	0.053	0.038	0.031
Beans	Not fed	Not fed	<0.001
Grass	0.057	0.079	0.037
Grass silage	0.086	0.12	0.065
Maize silage	0.031	0.045	-
Vitamins & Minerals	<0.001	<0.001	<0.001
Milk replacers (milk for organic)	0.004	0.006	0.11
Straw	0.003	0.005	0.009
(Total feed & bedding)	**(0.36)**	**(0.41)**	**(0.33)**
Replacements from outside cycle	<0.01	<0.01	<0.01
Veterinary medications	<0.01	<0.01	<0.01
Total	**0.36**	**0.41**	**0.33**

Processes

In all systems, animal and soil emissions (N_2O and CH_4) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 40).

Table 40 GHG emissions (kg CO_2e) per functional unit (FU; 1 L milk) from processes.

Category	GHG emissions (kg CO_2e/FU)		
	Intensive – High yielding milk	Extensive – Low yielding milk	Organic – Milk
Electricity (inc. milk cooling)	0.021	0.022	0.021
Other	0.014	0.014	0.012
(Total energy)	**(0.035)**	**(0.036)**	**(0.033)**
Plastics (land-filled)	0.001	0.001	0.001
Animal waste (incineration of dead stock & slaughter house waste)	0.089	0.024	0.095
Other waste disposal	<0.001	<0.001	<0.001
(Total waste)	**(0.090)**	**(0.025)**	**(0.096)**
N_2O emissions	0.18	0.23	0.24
CH_4 emissions	0.55	0.62	0.63
(Total animal and soil emissions)	**(0.74)**	**(0.95)**	**(0.86)**
Refrigeration of cull meat (inc. electricity & leakage)	0.001	0.001	0.002
Total for processes	**0.86**	**1.0**	**0.99**

Co-products and yields

Table 41 Intensive high yielding milk – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Milk	1,100,000	L	£0.25	92	1.2
Cull meat	9,200	kg	£1.80	5.5	8.9
Slurry	3,000	t	£1.09	1.1	5.4
Hide	28	hide	£21.00	0.19	100
Pet food	2,500	kg	£0.07	0.057	0.35
Dairy beef calves	81	animals	£54.90	0.44	81
Replacements	44	animals	NA returned to beginning of cycle		

Table 42 Extensive low yielding milk – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Milk	770,000	L	£0.25	92	1.4
Cull meat	5,900	kg	£1.80	5.0	10
Slurry	2,500	t	£1.09	1.28	6.3
Skins	20	skin	£21.00	0.20	120
Pet food	1,700	kg	£0.07	0.058	0.40
Dairy beef calves	87	animals	£54.90	0.70	95
Replacements	38	animals	NA returned to beginning of cycle		

Table 43 Organic yielding milk – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Milk	840,000	L	£0.28	92	1.3
Cull meat	6,700	kg	£1.90	5.0	9.1
Slurry	2,500	t	£1.09	1.1	5.2
Skins	22	skin	£21.00	0.19	100
Pet food	2,000	kg	£0.07	0.055	0.33
Dairy beef calves	87	animals	£54.90	0.56	78
Replacements	38	animals	NA returned to beginning of cycle		

Acknowledgements

Nick Holt-Martyn, The Dairy Group – additional information about dairy systems.

3.2.2 Livestock feed crops

The assessment of livestock feed crops included all the emissions associated with the manufacture and transport of raw materials (e.g. seed, fertilisers, pesticides, plastics), all fuel requiring processes (e.g. cultivation, drilling, harvesting / baling), wastes produced as a result of production (e.g. plastic packaging for raw materials), soil emissions and all transport of raw materials, co-products and waste to or from the field.

Emission factors for the production of nitrogen and other fertilisers[21] included all costs of manufacture, packaging and transport. Pesticide[22] emissions factors included manufacture and packaging, with transport calculated separately. Emissions factors for seed (unless otherwise stated) were calculated using the end product. This provided a reasonable estimate of emissions, where details for seed production were not available, although management of seed crops may differ slightly from the production of food crops.

Emission factors for energy use from tractor activities on farm (eg cultivations, drilling, harvesting) came from fuel usage in Cormack, W. F. and Metcalfe, P. (2000)[23] combined with fuel emissions factors from Defra's GHG conversion factors [8]. These values were used for livestock and crop calculations, where direct measurements were not available.

3.2.2.1 Cereals

Product description

The functional unit (FU) was 1 tonne cereal grain delivered to a distributer. Four cereal feed crops were assessed.

1. Intensive winter feed wheat
2. Extensive spring feed wheat
3. Organic winter feed wheat
4. Winter feed barley

Process description

Intensive winter feed wheat was drilled following min-til (heavy discs) cultivation. After the crop was drilled it was rolled, then 5.9[24] spray applications were made using average pesticide application rates from PUS. Fertiliser application rates were taken from the British Survey of Fertiliser Practice 2007[25]. Grain was harvested using a large combine harvester, with the straw chopped and left in the field for incorporation. Once harvested the grain was transported to the farm where it was dried by 3%. It was then transported to the distributer.

Extensive spring feed wheat was drilled in the spring following ploughing and discing cultivations. Lower inputs were required due to later sowing. Combining and drying as per winter wheat except that the straw was baled and removed from the field.

Organic feed wheat was drilled following ploughing and heavy cultivator cultivations. No pesticides were applied to the crop, instead three passes with a guided hoe were used for weed control. Fertility for the wheat came from a previous fertility building grass clover ley with 40% of the emission from that crop being allocated to the wheat. Combining and drying as per winter wheat except that the straw was baled and removed from the field.

Winter barley drilled using min-til cultivation using a heavy cultivator, on medium soil, fertiliser was applied as per BSFP.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 44. The extensive spring wheat system had the lowest emissions. Raw materials and soil emissions were the greatest component (due predominantly to nitrogen manufacture and application, in conventional systems, and fertility building in organic).

Table 44 GHG emissions (kg CO_2e) per functional unit (FU; 1 t grain delivered).

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive winter feed wheat	Extensive spring feed wheat	Organic feed wheat	Winter feed barley
Raw Materials	**230**	**150**	**480**	**190**
Processes				
Energy	33	47	53	47
Waste	<1	<1	<1	0.061
Animal & soil emissions	290	200	210	220
(Total processes)	**(320)**	**(250)**	**(260)**	**(270)**
Transport	**2.9**	**13**	**11**	**78**
Total	**550**	**390**	**740**	**460**

Raw materials

In all conventional systems nitrogen was the major contributor to the GHG emissions of raw materials (Table 45). In organic systems the emissions from the fertility building crop were the predominant raw material emission.

Table 45 GHG emissions (kg CO_2e) per functional unit (FU; 1 t grain delivered).from raw materials.

Category	GHG emissions (kg CO_2e/FU)			
	Intensive winter feed wheat	Extensive spring feed wheat	Organic feed wheat	Winter feed barley
N	160	94	-	130
P_2O_5	6.7	3.1	-	8.8
K_2O	9	5.8	-	14
Lime	25	17	54	16
S	6.3	7.8	-	7.9
Previous fertility building crop	-	-	400	-
(Total Nutrients)	**(210)**	**(130)**	**(460)**	**(180)**
Pesticides	10	2.9	-	3.5
Seed	14	14	18	8.8
Total	**230**	**150**	**480**	**190**

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 46).

Table 46 GHG emissions (kg CO_2e) per functional unit (FU; 1 t grain delivered).from processes.

Category	GHG emissions (kg CO_2e/FU)			
	Intensive winter feed wheat	Extensive spring feed wheat	Organic feed wheat	Winter feed barley
Total energy (diesel)*	**33**	**48**	**53**	**47**
Total waste (inc plastics)	**<1**	**<1**	**<1**	**0.061**
N_2O emissions from N application	140	82	-	110
Emission from lime application	73	49	170	49
Emissions from residues (inc out grades)	76	69	51	57
(Total soil emissions)	**(290)**	**(200)**	**(210)**	**(220)**
Total for processes	**320**	**250**	**260**	**270**

Co-Products and yields

Table 47 Conventional feed wheat – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Conventional feed wheat	8.3	t		100	553

Table 48 Extensive spring feed wheat – co-products. FU = functional unit.

Co-Product	Yield / ha	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Spring feed wheat	5.8	t	£155	94	390
Spring wheat straw	2.75	t	£20	5.8	50

Table 49 Organic feed wheat – co-products. FU = functional unit.

Co-Product	Yield / ha	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Organic feed wheat	3.5	t	£200	93	740
Organic wheat straw	2.0	t	£27	7.4	100

Table 50 Barley – co-products. FU = functional unit.

Co-Product	Yield / ha	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Barley	6.6	t		90	460
Barley straw	2.75	t		10	120

3.2.2.2 Beans

Product description

The FU was 1 tonne of beans delivered to a distributer. Two types of field beans were assessed.

1. Conventional field beans

2. Organic field beans

Process description

Conventional winter field beans were drilled and ploughed down, with power-harrow to level off. Fertiliser applications were calculated using BSFP, 2007. 4.4 spray applications were made using pesticide rates taken from PUS 2006. The crop was harvested using a conventional combine and beans were dried by 3% moisture after harvest.

Organic winter field beans were grown as part of an organic rotation with no additional fertilisation or pesticide applications.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 44. The conventional winter beans system had the lowest emissions. Energy was the greatest component of the emissions.

Table 51 GHG emissions (kg CO_2e) per functional unit (FU; 1 t beans delivered)

Category	**GHG emissions (kg CO_2e/FU)**	
	Conventional winter beans	Organic winter beans
Raw Materials	**18**	**23**
Processes		
Energy	46	65
Waste	<1	<1
Soil emissions	24	28
(Total processes)	**(70)**	**(92)**
Transport	**8.0**	**8.0**
Total	**96**	**120**

Raw materials

In all systems seed was the major contributor to the GHG emissions of raw materials (Table 52).

Table 52 GHG emissions (kg CO_2e) per functional unit (FU; 1 t beans delivered) from raw materials

Category	GHG emissions (kg CO_2e/FU)	
	Conventional winter beans	Organic winter beans
N	-	-
P_2O_5	4.2	-
K_2O	8.0	-
Lime	-	-
S	-	-
Previous fertility building crop	-	-
(Total Nutrients)	**(12)**	**(0.0)**
Pesticides	1.7	-
Seed	4.2	23
Total	**18**	**23**

Processes

In all systems, energy (diesel) usage was the major contributor to the GHG emissions of processes (Table 53).

Table 53 GHG emissions (kg CO_2e) per functional unit (FU; 1 t beans delivered) from processes.

Category	**GHG emissions (kg CO_2e/FU)**	
	Conventional winter beans	Organic winter beans
Total energy (Diesel)	**46**	**65**
Total waste (inc. plastics)	**<1**	**<1**
N_2O emissions from N application	-	-
Emission from lime application	-	-
Emissions from residue incorporation (inc out grades)	24	28
(Total soil emissions)	**(24)**	**(28)**
Total for processes	**70**	**92**

Co-Products

No co-products were allocated emissions as part of this assessment. The products, had yields of 6.6 t/ha (conventional beans) and 4.0 t/ha (organic beans).

3.2.2.3 Oilseed rape (meal)

Product description

The functional unit (FU) was 1 tonne oilseed rape meal delivered to distributer. Two types of oilseed rape meal were assessed.

1. Conventional OSR meal
2. Organic OSR meal

Process description

Conventional OSR was drilled after min-til cultivations, using heavy discs. Fertiliser applications were made as per BSFP, 2007. The oilseed rape crop was harvested and dried by 3%, then processed for oil. The OSR meal was produced as a co-product was then feed to livestock.

Organic OSR was drilled after discing, then rolled. Nutrition was supplied as a result of clover ley earlier in the rotation (50% of emissions allocated from clover ley). The oilseed rape crop was harvested dried by 3% and then processed for oil. The meal was produced as a co-product was then feed to livestock.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 54. The organic system had the lowest emissions. Raw materials and soil emissions were the greatest component of the conventional system (due predominantly to nitrogen manufacture and application). In the organic system raw materials and energy were the greatest component.

Table 54 GHG emissions (kg CO_2e) per functional unit (FU; 1 t meal delivered)

Category	**GHG emissions (kg CO_2e/FU)**	
	Conventional OSR meal	Organic OSR meal
Raw Materials	**260**	**360**
Processes		
Energy	130	120
Waste	0.065	0.014
Soil emissions	310	160
(Total processes)	**(440)**	**(280)**
Transport	**2.3**	**1.6**
Total	**700**	**640**

Raw materials

In the conventional system nitrogen was the major contributor to the GHG emissions of raw materials (Table 55). In the organic system the emissions from the fertility building crop were the predominant raw material emission.

Table 55 GHG emissions (kg CO_2e) per functional unit (FU; 1 t meal delivered) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**	
	Conventional OSR meal	Organic OSR meal
N	200	-
P_2O_5	8	-
K_2O	10	-
Lime	26	30
S	12	-
Previous fertility building crop (50% emissions)	-	330
(Total Nutrients)	**(260)**	**(360)**
Pesticides	4	-
Seed	<1	<1
Total	**260**	**360**

Processes

In the conventional system, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 56). In the organic system the energy used in production was a larger contributor to the process emissions.

Table 56 GHG emissions (kg CO_2e) per functional unit (FU; 1 t meal delivered) from processes.

Category	**GHG emissions (kg CO_2e/FU)**	
	Conventional OSR meal	Organic OSR meal
Total energy (diesel)	**130**	**120**
Total waste (inc plastics)	**<1**	**<1**
N_2O emissions from N application	170	-
Emission from lime application	76	89
Emissions from residue incorporation (inc out grades)	65	75
(Total soil emissions)	**(310)**	**(164)**
Total for processes	**440**	**280**

Co-Products and Yields

Table 57 – Conventional OSR meal – co-products. FU = functional unit.

Co-Product	**Yield / ha**	**FU**	**Value (£/FU)**	**% allocation of CO_2e emissions**	**kg CO_2e / FU**
OSR oil	1.2	t	£350	71	2,700
OSR meal	2.0	t	£90	29	700

Table 58 Organic OSR meal – co-products. FU = functional unit.

Co-Product	Yield / ha	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
OSR oil	1.1	t	£350	71	2,500
OSR meal	1.7	t	£90	29	640

3.2.2.4 Grass

Product description

The FU 1 tonne dry matter of grazed grass. Five types of grass crop were assessed.

1. Intensive 5 year ley
2. Extensive permanent grass
3. Organic grass
4. Overseas – New Zealand grass

Process description

Intensive grass 5 Year ley – Grass re-drilled every 5 years with high inputs of fertilisers. Used to feed dairy cattle.

Extensive Permanent – low input permanent grass. Used to feed upland and lowland sheep and suckler beef.

Organic – low input grass / clover sward. Fertilised using animal manures. Used to feed organic cattle and sheep.

Overseas New Zealand grass – low input permanent grass used for feeding New Zealand lamb.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 59. The New Zealand permanent grass system had the lowest emissions. Raw materials and soil emissions were the greatest component (due predominantly to nitrogen manufacture and application, in conventional systems, and fertility building in organic).

Table 59 GHG emissions (kg CO_2e) per functional unit (FU; 1 t DM).

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – 5 year ley	Extensive – permanent	Organic – permanent	Overseas – New Zealand permanent
Raw Materials	**95**	**70**	**28**	**18**
Processes				
Energy	9.1	5.6	4.7	2.7
Waste	<1	1.3	<1	1.3
Soil emissions	110	83	35	9.0
(Total processes)	**(120)**	**(90)**	**(40)**	**(13)**
Transport	**0.021**	**0.022**	**<0.001**	**0.019**
Establishment of temporary perennial crops	**6.6**			
Total	**220**	**160**	**67**	**30**

Raw materials

In all conventional systems nitrogen was the major contributor to the GHG emissions of raw materials (Table 60). In organic systems the emissions from the fertility building crop were the predominant raw material emission.

Table 60 GHG emissions (kg CO_2e) per functional unit (FU; 1 t DM) from raw materials

Category	**GHG emissions (kg CO_2e/FU)**			
	Intensive – 5 year ley	Extensive – permanent	Organic – permanent	Overseas – New Zealand permanent
N	65	44	-	8
P_2O_5	4	2	-	4
K_2O	5	2	-	<1
Lime	13	15	12	1
S	-	6	-	2
Cattle slurry / FYM	6	-	16	
(Total nutrients)	**(91)**	**(70)**	**(28)**	**(16)**
Pesticides	**<1**	**2**	**-**	**2**
Seed*	**3**	**-**	**-**	**-**
Total	**95**	**70**	**28**	**18**

*Emission factor available[26]

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 61).

Table 61 GHG emissions (kg CO_2e) per functional unit (FU; 1 t DM) from processes.

	GHG emissions (kg CO_2e/FU)			
	Intensive – 5 year ley	Extensive – permanent	Organic – permanent	Overseas – New Zealand permanent
Total energy (Diesel)	**9**	**6**	**5**	**3**
Total waste (inc plastics)	**<1**	**<1**	**<1**	**<1**
N_2O emissions from N application	67	39	-	6
Emission from lime application	38	44	35	3
Emissions from residue incorporation	20	-	-	-
(Total soil emissions)	**(110)**	**(83)**	**(35)**	**(9)**
Total for processes	**120**	**90**	**40**	**13**

Co-Products and Yields

No co-products were allocated emissions as part of this assessment. For primary production, the sole product, grazed grass yielded:

1. Intensive 5 year ley grass 10 tDM
2. Extensive permanent grass 8 tDM
3. Organic grass 10 tDM
4. Overseas New Zealand grass 9.5tDM

3.2.2.5 Winter forage

Product description

The FU 1 tonne dry matter of forage. Five types of winter forage were assessed.

1. Maize silage
2. Intensive grass silage
3. Extensive grass silage
4. Organic grass silage
5. Stubble turnips

Process description

Maize silage – whole crop maize, cut and clamped for feeding dairy cattle.

Intensive grass silage - 5 year grass ley, high fertiliser input, cut 3-4 times a year and clamped. Used to feed dairy cattle.

Extensive grass silage – 10 year grass ley, lower fertiliser inputs, cut 2 times a year and clamped. Used to feed beef cattle.

Organic grass silage – 3 year grass clover ley, fertility from clover in sward, cut once a year. Used to feed organic cattle.

Stubble turnips – low input over winter forage crop used to feed New Zealand and Upland lamb.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 62. The organic 3 year ley silage system had the lowest emissions of the silage systems, whilst organic stubble turnips were lowest overall. Raw materials and soil emissions were the greatest component (due predominantly to nitrogen manufacture and application, in conventional systems, and fertility building in organic).

Table 62 GHG emissions (kg CO_2e) per functional unit (FU; 1 t DM).

Category	**GHG emissions (kg CO_2e/FU)**				
	Maize silage	Intensive – 5 year ley silage	Extensive – 10 year ley silage	Organic – 3 year ley silage	Organic - stubble turnips
Raw Materials	**64**	**82**	**110**	**26**	**0.010**
Processes					
energy	27	42	24	15	3.3
waste	0.082	0.45	1.0	0.033	0.022
Soil emissions	88	110	120	84	1.0
(Total processes)	**(110)**	**(150)**	**(140)**	**(99)**	**(4.3)**
Transport	**0.61**	**0.006**	**0.047**	**0.148**	**0.079**
Establishment of crop (perennial crops)*		**19**	**2.6**	**11.4**	
Total	**180**	**250**	**250**	**120**	**4.3**

* includes raw materials, energy, transport, waste & soil emissions from year of establishment, divided by the number of years ley is productive (total tonnes of DM produced in 3, 5 or 10 years of cropping)

Raw materials

In all conventional systems nitrogen was the major contributor to the GHG emissions of raw materials (Table 63). In organic systems the emissions from the fertility building crop were the predominant raw material emission.

Table 63 GHG emissions (kg CO_2e) per functional unit (FU; 1 t DM) from raw materials. NA = not applicable.

Category	**GHG emissions (kg CO_2e/FU)**				
	Maize Silage	Intensive – 5 year ley silage	Extensive – 10 year ley silage	Organic – 3 year ley silage	Organic - Stubble turnips
N	32	61	79	NA	NA
P_2O_5	7	3.4	3.9	3	NA
K_2O	5	5.2	5.6	3	NA
Lime	10	9.0	13	12	NA
S	NA	3.5	4.9	NA	NA
Cattle slurry / FYM	8	NA	NA	7.5	NA
(Total nutrients)	**(62)**	**(82)**	**(110)**	**(26)**	NA
Pesticides	0.11	0.10	0.14	NA	NA
Seed*	1.4	2.4	1.2	0.005	0.010
Total	**64**	**82**	**110**	**26**	**0.010**

*Emission factor available for grass seed, maize seed calculated by ADAS from grain maize calculation [22] figure for seed included in establishment figure in Table 62 not raw materials.

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 64).

Table 64 GHG emissions (kg CO_2e) per functional unit (FU; 1 t DM) from processes

Category	GHG emissions (kg CO_2e/FU)				
	Maize silage	Intensive – 5 year ley silage	Extensive – 10 year ley silage	Organic – 3 year ley silage	Organic - stubble turnips
Total energy (Diesel)	**27**	**42**	**24**	**15**	**3.3**
Total waste (Inc plastic)	**0.051**	**0.033**	**0.048**	**0.005**	**0.022**
N_2O emissions from N application	28	58	69	-	-
Emission from lime application	31	28	37	38	-
Emissions from residue incorporation	29	20	10	49	1.0
(Total soil emissions)	**(88)**	**(105)**	**(115)**	**(84)**	**(1.0)**
Total for processes	**110**	**150**	**140**	**99**	**4.3**

Co-products and Yields

No co-products were allocated emissions as part of this assessment. For primary production, the sole product, silage yielded:

1. Maize Silage 11 tDM
2. Intensive 5 year ley silage 14 tDM
3. Extensive 10 year ley silage 9.5 tDM
4. Organic 3 year ley silage 10 tDM
5. Organic stubble turnips 20 tDM

3.2.3 Crop commodities

Crop commodities were assessed in a similar manner to feed crops with the same emission factors used where appropriate.

All crops that required lime were assumed to be limed once every 5 years, therefore one fifth of the lime rate from BSFP was allocated to the crop, with just one fifth of the emissions for application allocated to the crop.

Where refrigeration was required it was based on an Ammonia system cooling 100m^2 having CO_2e emissions of 2016 kg CO2e/day – Prof Savvas Tassou pers. comm.

3.2.3.1 Bread wheat

Product description

The FU was 1 tonne of cereal grain delivered to a distributer. Three bread wheat production systems were assessed.

1. Conventional winter bread wheat
2. Conventional spring bread wheat
3. Organic winter bread wheat

Process description

Conventional winter bread wheat drilled after ploughing and discing. After the crop was drilled it was rolled, then 5.9 (PUS) spray applications were made using average pesticide application rates from PUS. Fertiliser application rates were taken from the British Survey of Fertiliser Practice. Grain was harvested using a large combine harvester, with the straw chopped and left in the field for incorporation. Once harvested the grain was transported to the farm, where it was dried by 3%, it was then transported to the distributer.

Extensive spring bread wheat was drilled in the spring following ploughing and discing cultivations. Lower inputs were required due to later sowing date. Combining and drying as per winter wheat except that the straw was baled and removed from the field.

Organic bread wheat was drilled following ploughing and heavy cultivator cultivations. No pesticides were applied to the crop, instead three passes with a guided hoe were used for weed control. Fertility for the wheat came from a previous fertility building grass clover ley with 40% of the emissions from that crop being allocated to the wheat. Some additional lime was applied. Combining and drying as per winter wheat except that the straw was baled and removed from the field.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 65. The extensive spring wheat system had the lowest emissions. Raw materials and soil emissions were the greatest component (due predominantly to nitrogen manufacture and application, in conventional systems, and fertility building in organic).

Table 65 GHG emissions (kg CO_2e) per functional unit (FU; 1 t grain delivered).

Category	**GHG emissions (kg CO_2e/FU)**		
	Conventional winter bread wheat	Extensive spring bread wheat	Organic bread wheat
Raw Materials	**260**	**140**	**480**
Processes			
energy	41	47	53
waste	<1	<1	<1
Soil emissions	330	200	210
(Total processes)	**(370)**	**(250)**	**(260)**
Transport	**3**	**13**	**11**
Total	**640**	**400**	**750**

Raw materials

In all conventional systems nitrogen was the major contributor to the GHG emissions of raw materials (Table 66). In organic systems the emissions from the fertility building crop were the predominant raw material emission.

Table 66 GHG emissions (kg CO_2e) per functional unit (FU; 1 t grain delivered) from raw materials. NA = not applicable.

Category	GHG emissions (kg CO_2e/FU)		
	Conventional winter bread wheat	Extensive spring bread wheat	Organic bread wheat
N	200	94	NA
P_2O_5	7	3	NA
K_2O	9	6	NA
Lime	27	17	54
S	7	8	NA
Previous fertility building crop	NA	NA	410
Total (Nutrients)	**(250)**	**(130)**	**(460)**
Pesticides	**4**	**4**	NA
Seed	**11**	**14**	**19**
Total	**260**	**140**	**480**

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 67).

Table 67 GHG emissions (kg CO_2e) per functional unit (FU; 1 t grain delivered) from processes. NA = not applicable.

Category	**GHG emissions (kg CO_2e/FU)**		
	Conventional winter bread wheat	Extensive spring bread wheat	Organic bread wheat
Total energy (Diesel)	**41**	**48**	**53**
Total waste (inc plastics)	**<1**	**<1**	**<1**
N_2O emissions from N application	170	82	NA
Emission from lime application	80	49	170
Emissions from residue incorporation (inc out grades)	76	69	51
(Total soil emissions)	**(330)**	**(200)**	**(210)**
Total for processes	**370**	**250**	**260**

Co-Products and Yields

Table 68 Bread wheat – yields & co-products. FU = functional unit.

Crop	Yield / ha	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Conventional winter bread wheat	7.5	t	£175.00	100	638
Conventional winter wheat straw	Straw was chopped behind the combine and remained in field				
Conventional spring bread wheat	5.75	t	£175.00	95	400
Conventional spring wheat straw	*2.75*	*t*	*£20.00*	*5*	*46*
Organic winter bread wheat	3.5	t	£200.00	93	740
Organic wheat straw	*2.0*	*t*	*£27.00*	*7*	*100*

3.2.3.2 Potatoes

Product description

The FU was 1 tonne of potatoes delivered to the next user. Three potato production systems were assessed.

1. Pre-pack potatoes.
2. Processing potatoes.
3. Organic pre-pack potatoes.

Process description

Pre-pack potatoes

A crop of variety Estima (for pre-packing) was grown on a farm producing potatoes on 100 ha. The sequence of operations was: plough, apply fertilisers, power harrow, plant forming ridges with seed treatment and nematicide applied at the same time, and re-ridge. Irrigation and crop protection products (one herbicide application, one insecticide application, one molluscicide application, eight fungicide applications and two haulm destruction (desiccant) applications were applied as needed, followed by harvest, store loading, cold storage (4°C) for 6 months, out loading and grading, and transport to the packing plant. Average GB yield was assumed.

Processing potatoes

A crop of variety Maris Piper (for chips) was grown on a farm producing potatoes on 100 ha of land. The sequence of operations was: plough, apply fertilisers, power harrow, plant forming ridges with seed treatment and nematicide applied at the same time, and re-ridge. Irrigation and crop protection products (one herbicide application, one insecticide application, one molluscicide application, 10 fungicide applications and two haulm destruction (desiccant) applications were applied as needed, followed by harvest, store loading, warm storage (8°C) for 6 months, out loading and grading, and transport to the processing factory. Average GB yield was assumed.

Organic pre-pack potatoes

A crop of variety Sante (for pre-packing, chosen for partial blight resistance) was grown on a stockless, organic farm producing potatoes on 50 ha of land. The potato crop was preceded by a fertility-building crop of red clover, established by under sowing of the previous cereal crop. The sequence of operations was: plough, power harrow, plant forming ridges, re-ridge as late as possible to aid weed control. Irrigation was applied as needed, followed by harvest, store loading, cold storage (4°C) for 6 months, out loading and grading, and transport to the packing plant. No blight sprays (e.g. Bordeaux mixture) were used, but blight was monitored and harvest was timed to maximise yield in relation to blight progress. Yield was based on saleable yield data from ADAS Terrington stockless organic system[27] .

Greenhouse gas emissions

Emissions values for raw materials, energy and waste were important in all systems, but for organic pre-pack potatoes, soil emissions were smaller and energy emissions were greater per FU, compared with the other two systems (Table 69).

Table 69 Emissions of GHGs (kg CO_2e) for production of 1 t potatoes.

Category	**GHG emissions (kg CO_2e/FU)**		
	Pre-pack potatoes	Processing potatoes	Organic pre-pack potatoes
Raw Materials	**64**	**54**	**35**
Processes			
Energy	58	38	64
waste	<0.001	<0.001	<0.001
soil emissions	38	32	12
(Total processes)	**(95)**	**(70)**	**(76)**
Transport	**5.4**	**6.4**	**6.4**
Total	**160**	**130**	**120**

Raw materials

For conventional (non-organic) crops, emissions from raw materials (Table 70) were dominated by nutrients, but this was no so for organic pre-pack potatoes, where emissions from seed tubers were 60% of the total for raw materials.

Table 70 Emissions of GHGs (kg CO_2e) from raw materials used in production of 1 t potatoes.

Category	GHG emissions (kg CO_2e/FU)		
	Pre-pack potatoes	Processing potatoes	Organic pre-pack potatoes
N	32	26	Not applicable
P_2O_5	7	3	Not applicable
K_2O	12	11	Not applicable
Previous fertility building crop	Not applicable	Not applicable	14
(Total Nutrients)	**(51)**	**(40)**	**(14)**
Pesticides	2	2	Not applicable
Seed	11	12	21
Total	**64**	**54**	**35**

Processes

In all systems soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 71).

Table 71 Emissions of GHGs (kg CO_2e) from processes used in production of 1 t potatoes.

Category	**GHG emissions (kg CO_2e/FU)**		
	Pre-pack potatoes	Processing potatoes	Organic pre-pack potatoes
Electricity	46	25	46
Diesel	12	12	18
(Total energy)	**(58)**	**(38)**	**(64)**
Waste (inc. plastics)	**<0.001**	**<0.001**	**<0.001**
N_2O emissions from N application	27	22	Not applicable
Emissions from crop residue incorporation (inc outgrades)	10	10	12
(Total soil emissions)	**(38)**	**(32)**	**(12)**
Total	**95**	**70**	**76**

Co-products and yields

No co-products were allocated emissions as part of this assessment. Average GB yields were assumed these were:

1. Intensive - pre-pack potatoes, 45 t/ha.
2. Extensive - processing potatoes, 45 t/ha.
3. Organic - pre-pack potatoes, 24 t/ha.

3.2.3.3 Tomatoes

Product description

The FU was 1 tonne tomatoes delivered to a UK distributer. Three tomato production systems were assessed.

1. UK conventional oil heated tomatoes – Produced intensively in UK glasshouses heated using oil or LPG.

2. UK conventional waste heat tomatoes – Produced intensively in UK glasshouses heated using waste heat from alternative supplies.

3. Spanish conventional tomatoes – Produced intensively in Spanish glasshouses with low heat requirements and slightly reduced fertiliser inputs. Shipped by refrigerated truck from Spain to the UK.

Process description

In all systems tomato plants were raised at a plant raiser and then shipped to the tomato grower for planting. All tomatoes were grown in rock wool slabs under glass. Nutrients were applied through the irrigation system. Higher levels of nutrients and a greater density of plants were used in the UK systems compared to the Spanish one. As nutrients were applied through the irrigation system there were assumed to be no emissions of N_2O from ‘soils’. All tomatoes are handpicked and packed. They are then transported in refrigerated lorries to the UK distributer.

The UK conventional oil heated glass house used oil and LPG to provide the heat required for optimal yields. The planting density was 20,000 plants per hectare. Nutrition optimised for yields of 500 t/ha. Tomatoes were refrigerated for 0.5 days before arrival at distributer. Emissions were based on an Ammonia system cooling 100m^2 having emissions of 2016 kg CO_2e/day (pers comm. Savvas Tassou, Brunel University).

UK Conventional waste heat systems used water that had been heated as a result of other processes, e.g. as a bi-product of sugar production, to heat the glass house. This heat source was assumed to have no carbon associated with it, as the source of the heat is allocated all of the emissions. Aside from an alternative heat source this system was exactly the same as the UK conventional oil heated system. Tomatoes were refrigerated for 0.5 days before arrival at distributer.

Spanish conventional tomatoes were grown under glass, in rock wool slabs, but the heat required for the glasshouse was provided naturally by the sun. Planting density was 15,000 plants per ha, with slightly lower rates of nutrition per plant to reflect a slightly lower expected yield of 300 t/ha. Tomatoes were refrigerated for 1.5 days before arrival at distributer.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 70. The UK waste heat system had the lowest emissions. In UK waste heat it was the raw materials that were the greatest component, but in oil heats UK systems the energy used for heating was the most significant component. In Spanish systems the transport was a significant component.

Table 72 GHG emissions (kg CO_2e) per functional unit (FU; 1 t tomatoes delivered to UK distributer).

Category	**GHG emissions (kg CO_2e/FU)**		
	UK Conventional oil heated tomatoes	UK Conventional waste heated tomatoes	Spanish conventional tomatoes.
Raw Materials	**220**	**220**	**320**
Processes			
energy	1,900	4.7	4.7
waste	<0.01	<0.01	<1
Soil emissions	1.5	1.5	1.5
refrigeration (inc. energy & leakage)	140	140	420
(Total processes)	**(2,000)**	**(150)**	**(430)**
Transport	**21**	**21**	**1,000**
Total	**2,300**	**390**	**1,800**

Raw materials

In all systems nitrogen and Rockwool slabs were the major contributors to the GHG emissions of raw materials (Table 73).

Table 73 GHG emissions (kg CO_2e) per functional unit (FU; 1 t tomatoes delivered to UK distributer) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**		
	UK Conventional oil heated tomatoes	UK Conventional waste heated tomatoes	Spanish conventional tomatoes.
N	37	37	38
P_2O_5	2.0	2.0	2.1
K_2O	23	23	24
Other nutrients	8.0	8.0	8.2
(Total Nutrients)	**(70)**	**(70)**	**(72)**
Pesticides	0.25	0.25	0.82
Young plants*	26	26	32
Rockwool slabs**	130	130	210
Total	**220**	**220**	**320**

*Emissions for plant raiser calculated by ADAS using PAS 2050

** Emission factor available[28]

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 74).

Table 74 GHG emissions (kg CO_2e) per functional unit (FU; 1 t tomatoes delivered to UK distributer) from processes.

Category	GHG emissions (kg CO_2e/FU)		
	UK Conventional oil heated tomatoes	UK Conventional waste heated tomatoes	Spanish conventional tomatoes.
Total energy	**1,900**	**4.7**	**4.7**
Total waste (inc plastics)	**0.008**	**0.008**	**0.013**
N_2O emissions from N application	-	-	-
Emissions from composting residues (inc out grades)	1.5	1.5	1.5
(Total soil emissions)	**(1.5)**	**(1.5)**	**(1.5)**
Emissions from refrigeration (inc. energy & leakage)	140	140	420
Total for processes	**2,000**	**150**	**430**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yields were[29]:

1. UK Conventional oil heated tomatoes, 500 t/ha.
2. UK Conventional waste heated tomatoes, 500 t/ha.
3. Spanish conventional tomatoes, 300 t/ha.

3.2.3.4 Apples

Product description

The FU was 1 tonne of apples. Three apple production systems were assessed.

1. Intensive – Cox apples
2. Extensive – Cox apples
3. Organic – Cox apples

Process description

All orchards are planted using grafted stock imported from Belgium. Prior to planting the land was ploughed sub soiled and then cultivated to produce an even surface for planting.

Intensive – Cox orchard – With high inputs of fertilisers and high planting density 2333 trees / ha. Trees took 3 years to reach maturity and the orchard was productive for 15 years. To aid weed control the orchard was under sown with grass (about 50% of the area), with a burnt out herbicide strip along the lines of trees. Harvest occurred annually, with apples cooled and then stored for 2.5 months prior to delivery to distributer.

Extensive – Cox orchard – With low inputs of fertilisers and low planting density 1111 trees per ha. Trees took 5 years to reach maturity and the orchard was productive for 15 years. To aid weed control the orchard was under sown with grass (about 50% of the area), with a burnt out herbicide strip along the lines of trees. Harvest occurred annually, with apples cooled and then stored for 2.5 months prior to delivery to distributer.

Organic – Cox orchard – Fertilisation was based on a fertility building period prior to planting and applications of plant stimulants such as Maxicrop, a sea weed based product. Planting density 1111 trees per ha. Trees took 5 years to reach maturity and were productive for 15 years. At planting young trees were mulched with straw to keep weeds down, then eventually the entire orchard was under sown with grass. Harvest occurred annually, with apples cooled and then stored for 2.5 months prior to delivery to distributer.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 75. The intensive system had the lowest emissions. In all systems it was the energy and soil emissions that were the greatest component of the GHG emissions.

Table 75 GHG emissions (kg CO_2e) per functional unit (FU; 1 t apples).

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive - Cox	Extensive - Cox	Organic - Cox.
Raw Materials	**18**	**18**	**5.7**
Processes			
Energy	26	27	38
Waste	0.061	<0.001	<0.001
Soil emissions	14	25	36
(Total processes)	**(39)**	**(52)**	**(74)**
Transport	**9.3**	**8.3**	**19**
Total	**66**	**78**	**100**

Raw materials

In all conventional systems nitrogen was the major contributor to the GHG emissions of raw materials (Table 76). Emissions for organic systems were difficult to calculate due to lack of emissions factors for substances such as seaweed.

Table 76 GHG emissions (kg CO_2e) per functional unit (FU; 1 t apples) from raw materials.

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive - Cox	Extensive - Cox	Organic - Cox.
N	7.3	6.0	
P_2O_5	3.9	3.3	
K_2O	2.4	2.0	
Lime	0.6	0.9	
Other*			?
(Total Nutrients)	**(14)**	**(12.2)**	**(?)**
Pesticides	3.5	5.6	0.51
Straw mulch			0.51
Grafted trees*	?	?	?
Total	**18**	**18**	**5.7?**

* no emissions data found on the production of grafted trees (although their transport from Belgium was included in transport section) or maxicrop foliar nutrients - values are likely to be small (<1%) and have little effect upon the final result.

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 77).

Table 77 GHG emissions (kg CO_2e) per functional unit (FU; 1 t apples).from processes.

Category	**GHG emissions (kg CO_2e/FU)**		
	Intensive - Cox	Extensive - Cox	Organic - Cox.
Electricity	19	19	19
Diesel	6.8	8.5	19
LPG	0.039	0.062	0.10
(Total energy)	**(26)**	**(28)**	**(38)**
Total waste	**0.061**	**<0.001**	**<0.001**
N_2O emissions from N application	6.4	5.7	8.7
CO_2 emissions from lime application	1.8	2.9	0
Emissions from residue incorporation (inc out grades)	4.6	17	25
(Total soil emissions)	**(14)**	**(25)**	**(36)**
Total for processes	**39**	**52**	**74**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yields were:

1. Intensive Cox, 40 t/ha
2. Extensive Cox, 25 t/ha
3. Organic Cox, 15 t/ha

3.2.3.5 Onions

Product description

The FU was 1 tonne of onions. Two onion production systems were assessed.

1. Conventional UK field grown onions, dried and stored from harvest through until March.

2. Organic UK field grown onions, dried and stored through until March.

Process description

Conventional onions were planted as seed into land that had been ploughed, then ridged to form beds. Weeds were controlled through a combination of herbicides and precision hoeing.

Organic onions were planted as seed into land that had had a previous application of FYM, this was ploughed in and then the beds were formed. Weed control occurred through a combination of precision hoeing and thermal weeding.

All onions were irrigated 6 times during growing season. All onions were harvested in the autumn, cleaned, graded & dried, then chilled and stored through until March. Grade out onions and soil were returned to the field.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 78. The intensive system had the lowest emissions. In all systems it was the energy and soil emissions that were the greatest component of the GHG emissions.

Table 78 GHG emissions (kg CO_2e) per functional unit (FU; 1 t onions dried and stored).

Category	**GHG emissions (kg CO_2e/FU)**	
	Conventional UK Onions	Organic UK Onions
Raw Materials	**42**	**10**
Processes		
Energy (excluding refrigeration)	140	250
Waste	<0.001	<0.001
Soil emissions	24	93
Refrigeration (inc. electricity & leakage)	210	210
(Total processes)	**(370)**	**(550)**
Transport	**10**	**22**
Total	**420**	**590**

Raw materials

In all conventional systems nitrogen was the major contributor to the GHG emissions of raw materials (Table 79). In organic systems the emissions associated with manure production where the major contributor to emissions from raw material.

Table 79 GHG emissions (kg CO_2e) per functional unit (FU; 1 t onions dried and stored) from raw materials.

Category	GHG emissions (kg CO_2e/FU)	
	Conventional Onions	Organic Onions
N	24	Not applicable
P_2O_5	2.1	Not applicable
K_2O	5.9	Not applicable
Other Nutrients	7.5	Not applicable
FYM	Not applicable	7.2
(Total Nutrients)	**(39)**	**(7.2)**
Pesticides	2.6	1.1
Seed*	0.54	1.9
Total	**42**	**10**

*Emissions factor for seed based on emissions per ha for main crop but with seed yield provided by Elsom's Seeds.

Processes

In all systems, soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 80).

Table 80 GHG emissions (kg CO_2e) per functional unit (FU; 1 t onions dried and stored) from processes.

Category	GHG emissions (kg CO_2e/FU)	
	Conventional Onions	Organic Onions
Electricity	60	61
Diesel	40	154
LPG	33	33
Other	<1	2
(Total energy excluding refrigeration)	**(133)**	**(250)**
Total waste	**<1**	**<1**
N_2O emissions from N application (or FYM)	20	80
Emissions from residue incorporation (inc out grades)	3.6	11
(Total soil emissions)	**(24)**	**(91)**
Refrigeration (inc. electricity & leakage)	210	210
Total for processes	**370**	**550**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yields were:

1. Conventional UK onion, 46 t/ha

2. Organic UK onion, 13 t/ha

Acknowledgements

Conventional onion basic details (yields, fertiliser rates) - O & P O Jolly Roudham Farm Norwich NR16 2RJ.

Organic onion basic details (yields, manure application rates) - University of Wales Aberystwyth & Organic Advisory Service 2007. Organic Farm Management Handbook.

3.2.4 Foods made from overseas commodities

3.2.4.1 Instant coffee

Product description

The FU was 100 g pack of freeze-dried instant coffee in a glass jar. The coffee was grown in Kenya (small-scale production) and for the production stage the assessment was based on 1 kg of cherries delivered to a processing factory.

Process description

Crop production

Kenyan coffee is a low input coffee of high quality. The majority of the work in the field was done by hand and pesticide and fertiliser usage was low compared with more intensive coffee production systems in South America and Asia that use greater amounts of mechanisation and higher inputs. FAO statistics show that in 2006 there were 170,000 ha of coffee grown in Kenya, producing 48,300 tonnes of green coffee per year. Over one third of this coffee was grown in the Kiambu region of Kenya about 150 km north and east of Nairobi. This region was chosen as the source of green coffee beans.

Kenya is a net importer of pesticides, with the majority of the manufacturing that occurs in Kenya involving the import of ingredients that are then reformulated and repackaged for sale within Kenya[30]. There are also a number of firms that are involved in the import of finished and packaged pesticide products. For this exercise it was assumed that pesticides were all imported from India, fully processed and packaged.

There are currently no fertiliser factories in Kenya so all nitrogen fertiliser has to be imported. The nearest large exporter of nitrogen fertiliser is Saudi Arabia, so it has been assumed that this was the source of nitrogen. Although there are some potential phosphate deposits in Kenya[31] these have not been fully explored and are not commercially exploited. There are no commercial potassium producers in Kenya either. As a result Kenya is dependant upon imports of both phosphate and potassium. The nearest large exporter of these minerals is South Africa, so it was assumed that they were shipped from Durban to Mombasa by bulk carrier and then by road to Nairobi before being distributed to the growers (see Table 89 for distances between ports).

There are dolomitic lime deposits in Kajiado, 100 km south of Nairobi. These are exploited for agricultural use, amongst other purposes and were assumed to be the source of lime used in this assessment.

Table 81 Distance Kenyan imports and exports travel by sea freight

Product	**Export port**	**Import port**	**Distance (km)***
PK	Durban, SA	Mombasa	4200
Pesticides	Mumbai, India	Mombasa	4450
N	Jeddah, Saudi Arabia	Mombasa	4200

* Source:http://www.searates.com/reference/portdistance/

Coffee seedlings were grown from cherries specially saved from productive trees. These cherries do not go through the normal processing stages that the rest of the green coffee goes through. Instead the pulp was removed from the seed, before it was allowed to dry out naturally in the shade. This seed was either collected on farm or provided by specialist breeders. The seeds were planted within two weeks of harvest to avoid loss of viability[32]. Seedlings were planted out into a nursery bed with soil that was enriched with locally produced animal manures. The seeds were allowed to germinate and grow on for 9-12 months before being planted out into the new plantation. The area for the new plantation was first cleared.

There are two ways of growing coffee; extensive shade-grown or intensive sun-grown coffee. In shade-grown coffee when a forested area is cleared some of the trees are left to provide shade. In sun-grown coffee all of the pre-existing vegetation is cleared to allow maximum sunlight to reach the trees. This method of growing puts greater stress on the trees and requires higher inputs of both fertilisers and pesticides to optimise yield. In this exercise the plantation was a sun-grown plantation.

The land was prepared by removing the vegetation by hand, with the wood used for burning or building. Any cultivations that were carried out were done by hand. When the young trees were large enough, about 6 months old, they were transplanted from the nursery plots into the coffee plantation[33]. About 1000 trees per ha were planted in rows. It took three years after planting for the coffee plantation to start yielding, and it was assumed that it will then be productive for about 20 years.

During the establishment phase the young trees required nutrients such as nitrogen, phosphorous, potassium and lime. These nutrients were all applied by hand.

Once established annual applications of N (140 kg/ha), P (35 kg/ha) and K (140 kg/ha) were required.

Coffee cherries were picked by hand, placed in baskets and carried to the edge of the plantation. From here the cherries were rapidly transported to a local processing plant where the process of preparing green coffee began.

Processing

The life cycle stages for processing (post crop production) of coffee were (1) raw materials processing (including packaging), (2) transportation of raw materials and of final products, (3) resource use during manufacture and (4) waste treatment and disposal.

Little primary data was available in terms of resource consumption by the process. However, a detailed description of the instant coffee production process was provided, allowing for theoretical energy and water consumption values to be calculated from thermodynamic principles. This method was used to estimate the GHG emissions from instant coffee processing.

In this particular example, waste spent coffee solids underwent a combustion process with energy recovery. This process was considered to contribute negative emissions as it was assumed that the energy recovered diverted a portion of fossil fuel use in the factory. The energy recovered accounted for just under 14% of the positive carbon emissions of the process.

Greenhouse gas emissions

Emissions of GHGs from production of coffee cherries are dominated by raw materials (59%) and soil emissions (40%; Table 82).

Table 82 GHG emissions (kg CO_2e) for 1 tonne coffee cherries (pre-processing).

Category		**GHG emissions (kg CO_2e/tonne cherries)**
Raw Materials		870
Processes		
	Energy	<0.1
	waste	<0.1
	Soil emissions	580
(Processes total)		**(580)**
Transport		46
Total		**1,500**

Greenhouse gas (GHG) emissions for the processing and manufacture stage, per FU (100 g pack of freeze-dried instant coffee in a glass jar) were 0.86 kg CO_2e/FU. Without energy recovery, the carbon footprint of the process would have been 0.99 kg CO_2e/FU.

Total emissions for the FU, including production of cherries, and processing and manufacturing, were 3.3 kg CO_2e/FU (see Table 85).

Raw materials (agriculture)

Emissions of GHGs from raw materials used in production of coffee cherries are dominated by nitrogen fertiliser (75%; Table 83).

Table 83 GHG emissions (kg CO_2e) from raw materials used to produce 1 tonne coffee cherries (pre-processing).

Category	**GHG emissions (kg CO_2e/tonne)**
N	660
P_2O_5	46
K_2O	160
Lime	1.0
FYM	0.22
(Total nutrients)	**(870)**
Pesticides	<1
Seed	0.26
Total	**870**

Processes (agriculture)

Emissions of GHGs from processes used in production of coffee cherries are dominated by soil emissions of N_2O from soil (99%; Table 84).

Table 84 GHG emissions (kg CO_2e) from processes used to produce 1 tonne coffee cherries (pre-processing).

Category	GHG emissions (kg CO_2e/tonne)
Total energy	**<0.01**
Total waste	**<0.01**
N_2O emissions from N application	570
Emissions from residue incorporation	1.3
Emissions from lime application (establishment)	3.1
N_2O emissions manure application (establishment)	2.5
(Total soil emissions)	**(580)**
Total for processes	**580**

Post primary production, coffee cherries go through a number of processing steps to produce green coffee beans which go to instant coffee manufacturing process. The steps include sorting and cleaning, de-pulping, fermentation, washing and drying. These steps have been incorporated into the post-primary production calculations.

Raw materials and processes (processing and manufacture)

Table 85 summarises the GHG emissions for each life cycle stage of instant coffee production expressed in terms of the product unit - 100 g freeze-dried instant coffee – and in terms of 1 kg of coffee cherries.

Energy consumption in the manufacturing stage was estimated to have the greatest contribution to positive carbon emissions during processing and manufacture (54% of emissions after the primary production of cherries; Table 85). The manufacturing process for instant coffee involves extraction at high temperature and pressure, evaporative concentration and freeze-drying. All of these processes are highly energy intensive. Therefore a major contribution to the product carbon footprint by this process may be expected.

Table 85 Summary of GHG emissions across life cycle of freeze dried instant coffee for the functional unit (FU; 100 g pack of freeze-dried instant coffee in a glass jar) and per kg of coffee cherries.

Category	GHG emissions (kg CO_2e/FU)	GHG emissions (kg CO_2e/kg coffee cherries)
Raw mat. - fresh cherries production	2.4	1.5
Raw mat. – production of green coffee beans from cherries	0.060	0.038
Raw mat. - water	0.0017	0.0011
Raw mat. - packaging	0.32	0.20
Transport - green coffee beans	0.12	0.075
Transport - packaging	0.020	0.013
Manufacture - energy consumption	0.46	0.29
Waste - effluent treatment	0.0005	0.00031
Waste - spent solids*	-0.14	-0.085
Transport - of finished product	0.0072	0.0045
Total	**3.3**	**2.1**

*This waste was used as an energy source, decreasing the amount of energy used, as calculated two rows above; thus this item has a negative value.

It has been estimated that 5.5 kg of fresh coffee cherries are required to produce 1.0 kg of green coffee beans. In the instant coffee production process, 2.9 kg of green coffee beans are required to produce 1.0 kg of instant coffee. This gives an overall ratio of 15.95 : 2.90 : 1.00 for fresh cherries to green beans to finished product. Emissions from production of coffee beans make up 74% of the carbon emissions from 100g jar of instant coffee.

Another significant life cycle stage for this product was the manufacture of packaging (37% of emissions after the primary production of cherries; Table 85). The greatest proportion of the weight of the FU came from glass. The manufacture of glass is another energy intensive process.

Co-products and yield

No co-products were allocated emissions as part of this assessment. For primary production, the sole product, red coffee cherries, had a yield of 1.6 t/ha.

3.2.4.2 Tea bags

Product description

The product was 1 kg of black leaf tea (BLT), packed into tea bags and a carton (equivalent to a package of 320 tea bags). The tea was grown on plantations in Kenya.

Process description

Tea is grown in tea gardens around Kerichio on the western edge of the Great Rift Valley in Kenya. Tea has been produced from these gardens for many years and bushes are at least 25 years old, with many closer to 75 years old. Replanting was limited to the replacement of dead bushes, rather than the whole-scale removal and replanting of tea gardens. For this reason no emissions were calculated for the establishment of tea gardens but annual emissions were calculated for an established garden.

No pesticides were used in production except for occasional herbicides to clean pathways[34]. Tea bushes were grown in densely packed gardens with narrow walkways for the pickers. There was no access to the garden for tractors or other motorised vehicles so all fertiliser applications, pruning and harvesting were by hand. Once every five years the bushes in a plantation were cut back hard to maintain the cutting table at a height suitable for hand picking[35] . Between these events bushes were given a lighter pruning. Due to the small off take of nutrients in the tea that is harvested fertiliser inputs were low, with just 85 kg/ha of N applied per year.

Tea was picked by hand every 7 – 14 days with yield of tea varying but averaging a yield of 2.4 t per ha per year of fresh leaves. Fresh leaves were carried to the side of the field and then rapidly transported to the factory for processing. As most of the tea is grown locally to the factory much of this transport would be by human labour and/or small truck.

The factory for transformation of green tea leaves into BLT was on the grounds of the tea estate. Tea leaves were harvested and transported a short distance to the factory, where they underwent processes of withering, cut-tear-cut (CTC) rolling (a bruising process whereby two rollers crush the tea leaves to start the oxidation process), fermentation, drying and sorting before being packed into bulk aluminium lined paper sacks. Approximately 3.9 kg of green tea leaves were necessary to produce 1 kg of BLT. The tea estate received electricity partly from the Kenyan national grid. The electricity emission factor for Kenya was low, as a high percentage of Kenyan electricity was provided by hydropower stations. The tea estate also obtained part of its power from its own on-site hydropower station. In the case of a power cut, fuel oil was used for standby power generation. Heat for drying tea was provided by burning eucalyptus wood, which was grown on part of the estate.

Bulk packed BLT was transported by lorry to the port in Mombasa, from where it was shipped to the UK and then transported by road to the tea packing factory where secondary packaging took place. At this point bulk sacks were opened, with all sacks recycled, and the loose tea packed into tea bags and cartons then into secondary packaging (boxes) and placed on pallets. From this factory, the packed tea was transported to a distribution centre where it is then distributed to retail outlets. A flow diagram of the life cycle steps of raw materials production and manufacturing is shown in Figure 1.

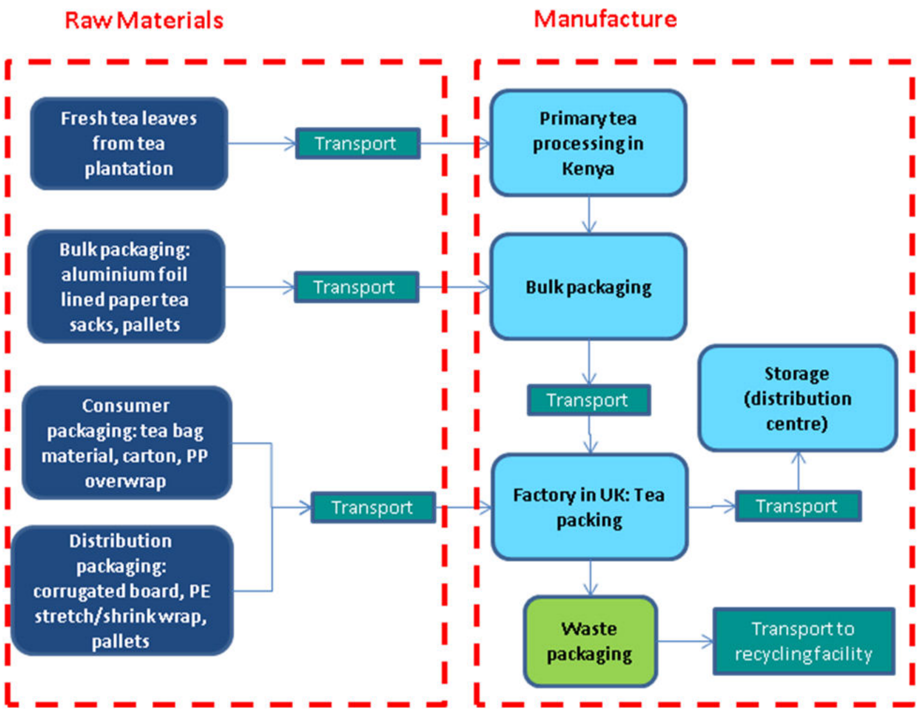

Figure 1 Flow diagram showing production of black leaf tea.

Greenhouse gas emissions

Emissions of GHGs during crop production (of green leaf tea) are shown in Table 86. The largest contributors are non-CO_2 emissions from agriculture (60%) and production of raw materials (38%).

Table 86 GHG emissions (kg CO_2e) for 1 tonne of green tea leaves.

Category	GHG emissions of green tea leaves (kg CO2e)
Raw Materials	330
Processes	
Energy	<0.1
Waste	<0.1
Soil emissions	520
(Processes total)	**(520)**
Transport	21
Total	**870**

The total carbon footprint of the manufacturing stage was 0.5 kg CO_2e per kg of packed (in tea bags and a carton) BLT delivered to the retail distribution centre. The life cycle steps of primary tea processing in Kenya (31%), transport from Kenya to the UK (31%) and tea packing in the UK (34%) contributed about equally to the carbon footprint of manufacturing packed black leaf tea. The transport of the packed tea to the retail distribution centre had a smaller impact (4%), and the impact of disposal of the bulk packaging was negligible (Figure 2).

With a carbon footprint of 0.87 kg CO_2e per kg of green tea leaves delivered to the factory, the overall carbon footprint of raw material production/agriculture and manufacturing of 1 kg black leaf tea was 4.1 kg CO_2e. This takes into account emissions from the production of packaging materials, which are additional to the manufacturing emissions given above and presented in Figure 2.

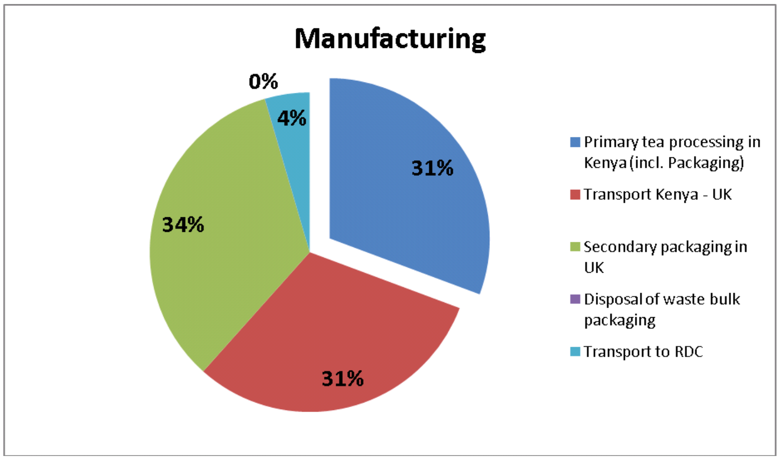

Figure 2 Contribution of the different manufacturing steps to the GHG emissions of manufacturing.

Raw materials

Nitrogen fertiliser was the major contributor to the GHG emissions of raw materials used in production of green leaf tea (Table 87).

Table 87 GHG emissions of raw materials used in production of green tea leaves (kg CO2e/tonne).

Category	GHG emissions of raw materials used in production (kg CO_2e/tonne of green tea leaves)
N	260
P_2O_5	8.7
K_2O	13
S	46
(Total nutrients)	**(330)**
Pesticides	1.9
Total	**330**

As shown in Figure 3, raw material production and agriculture contributed 88% of the total carbon footprint of the packaged product.

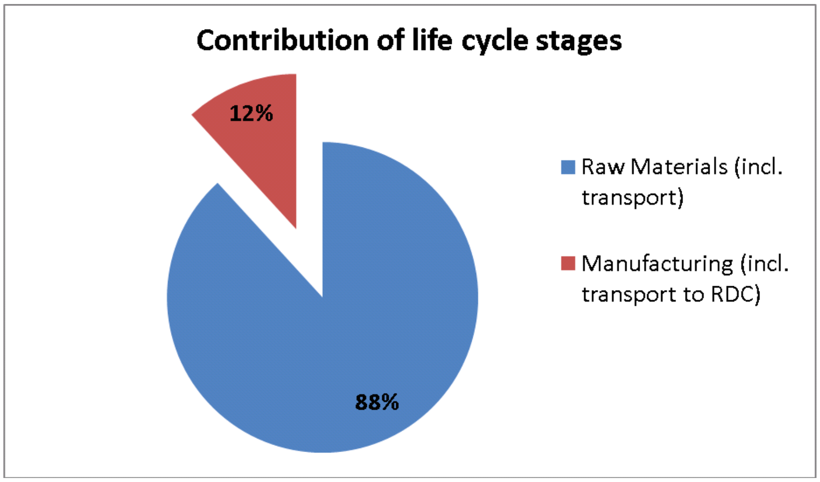

Figure 3 Impact of the GHG emissions of manufacturing.

Green leaf tea, as a raw material for the packaged product, has the biggest impact of all raw materials (see Figure 4).

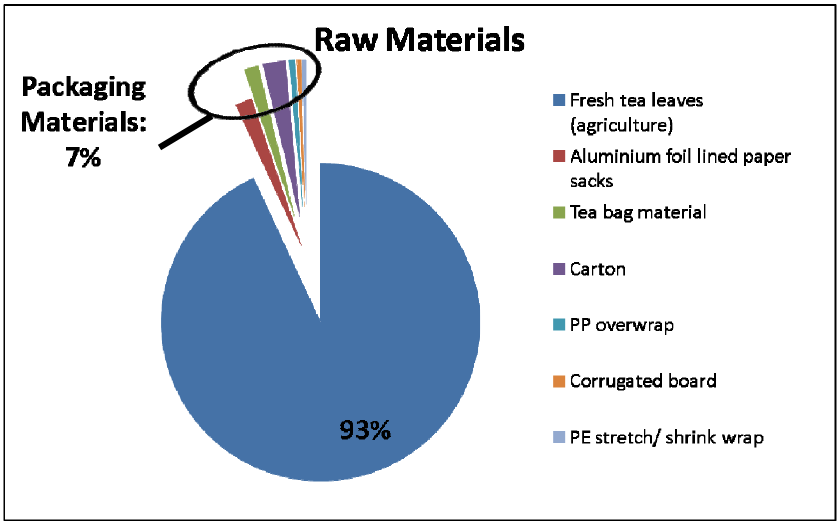

Figure 4 Contribution of the different raw materials to the GHG emissions of packaged black leaf tea.

Processes

Soil emissions of GHGs dominate emissions from the processes during green leaf tea production, whereas energy and waste make small contributions (Table 88).

Table 88 GHG emissions (kg CO_2e) from processes for production of 1 tonne green tea leaves.

Category	GHG emissions (kg CO_2e/FU)
Total energy (electricity and diesel)	**<1**
Plastics (land-filled)	<1
Other waste disposal	<1
(Total waste)	**(<1)**
N_2O emissions from N application	230
Emissions from residue incorporation (inc out grades)	290
(Total soil emissions)	**(520)**
Total for processes	**520**

The values calculated for the manufacturing of black leaf tea were specific to the case assessed. The use of hydropower and especially the use of eucalyptus wood as sources of energy lead to an extremely low impact of the manufacturing operations at the tea estate in Kenya. For comparison, the carbon footprint of manufacturing BLT was also calculated for the case of receiving all energy used on the estate from the Kenyan electricity grid. In that case, the GHG emissions associated with the manufacturing of black leaf tea would rise from 0.5 kg CO_2e per kg of BLT to 2.5 kg of CO_2e per kg of BLT.

Co-products and yield

No co-products were allocated emissions as part of this assessment. For primary production, the sole product, green leaf tea, had a yield of 2.35 t/ha.

Acknowledgements

Philip McKeown, Safety & Environmental Assurance Centre, Unilever.

3.2.4.3 Cocoa powder

Product description

The chosen FU was 100 g of cocoa powder in a glass jar. The cocoa was grown in Ghana and for the production stage, the assessment was based on 1 kg of cocoa beans.

Process description

Cocoa was grown in Ghana, the second largest African exporter of cocoa beans after Cote d'Ivoire. The majority of the Cocoa is grown in a belt of rainforest[36] that crosses the country. This covers the main growing regions - Eastern Region, Ashanti Region, Brong Ahafo Region, Central Region, Western Region and the northern half of the Volta Region[37]. Ashanti is the traditional growing region.

The majority of the cocoa that is grown in Ghana is grown on small farms of about 0.8 ha)[37]. There are three main types of land that are used to grow cocoa; in new cocoa growing areas virgin forest is cleared to make way for the plantation, in some areas secondary forest has to be cleared and in the more traditional farming regions old abandoned farmland is likely to be cleared for a new plantation. Once planted the cocoa plantation can be productive for many decades. Recently there has been an increase in the area of cocoa grown in Ghana, with 21% of the cocoa area in 2004 too young to produce fruit[38] and only 55% of the crop was at full production.

For this assessment, we have averaged land use to calculate GHG emissions, and particularly the land use change component. For the production stage, this assessment does not apply to a single, identifiable farm, but have used data typical for Ghanaian production.

Land use change

According to FAO statistics the cocoa area in Ghana has increased from 690,000 ha in 1990 to 1,700,000 ha in 2007, an increase of just over 1M ha. At the same time the total area of crops grown in Ghana increased by 2.4M ha, so the majority of the increase in Cocoa production is likely to have occurred on previously un-cropped land. This assessment used the 2006 IPCC Guidelines for National Greenhouse Gas Inventories to calculate carbon loss associated with land use change. Biomass, soil carbon and dead organic matter were taken into account. A value for mean carbon stock in thinned forest cocoa establishment in Cameroon (J Gockowski, personal communication) was used in this assessment. The land use change value calculated was 20.7 CO_2e per ha of forest converted to cocoa plantation. If 60% of cocoa land has under gone land use change since 1990, this gives an average of 12.4 t CO_2e released per ha of cocoa.

The uncertainty associated with the land use change part of this carbon footprint is large and further research is needed to investigate how representative this land use change value is for conversion of Ghanaian forest to cocoa plantation.

Crop establishment

There are currently three main types of cocoa grown in Ghana[37]:

- Amelonado – which takes 6-8 years to start bearing, produces 30-35 beans per pod and is resistant to many diseases;
- Amazon – which takes 4 yrs to start bearing and produces 35-40 beans per pod and is susceptible to disease;
- Tafo hybrids – which take 2-3 years to start bearing and produce 45-60 beans per pod.

Amelonado and Amazon are old types of cocoa that make up the majority of the old plantations. Growers are being encouraged to replace the Amelonado and Amazon plantations, with Tafo hybrid plantations, once they cease bearing. Seed for the Tafo hybrids is available from seed production units within the Ashanti region. It is most likely that the seed, if used would be collected by foot. Where growers are particularly poor they are likely to use home saved seed from their existing varieties, therefore it is assumed that there is little additional GHG emissions associated with the production of seed.

Recommended practice suggests that cocoa seeds should be started in a seed nursery. A small bed is dug near the homestead and a water source. The cocoa seeds are planted by hand and hand watered until they are large enough to establish in the field. To plant one hectare worth of seed, allowing for wastage, about 125 pods are needed[39], if 28 pods are required to make 1 kg beans[40] this means 4.5 kg beans are required to produce 1 ha of plantation. This phase is all done by hand, without the use of fertilisers or pesticides.

The area that is to become the new plantation must be cleared of all previous vegetation a year prior to planting. If this was forest the trees are removed using a chain saw, except for a few suitable trees that are left to provide shade for the cocoa. The wood might be used by local villagers as firewood or for building. The litter is left to rot and also as a mulch to suppress weeds. Some growers use a treatment of glyphosate at 255 ml/ha to control weeds prior to planting, but the majority of growers clear weeds by hand.

Once the land is cleared plantain suckers and coco yams are established to provide shade for the young cocoa plants. When the seedling cocoa trees have reached a sufficient size they are carried out to the plantation and planted at 3 m by 3 m spacing.

For the majority of cocoa plantations, each year about 2.5% of the plantation is replaced with new trees[41].

Once planted these trees have to be carefully pruned, by hand, to produce healthy productive trees. On average it takes 5 years for a plantation to reach bearing age, and then 10 -15 years before the trees reach full yield potential[42]. When they reach full yield potential Ghanan cocoa plantations can yield around 400 kg/ha cocoa beans. However, due to the number of young plantations, and plantations that are starting to lose their full potential, typical yields are closer to 300 kg/ha (J Gockowski, pers. comm.).

Pesticide use

For the first few years of establishment cocoa seedlings are likely to need hand weeding 3-4 times a year, although this could be replaced with three applications of glyphosate at 255 ml / ha. Once established the crop will require only two hand weeding operations per year or two applications of glyphosate at 170 ml/ha. The majority of growers still use hand weeding to control weeds therefore it has been assumed that no herbicides are used in the production of cocoa.

One of the main diseases that affects cocoa in Ghana is black pod disease. This can be controlled through good husbandry, however there are also chemical methods of control that are available for this disease. The standard recommendation for control is the application of a fungicide up to 9 times a year, once every 3 weeks during the wet season [37], however due to cost it is more likely to be applied less than 6 times per year. It is suggested that metalyxl plus copper oxide is the most commonly applied fungicide (J Gockowski, pers. comm.). This is applied at rates of 1.5 kg/ha twice a year. Fungicides are applied using hand-pumped knapsack sprayers.

Insect pests also affect cocoa. The main pest in Ghana is the capsid. This can be controlled, or the impact minimised, through the use of good husbandry. However, in 2004, 95% of growers were using insecticides[42] Imidacloprid (200 g/L) is applied at 1 L/ha is typically used in the control of insect pests (J Gockowski, pers. comm.). Although the use of mist blowers is recommended for the most efficient control of pests many growers do not have access to this sort of equipment and therefore still rely on a hand Pumped knapsack applicator. In this study it has been assumed that pesticides have been used to control pests and diseases at the rates mentioned above.

Fertiliser use

The Cocoa Research Institute of Ghana recommends that 129 kg/ha of P_2O_5 and 76.5 kg/ha of K_2O are applied annually to cocoa plantations[43]. The optimum rate of nitrogen application is 90 kg/ha[44]. A survey of cocoa growers in Ghana, carried out in 2004, and reported by Vigneri M, shows that on average 256 kg/ha of fertiliser is applied annually to 48% of cocoa crops, indicating that on average farmers are applying 86% of the recommended application rates. However, very little fertiliser is used in cocoa production, with most nutrients recycled through the return of cocoa husks and prunings to the soils (J Gockowski, pers. comm.). In this study it has been assumed that no artificial fertilisers have been used in the production of cocoa.

Pesticide imports

There are no pesticide production facilities in Ghana, therefore all pesticides have to be imported. It was assumed that the source of pesticides is India (Table 89). Once these products have been delivered to Takoradi or Tema ports they have to be transported to Kumasi, the main city in the Ashanti region, by large lorry (220 km), before being distributed to farmers, either by foot or small van (20 km).

Harvest and processing

Once the pods are ripe they are gathered by hand, using a sharp blade to cut them from a tree, then people collect the fallen pods and take them to the edge of the field for processing. The first step in the processing is to split open the pods by hand, using either a stone to smash them or a blade to split them. The cocoa beans are then scooped out by hand and placed in a heap on top of a pile of banana leaves. Once sufficient beans have been removed the heap is covered with more banana leaves and left to ferment for 6-7 days, being turned occasionally by hand. This fermentation process kills the embryo preventing germination, removes the Pulp or mucilage and softens the testa making processing easier. It is important that this process is carried out correctly otherwise the flavour of the chocolate is affected.

For every ha of plantation it is estimated that on average 300 kg of cocoa beans are produced, plus 1100 kg of cocoa husks and 2000 kg of prunings (J Gockowski, pers. comm.). The discarded husks and tree prunings are spread over the floor of the cocoa plantation to return any stored nutrients to the soils.

Once fermentation is complete the beans are transferred into baskets and carried on people's heads back to the homestead to be placed on drying mats. The beans are then dried in the sun, whilst being turned occasionally and having impurities and damaged beans removed by hand.

Export of cocoa

Once the cocoa has been fermented and dried it is packaged up into jute sacks and carried to the local trading centre for sale. Here the cocoa is sold to a Produce Buying Company, part of the Ghana Cocoa Board (Cocobod) or to other licensed buying companies. These companies transport the cocoa on lorries to the processing factories in Takoradi and Tema. Here the cocoa is graded by hand and eye before being packed in containers for export to the UK.

Table 89 Distance imports and exports travel by sea freight

Product	Export port	Import port	Distance (km)*
Pesticides	Mumbai, India	Takoradi and Tema, Ghana	13,500
Cocoa	Tema, Ghana	Southampton, UK	6,700

*Source: http://www.searates.com/reference/portdistance/

Production of cocoa powder in the UK

There are several stages in cocoa powder manufacture and these differ depending on the company. The example used for this GHG assessment was a generic processing system with the FU of 100g of cocoa powder packaged in a glass jar. Information for the study was taken from primary data supplied by Cadbury, and secondary sources such as the internet and textbooks.

Cocoa beans are first cleaned to remove most of the external contamination before undergoing a debacterisation step using steam. The beans are then put through a roasting process in furnaces, which is primarily designed to develop the aroma. Shells are removed in the winnowing process to leave the centre of the bean, known as the nib. Roasted nibs are broken into medium sized pieces in a crushing machine.

The crushed cocoa nibs, which are still fairly coarse, are pre-ground using milling equipment and fed to rollers where they are ground into a fine paste. The heat generated by the resulting pressure and friction causes the cocoa butter (approximately 50% of the bean) in the beans to melt, producing a thick, liquid mixture. This is dark brown in colour with a characteristic strong odour, and cools into cocoa paste. The paste is taken to large presses that extract the cocoa butter, and the remaining cakes are ground to powder. This is cocoa powder that is filled into consumer packages such as the glass jar used as the FU in this study. Table 90 presents the key stages in which GHG emissions are generated.

Table 90 Key stages in which GHG emissions are generated.

No.	Input	Input (g)	Process	Output	Output (g)
1	Raw, dried cocoa bean	100	Cleaning	Cleaned cocoa bean	100
2	Cleaned cocoa bean	100	Debacterisation	Debacterised cocoa beans	100
3	Debacterised cocoa beans	100	Roasting	Roasted cocoa beans	92
4	Roasted cocoa beans	92	Winnowing	Cocoa nibs	81-77.2
				Shells (approx. 12-16%)	11-14.8
5	Cocoa nibs	81-77.2	Grinding	Cocoa liquor	81-77.2
6	Cocoa liquor (e.g. 52% fat content)	81-77.2 (assume 52% fat)	Pressing	Cocoa butter	32.4-30.88
				Cocoa cake (12% fat)	48.6-46.32
7	Cocoa cake	48.6-46.32	Milling	Cocoa powder	48.6-46.32
8	Cocoa powder		Packaging		47

Conversion of cocoa beans to cocoa powder results in 46-49% powder from the beans that arrive in the factory. Therefore for the Purposes of connecting the ADAS and Campden BRI calculations, the GHG emission figures in Table 93 were also calculated as kg CO_2/kg of beans. A factor of 47% conversion was used.

Summary of cocoa powder greenhouse gas emissions (production, export and manufacture)

In Table 91 values are given for total GHG emissions for production and manufacture. The land use change value is shown separately to show the importance of this component.

Table 91 Greenhouse gas emissions for production of cocoa and manufacture of cocoa powder (kg CO_2e)

Component		**Greenhouse gas emissions (kg CO_2e per kg cocoa beans)**
Raw Materials (agriculture)		**0.11**
Processes (agriculture)		
	Energy	<0.01
	Waste	<0.01
	Soil emissions	0.38
(Total processes)		**(0.38)**
Transport		**0.17**
(Total production in Ghana (excluding land use change) and export)		**(0.94)**
Land use change for production in Ghana (see Process description above)		41
Manufacture of cocoa powder in UK		1.1
Total		**43**

Table 92 presents the summarised GHG emissions for the FU and per kg of cocoa beans. The latter enables the ADAS and Campden BRI calculations to be linked.

Table 92 Emissions of GHGs (kg CO_2e) for the functional unit (FU; a 100g jar of cocoa powder) and for production of cocoa powder in a glass jar, expressed per kg of cocoa beans used.

Category	**GHG emissions (kg CO_2e/FU)**	**GHG emissions (kg CO_2e/kg cocoa beans)**	**Comments**
Beans (production and export)	20	42	
Packaging	0.29	0.62	Assumed glass jar holding 100g powder
Manufacture	0.21	0.42	Energy, water
Transportation	0.020	0.042	Cocoa beans transported from Southampton docks to Midlands factory
Total	**21**	**43**	

Packaging

Most emissions associated with packaging are from the glass jar (Table 93).

Table 93 GHG emissions (kg CO_2e) for the FU packaging materials.

Component	Weight (g/FU)	Emission factor (kg CO_2e/kg)	GHG value (kg CO_2e/FU)
Glass jar	265	0.843	0.22
Plastic cap	15.0	2.0	0.030
Paper label	1.1	4.4	0.0048
Plastic shrink wrap	1.67	2.4	0.0041
Cardboard box	17.8	1.5	0.027
Total			**0.29**

Co-products and yields

No co-products were allocated emissions as part of this assessment, cocoa husks were returned to the land and therefore not given a separate emission value. For primary production, the sole product, cocoa beans, had a yield of 0.3 t/ha.

Acknowledgements

The assistance of James Gockowski, of the International Institute of Tropical Agriculture, Sustainable tree Crops Program, is gratefully acknowledged for provision of data for cocoa production in Ghana. We are also grateful to Rob Moss of West Africa Fair Fruit Company, for facilitating a visit to Ghana to research cocoa production.

Cooperation of Cadbury is acknowledged for providing data for estimating UK manufacturing emissions.

3.2.4.4 Granulated sugar (from cane)

Product description

The FU was a 1 kg paper bag of granulated sugar. The sugar was grown on the largest sugar plantation in Zambia, Nakambula Sugar Plantation in the Mazubuka district of southern Zambia. For the production stage, the assessment was based on 1 kg of sugar cane, harvested and delivered to the local factory.

Process description

Transport

Zambia is a land locked country in Southern Africa. In order to import or export products Zambia must transport them through one of its neighbouring countries to a suitable port. Dar es Salaam, 2,019 km from Lusaka, was the port for imports and exports and has a rail link most of the way.

Fertilisers and pesticides

The mineral contents of Zambia's soils mean that Dolomite lime is available from 16 km NW of Kabompo[45] which is about 600 km west of Lusaka. This is likely to be purchased from Lusaka and then transported down to Mazubuka, a distance of 125 km.

All P and K fertilisers are currently imported. According to FAO statistics South Africa is an exporter of P and K exporting just over 45,000 t of each in 2006. As this is a relatively 'local' source of nutrients this was assumed to be the location from which Zambia would import P and K. Fertilisers were assumed to be shipped from Durban to Dar-es-Salaam (3126 km) and then transported by rail to Lusaka and road from Lusaka to Mazubuka.

Saudi Arabia is the largest exporter of nitrogen fertiliser in the area surrounding Zambia therefore this was taken as the source of nitrogen fertilisers. The nitrogen fertiliser was assumed to be shipped from Jeddah to Dar-es-Salaam (4493 km).

There are no facilities for the production of pesticides within Zambia so it is reliant upon exports. India exports 635,000 tonnes of pesticides a year and has been assumed to be the source for pesticides, exporting from the port of Mumbai to Dar es Salaam (2522 km).

Production

Sugarcane is a perennial grass crop that is grown in tropical or subtropical climates. It requires a minimum of 600 mm rainfall per year and warm temperatures in order to grow and produce sugar.

The majority of land that is used in the production of sugar cane has been in production for a number of years, but in areas where expansion is occurring new land is being taken into production. There has been a sugar estate in Nakambula since the 1960s so it was assumed that the majority of the sugar that is currently grown on the estate is grown on land that has been in cultivation for over 20 years.

The sugar cane was planted using cuttings or 'sets', which are sections taken from a sugar cane stem and then placed in a trench and allowed to take root. Before planting, cane sets were drenched in a fungicide drench, in order to protect them from diseases such as cane smut. This drench was applied at a rate of 100 g of active ingredient / 100 L of water, sufficient to treat 1 ha of cane sets. For each ha of crop, approximately 5 t/ha of sets were required (Patrick Jarvis, British Sugar, pers. comm.).

Once the previous crop was removed, stones or large debris were removed by hand, followed by tractor ploughing, discing, harrowing and ridging using standard agricultural machinery. The sets were laid in the furrows by hand.

The crop took about 12 months to reach a harvestable size. Each crop can be harvested 8-10 times before noticeable drops in yield occur[46], at this point the crop is removed and replanted. Typical sugarcane yields for Zambia are 127 t/ha with a 10% sugar content (Patrick Jarvis, British Sugar, pers. comm.).

During the early stages of growth, either immediately after planting or after harvest, it is important that the young cane shoots are kept free of weeds. Weeds were controlled through the application of herbicides using hand-Pumped knapsack applicators, and persistent large weeds were removed by hand. Army worms were treated with insecticide in a similar manner.

Sugar cane requires regular fertilisation with NPK and other trace elements. These were applied immediately after planting, then after the first year of crop establishment, three applications per year were also made. All nutrients were applied to the crop by hand.

Cane crops in Zambia need irrigation in order to supplement natural rainfall. Water was extracted from local rivers and Pumped into a reservoir. From there about 75% of the water was passed through a series of trenches, made by hand, in the cane fields, whilst a further 25% was applied using rotary sprayers, with approximately 1000 m^3 of water applied per ha per year.

Once the cane is ready for harvest the water is withheld to stop active growth and encourage the plants to store sucrose, rather than using it to grow. In the past once the crop had dried out sufficiently the plantation was burnt, removing excess trash and killing or scaring off any poisonous snakes that would otherwise make it dangerous for the cane harvesters. The cane was cut by hand and stacked into mounds. These mounds were picked up using a hydraulic grab that placed them onto large trucks for transport to the factory. This had a work rate of 120 t/hour.

Because the concentration and quality of the sugar present in the stems starts to decrease after harvest it is important that the processing factory is close to the cane fields (ideally the crop should be processed with in 24 hours of cutting). At the Nakambula Sugar Plantation there is a factory at the centre of the cropped land area, and it was assumed that the cane travelled 10 km between field and factory.

Processing

Before shipping away from the growing region, sugar cane is processed to remove impurities and more importantly stabilise the sugar and prevent fermentation. The raw syrup that arrives in the UK would then be refined and crystallised to give the final product[47].

The initial harvesting of the sugar syrup is done in mechanised mills, close to the farm. In this stage, the sugar cane is crushed to release the syrupy juice. The juice is then concentrated to produce a thick liquid. To maximise recovery, the plant residue may be washed several times to remove as much sugar as possible. The remaining plant material, known as bagasse, is then burnt to produce the energy for the rest of the processing plant, and in some cases surplus energy can be sold as electricity.

This energy generation releases the majority of the CO_2 that has been stored in the sugar cane plant during its growth and make the initial processing approximately carbon neutral.

The thick sugar syrup is then transported to the country of use in large tanks.

Once the sugar syrup has arrived in the UK it can be refined into granulated white sugar. This process removes impurities, and produces regular-sized crystals.

Lime can be added to assist the precipitation of impurities and activated carbon can be used to absorb colours.

Greenhouse gas emissions

The largest component of the emissions of GHGs from production of sugar cane was soil emissions (46%; Table 94).

Table 94 Emissions of GHGs (kg CO_2e) for 1 tonne unprocessed sugar cane.

Category	GHG emissions (kg CO_2e/tonne)
Raw Materials	**13**
Processes	
Energy	8.4
waste	<1
Soil emissions	23
(Total processes)	**(32)**
(Transport)	**(6.6)**
Total	**50**

There are currently two produces of granulated sugar in the UK, British sugar and Tate and Lyle. Both companies were approached as part of this project, in order to obtain data on energy and resource use in refining and processing. In the timescale of this project no data was forthcoming, however both companies have published details of the carbon footprint of their products. Tate and Lyle claim that the carbon footprint of their 1 kg bag of granulated sugar from sugar cane is 0.43 kg CO_2e[48], however it is not clear whether they have followed the methods set out in PAS 2050.

British Sugar claim to have followed the PAS 2050 method and have arrived at a value of 0.5 kg CO_2e[49] for a 1 kg bag of sugar from sugar beet

No data was available for the individual stages in this further processing however some data was obtained from British sugar for the production of sugar from sugar beet.

The overall value Published was 0.5 kg per kg granulated sugar. In the Published information, this was broken down into percentages for the processing stages. This enabled the stage breakdown to be calculated in terms of kg CO_2e (Table 95).

Table 95 Emissions of GHGs (kg CO_2e) from British Sugar, for granulated sugar produced from sugar beet.

Processing stage	Percentage	kg CO_2e
Farming	48.7	0.24
Transport	7.2	0.04
Sugar processing	27.4	0.14
Packaging	7.9	0.04
Distribution and disposal	8.8	0.04

In the absence of other data for processing, these figures were used as a basis for the study for the production of cane sugar.

The farming figures and transport figures were combined with the data for processing from British Sugar to give the following overall values.

Table 96 Greenhouse gas emissions for processing of granulated sugar from sugar cane (kg CO_2e per kg processed sugar rounded to 2 significant figures)

Processing stage	**kg CO_2e/ per kg sugar**
Farming	0.50
Transport	0.15
Sugar processing	0.14
Packaging	0.04
Total	0.87

The figure used in Table 96 for the emissions from farming has been increased by a factor of 10 due to the yield of sugar syrup from the cane. It takes in excess of 10 kg of raw cane to produce 1 kg of finished sugar.

The overall carbon footprint generated in this study of 0.87 kg CO_2e per FU (1kg sugar) is similar to the figures Published by both UK sugar producers' products. However, it must be noted that the figures were calculated independently and the assumptions used in the calculations may be very different.

Raw materials

Fertilisers were the main raw materials in terms of GHG emissions (Table 97).

Table 97 Emissions of GHGs (kg CO_2e) from raw materials used to produce 1 tonne unprocessed sugar cane.

Category	GHG emissions (kg CO_2e/tonne)
Urea*	5.7
P_2O_5	0.29
K_2O	3.1
S	0.46
Lime	1.4
Other Nutrients	0.25
Total Nutrients	**(12)**
Pesticides	0.64
Seed – cane cuttings	0.47
Total	**13**

* emission factor available[50]

Processes

The largest component of the emissions of GHGs from processes used in the production of sugar cane was soil emissions (72%; Table 98).

Table 98 Emissions of GHGs (kg CO_2e) from processes used to produce 1 tonne unprocessed sugar cane.

Category	GHG emissions (kg CO_2e/tonne)
Total energy (diesel)	**8.4**
Total waste	**<1**
Emissions from urea application	12
Emissions from liming	4.4
Emissions from residue burning	8.2
(Total soil emissions)	**(23)**
Total for processes	**32**

The packaging for cane sugar is identical to beet sugar so the same figures were used (Table 96).

The waste generated by the refining of sugar from sugar cane is different from the waste from sugar beet, as a greater proportion is saleable as molasses. In the absence of data for the disposal this was omitted from the calculations.

Transport from Zambia to UK

The transport element (Table 99) was worked out from the distances travelled by the unrefined sugar, to Dar-es- Salam[51] (assumed to have emissions the same UK rail transport), then travel by sea from Dar-es- Salam to Felixstowe, direct with no intermediate stops, total distance 11700 km.

The unrefined sugar was assumed to be 100% sugar as there was no data on the true composition. It would be in the interest of the manufacturer to approach this percentage to minimise transport costs so this should be a reasonable assumption.

The processing plant in the UK was chosen to be British Sugar's plant at Cantley Norfolk, as it has been stated that they plan to refine cane sugar from overseas.

Table 99 Greenhouse gas emissions for transport of unrefined sugar from Tanzania to processing plant (kg CO_2e rounded to 2 significant figures).

Transport stage	Transport type	Distance[52] (km)	kg CO_2e/kg
Mazubuka- Lusaka	Rail	125	0.004
Lusaka-Dar-es-Salam	Rail	2019	0.061
Dar-es-Salam- Felixstowe	Ship	11700	0.082
Felixstowe to Cantley	Road	113	0.003
Total			**0.15**

Co-products and yield

No co-products were allocated emissions as part of this assessment. For primary production, the sole product, unprocessed sugar cane, had a yield of 108 t/ha.

Acknowledgements

Patrick Jarvis, British Sugar – Sugar cane production in Zambia.

3.2.4.5 Fresh pineapple

Product description

The product was whole, fresh pineapple, variety MD2, conventionally produced in Ghana and transported to the UK by sea. The FU was one whole pineapple with a weight of 1.35 kg.

Process description

Identification of the farm, location, and many details of crop husbandry and transport distances are withheld to preserve confidentiality as requested by the company that has provided the information.

The pineapple crop was grown on a large farm in southern Ghana. The production cycle comprised 14 months from planting of suckers to harvest, a further eight months until harvest of the suckers for planting another crop, and then a fallow period of six months. Tractors and other large machines were used to clear the land and form beds before planting. Planting and harvest was by hand. The crop was not irrigated. Fruits were graded nearby and export quality fruits were packed into boxes and onto pallets, cooled to 7°C, transported to the port of Tema in a shipping container, shipped to Southampton by boat, with containers maintained at 7°C, then transported by road to a supermarket distribution centre.

The calculations of greenhouse gas emissions included raw materials for crop production (e.g. fertilisers, polythene, crop protection chemicals), emissions from soil, fuel use on farm, fuel to generate electricity at the pack house, packing materials (including boxes[53], corner boards and pallets, and treatment of pallets to eradicate timber pests), all transport steps, and refrigerant leakage.

Fruits that were below export quality were sold locally and were treated as a co-product with export fruit, using economic value to allocate emissions between these two co-products.

Greenhouse gas emissions

Total GHG emissions were 1.8 kg CO_2e per pineapple (Table 100). Refrigeration and emissions from soil were the largest contributors (66%).

Table 100 GHG emissions (kg CO_2e) for one whole, fresh pineapple (1.35 kg) at UK supermarket distribution centre.

Category	GHG emissions (kg CO_2e/pineapple)
Raw Materials	**0.24**
Processes	
Energy (exc. refrigeration)	0.081
waste	<0.001
soil emissions	0.18
Refrigeration (energy & leakage)	0.86
(Processes total)	**(1.2)**
Transport	**0.38**
Total	**1.8**

Raw materials

Emissions from nitrogen fertilisers (manufacture and delivery) were the largest component of the raw materials GHG emissions (Table 101).

Table 101 GHG emissions (kg CO_2e per 1.35 kg pineapple) from raw materials used in pineapple production.

Category	GHG emissions (kg CO_2e/pineapple)
N	0.024
Urea	0.064
P_2O_5	0.007
K_2O	0.029
Other nutrients	0.007
(Total Nutrients)	**(0.15)**
Pesticides	0.012
Packaging	0.077
Total	**0.24**

Processes

Refrigeration and soil emissions dominated emissions associated with processes used in pineapple production (Table 102).

Table 102 GHG emissions (kg CO_2e per 1.35 kg pineapple) associated with processes used in pineapple production.

Category	GHG emissions (kg CO_2e/pineapple)
Electricity	0.035
Diesel	0.047
(Total energy)	**(0.081)**
Plastics (land-filled)	<0.001
Other waste disposal	<0.001
(Total waste)	**(<0.001)**
N_2O emissions from N application	0.021
Emissions from residue incorporation	0.019
CO_2 emissions from urea application	0.14
(Total soil emissions)	**(0.18)**
Refrigeration	0.86
Total for processes	**1.2**

Co-products and yields

Fruits were graded and some were used for export and others that were too small, or out-graded for other reasons, were sold locally. The non-export fruit were treated as a co-product (Table 103).

At the end of each cycle suckers were harvested from the pineapple plants, with sufficient to replant a similar area for the next cropping cycle. No emissions have been allocated to sucker production as they do not leave the boundary of the production process.

Table 103 Pineapple yields (functional unit (FU) per ha) and co-products.

Crop	Yield / ha	FU	% allocation of CO_2e emissions	kg CO_2e / FU
Export pineapples	43,000	pineapples	95	2.0
Out-grade pineapples (local consumption)	28,000	pineapples	5	0.17
Suckers	71,000	suckers	Returned to beginning of cycle to replant	Not applicable

Acknowledgements

We are grateful to the following for helping with this assessment.

- Farm data were provided by a pineapple producer in Ghana, but the identity of this business is confidential.
- Rob Moss (West Africa Fair Fruit Company, Accra, Ghana) provided some details of pineapple crop production processes and organised visits to pineapple producers in Ghana.
- Alain SOLER (CIRAD –PRAM, Martinique) provided information on pineapple crop residues.

3.2.5 Manufactured foods

3.2.5.1 Beef cottage pie

Product description

The scope of the study was to estimate the embodied greenhouse gas emissions of one FU of beef cottage pie, sold as a chilled ready meal. The composition of a FU is shown in Table 104.

Table 104 Beef cottage pie functional unit composition by mass.

Type	Units	Value
Cottage pie mix	g	400.0
Aluminium tray	g	27.2
Carton box	g	7.7
Total	**g**	**434.9**

Process description

The beef cottage pie is manufactured in a factory that produces more than 150 different products. The differences in the characteristics and processing steps required for different products are significant. Some products require cooking operations while some do not; some products are frozen while some are chilled. However, the factory monitors energy use only at a facility level and differentiation of energy use by production lines or at a product level cannot be done at present. This imposes a limitation on the calculation of product specific GHG emissions from processing operations.

The product recipe contains higher proportion of potato and lesser proportion of beef and fat than a normal recipe because it belongs to a line of healthy products. The main ingredients are potato, water, beef and skimmed milk. All these main ingredients are of UK origin. The country of origin of the rest of the products is known to some extent (raw material specifications provide this information) but it is highly complicated to determine the exact route followed by each raw material, as each is sourced from more than one country depending on the season and market circumstances. This imposes a limitation in the assessment of product specific GHG emissions from transport operations.

The main stages in the production process are potatoes preparation (including washing, peeling and mashing), vegetables preparation, mash preparation, fill cooking, pie assembly and packing. Food waste generated in the factory is classified as category 3 food waste and is sent to land injection/composting with a previous heat treatment stage. Packaging waste is recycled although a minor part is sent to landfill

Greenhouse gas emissions

For beef cottage pie, Table 105 shows a breakdown of the estimated embodied GHG emissions of one FU. These results are estimates and the assumptions made through the calculation process might have had a significant impact on the values obtained. In particular, estimated emissions for waste and transport might not represent the total impact of these activities. Emissions were calculated for the main raw materials, which were beef, water, potato, milk, buttermilk powder and vegetables (97% in mass of total raw materials). The emission values were then scaled up to account for the rest of materials.

Table 105 Breakdown of GHG emissions per functional unit (FU; see Table 104).

Category	kg CO_2e/FU	Data values and sources
Raw Materials	2.4	Data worked out for major raw materials that make up 97% of product. Figure then scaled up to account for minor raw materials
Packaging	0.38	Product was packaged in an Aluminium tray and then Put into cardboard sleeve. Aluminium 9.8kgCO_2e/kg[54] Cardboard[55] 1.03 kg CO_2e/kg
Transport	0.018	Estimations made of the distances travelled in delivering raw materials for the number of journeys and type of lorry. DEFRA figures for emissions factors[56]
Processing	0.417	Emissions calculated for site energy use and then allocated to the product throughput. No differentiation between products. DEFRA figures for emissions factors for electricity and gas use.
Waste	0.0032	Only emissions from waste water included as no data available for proportion of food waste.
Resources	0.0024	Emissions from service water, no data available for other resources used
Total	**3.3**	

Raw materials

Raw materials GHG emissions were calculated for the main ingredients beef, water[57], potato, milk, buttermilk powder and vegetables (97% in mass of total raw materials) and then scaled up to account for the rest of materials. Emissions from onion, leeks and celery were assumed to be the same as for carrots[58]. All vegetables were assumed to be imported from Spain. Buttermilk powder was assumed as having the same emissions as whey powder, and emissions for whey powder were calculated from the cheese case study information. To estimate the correspondent GHG emissions of the rest of materials, emissions were scaled by calculating the average emissions from the known materials and adjusting by mass. This was as recommended in PAS 2050 (Draft 1, V.6 October 2007). However, results indicate that this approach might lead to a significant error in the results.

Processes

Emissions were calculated at a factory level basis and divided by the total site production. This did not allow product differentiated results and might imply some error in the results. However, at this stage, no other information was available.

Transport

Emissions from transport were calculated using Defra Guidelines for Company Reporting on Greenhouse Gas Emissions – Annexes 2005[59] (Diesel Freight Road Mileage Conversion Factors) and making the following assumptions:

1. Average distance from point of origin to delivery point was calculated through Google map tool.
2. If more than one country of origin, an average reference point was taken.
3. All transport by road.
4. Type of lorry: rigid.
5. % weight laden 75%.
6. Average load 22 tonne.
7. Only one way trip required to deliver the product.

Acknowledgements

RF Brookes (Rogerstone) - Premier Foods.

3.2.5.2 White loaf of bread

Product description

The scope of this case study was to estimate the embodied GHG emissions of one FU of sliced white bread. The composition of a functional unit is shown in Table 106.

Table 106 White loaf composition by mass.

Type	Units	Value
White bread	g	820
Plastic bag	g	7
Total	**g**	**827**

Process description

The product is manufactured in a bakery that produces a variety of bread products, mostly sandwich type bread. The formulation of the different products varies, but the process steps are the same for all types of bread except that a proportion of bread is frozen and sold as a frozen product. The product of study is a standard white bread and it is sold at ambient temperature. The main ingredient, white wheat flour, is supplied by a nearby mill. Currently the flour composition is 40% Canadian, 40% German and 20% UK. Flour composition varies from year to year depending on the quality of the UK wheat harvested and on wheat price fluctuations. This obviously will have an impact on the embodied GHG emissions of the product. The origin of the rest of ingredients is difficult to trace back. Yeast for example is produced in the UK but the raw materials are sourced from France, Poland and Pakistan. The situation is similar for the rest of raw materials. The main waste streams are food waste and packaging waste. Food waste goes to animal feed while packaging waste is partly recycled and partly sent to landfill.

Greenhouse gas emissions

Total GHG emissions for the white loaf are calculated to be 0.60 kg CO_2e. Data and sources on the GHG emissions for each stage of the process are given in Table 107.

Table 107 Breakdown of GHG emissions.

Type	kg CO_2e/ FU	Comments
Raw materials	0.40	CO_2 emissions scaled up to account for minor raw materials
Packaging	0.032	
Transport	0.0038	Transport of raw materials, packaging and waste
Processing	0.16	Emissions from refrigerant gas leakage not included
Waste[60]	0.0014	Only emissions from waste water to drain
Resources	0.0003	Emissions from service water
Total	**0.60**	

Raw materials

For the purpose of the assessment it was assumed that all wheat was of UK origin. Only wheat flour and water emissions were estimated. To estimate the correspondent to the rest of materials, emissions were scaled by calculating the average emissions from the known materials and adjusting by mass. This was as recommended in PAS 2050. However, results indicate that this approach might lead to significant variation in results.

Processes

Data was only available for the whole of the site consumption of electricity, and gas. As there was no data to estimate the breakdown of energy use, this was allocated to the FU by proportion of the overall factory output.

Transport

Emissions from transport were calculated by using Defra Guidelines for Company Reporting on Greenhouse Gas Emissions – Annexes 2005 (Diesel Freight Road Mileage Conversion Factors) and making the following assumptions.

- Average distance from point of origin to delivery point calculated through Google map tool.
- If more than one country of origin, an average reference point taken
- All transport by road
- Type of lorry: rigid
- % weight laden 75%
- Average load 22 tonne
- Only one way trip required to deliver the product

Acknowledgements

William Jackson Bakery.

3.2.5.3 Packed cheddar cheese

Product description

This report presents the results of the estimated GHG emissions of a cheddar cheese using the first draft of PAS 2050. The assessment is based in one product of The Cheese Company, a 500 g mild cheddar cheese produced at Taw Valley Creamery and packed at Oswestry facilities. The information used in the assessment comprises real data provided by the company (primary data), 'book' values (secondary data) obtained from literature sources and results from ADAS.

Process description

The product is manufactured in a creamery that produces cheese, whey powder and butter. Whey powder and butter are produced from whey, which is a co-product of the cheese process. At the end of the manufacturing process the off cuts of cheese blocks are grated and sold as grated cheese. This constitutes another co-product of the process of study. The creamery facilities are highly automated, the level of control over the processing operations is high and in overall, the facility operates efficiently in terms of energy and resource use. The facility also operates an effluent treatment plant. In the creamery cheese is manufactured and stored until it reaches the required grade of maturation. Then it is transported to a packaging facility where it is cut to the final product size, packed and arranged for distribution. Through the manufacturing process, in addition to the raw materials and product packaging, auxiliary packaging is used to keep and transport the product in appropriate conditions.

Greenhouse gas emissions

A breakdown of the estimated GHG emissions of one FU of mild cheddar cheese is shown in Table 108. Compared with milk production, the other inputs and outputs have a very low impact on the results. Emissions from milk production, milk transport and milk processing at the production facilities were allocated to cheese on a relative economic value basis (80% to cheese, 20% to whey). Of the cheese emissions, 2.9% were allocated to grated cheese, which is a co-product at the end of the cheese manufacturing process.

Table 108 Breakdown of the estimated GHG emissions (CO_2e) of one functional unit (FU) of mild cheddar cheese.

Type	kg CO_2e/FU	Comments
Raw Materials	4.7	Economic allocation (80% milk emissions to cheese)
Packaging	0.075	Transport of raw materials, packaging and waste
Transport	0.042	Transport of raw materials, packaging and waste
Processing	0.24	Emissions from refrigerant gas leakage not included
Waste	0.031	Includes energy from effluent plant
Resources	0.0006	Emissions from water usage
Total	**4.9**	**Economic allocation (2.9% emissions to grated cheese)**

Processing

Emissions were calculated using primary data supplied by the collaborative company. To separate the total facility consumption from the processes included in the boundary, information from sub-meters, equipment location and consumption rates provided by the factory engineering team was used. The quality of energy-related information on site was good, but assumptions were required as sub-metering systems did not allow for a product (or production area) specific calculation. It is believed, however, that the calculated values are a good representation of the real situation.

Transport

Fuel consumption for milk transport from the farms to the factory was known, so GHG emissions for milk transport were calculated from these primary data.

The rest of transport emissions were calculated by using Defra Guidelines for Company Reporting on Greenhouse Gas Emissions – Annexes 2005 (Diesel Freight Road Mileage Conversion Factors) and making the following assumptions:

- Average distance from point of origin to delivery point calculated through Google map tool.
- If more than one country of origin, an average reference point taken
- All transport by road
- Type of lorry: rigid
- % weight laden 75%
- Average load 22 tonne
- Only one way trip required to deliver the product

Acknowledgements

The Cheese Company.

3.2.5.4 Apple juice

Product description

The scope of this case study was to estimate the embodied GHG emissions during manufacture of a 75 cL bottle of Cox's apple juice. The chosen variety of apple is Cox's Orange Pippin, however, the data calculated for manufacture and packaging of apple juice is not specific to this variety. End point was bottle of apple juice ready for despatch from the farm.

Composition of the FU is shown in Table 109. In addition to the primary packaging in Table 1 the apple juice bottles are packaged into cardboard boxes of 12 bottles per box. Each empty box weighs 570 g.

Table 109 Composition of the FU; 75 cL bottle of Cox's apple juice

Component	Value (g)
Apple juice	790
Glass bottle	400
Plastic cap	3
Paper label/adhesive	0.5
Plastic cap wrapping	0.5
Total	**1,200**

Process description

Apples are grown both on the farm and at a nearby farm 12 miles away. Transportation of apples from the trees to the juicing process is by tractor, with the apples packed in large wooden bins. These wooden bins are re-used.

Figure 5 shows an outline flow diagram from the point at which apples are taken into the juicing room, up to when the bottled juice is ready for distribution from the farm. It shows the single raw material input (apples), the various packaging inputs and the two waste streams (pressed pulp and waste water). The juicing operation takes place in a dedicated room, shown with a dotted line.

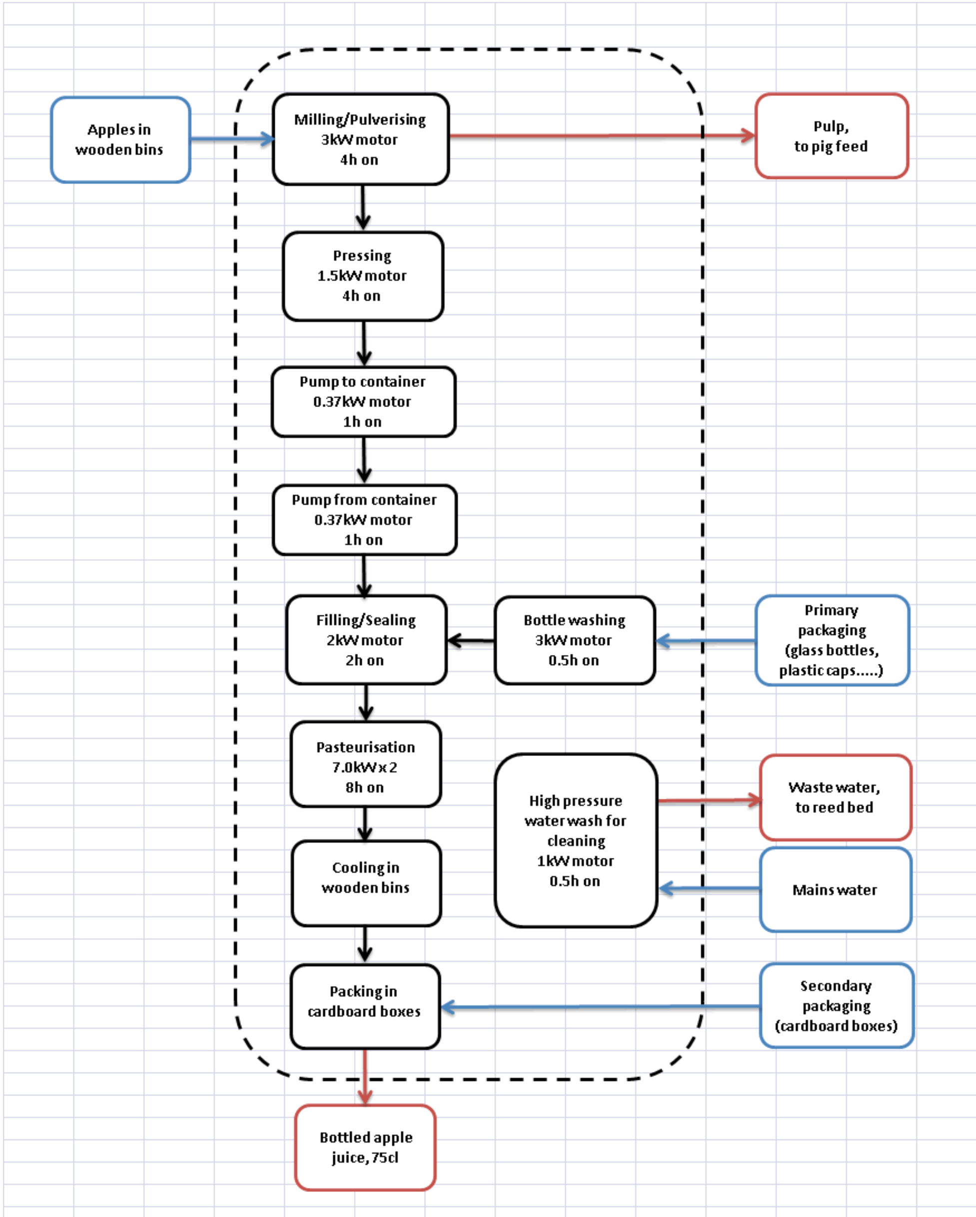

Figure 5 Outline flow diagram for bottled apple juice manufacture.

Greenhouse gas emissions

Total GHG emissions for the 75 cL bottle of Cox's apple juice are calculated to be 0.50 kg CO_2e. Data and sources on the GHG emissions for each stage of the process are given in Table 110.

Table 110 Breakdown of GHG emissions per functional unit (FU; 75 cL bottle of Cox's apple juice).

Category	kg CO_2e/FU	Data values and sources
RAW MATERIALS – INC. TRANSPORT		
Apples	0.082	Cox's Orange Pippin value from ADAS
Glass bottle	0.24	Virgin glass and recycled glass GHG values 0.843 and 0.529 kg CO_2e/kg[61] respectively, with recycle rate for green glass taken as 81%, therefore GHG value for glass is 0.589 kg CO_2e/kg.
Plastic cap (polypropylene)	0.013	4.4 kg CO_2e/kg[62]
Plastic wrapping over the cap (low density polyethylene	0.0012	2.4 kg CO_2e/kg
Paper label/adhesive	0.0005	1.03 kg CO_2e/kg[63]
Secondary packaging – cardboard box 12 bottles	0.049	1.03 kg CO_2e/kg
Transport of above raw materials to processing unit	0.057	Estimations made for distances travelled in delivering raw materials, for the number of journeys and type of lorry.
TOTAL RAW MATERIALS – INC. TRANSPORT	0.44	
PROCESSING		
Two Pasteurisers	0.051	Estimation of motor duration and motor power. Conversion of kWh to kg CO_2e uses Defra (2007) figures for electrical power.
Two pumps	0.0003	As above
Bottle Sealer	0.0018	As above

Category	kg CO_2e/FU	Data values and sources
pulveriser / Mill	0.0054	As above
Press	0.0027	As above
Bottle Washing Machine	0.0007	As above
High Pressure Washer	0.0002	As above
Waste water from cleaning and washing	0	Waste water gravity fed to a reed bed, assumed zero emissions.
Waste apple Pulp from pressing	0	Pulp fed to pigs on farm, assumed zero emissions.
TOTAL PROCESSING	0.061	
TOTAL FOR 75 cL BOTTLE OF APPLE JUICE	0.50	

Raw materials

The variety of apples is Cox's Orange Pippin, although there is likely to be minimal difference between varieties in terms of the GHG emissions during growing or bottling.

This study used a product sold in green bottles, which have the advantage of allowing a higher proportion of recycled glass than for a clear bottle. A recycle rate for green glass was taken as 81%, therefore the GHG value for glass was 0.589 kg CO_2e/kg.

The plastic cap is polypropylene, which has a GHG value from the Plastics Europe web-site of 4.4 kg CO_2e/kg. Minor components of the packaging were also considered; these were the paper label and adhesive (GHG value assumed for cardboard), and the plastic wrapping over the cap (assumed to be low density polyethylene).

Bottles are packed into cardboard boxes in units of twelve. A GHG value of 1.03 kg CO_2e/kg for cardboard was taken from the FEFCO LCA inventory. Each box weighed 570g and so the pro-rata weight for a one bottle FU was 47.5 g, therefore the GHG value was 0.0489 kg CO_2e/FU.

Processes

Estimations were made for the duration of each stage that involved an electric motor, which was required because operation of these stages was intermittent. Total electrical energy required to process 1,200 bottles of juice is 136.74 kWh or 0.114 kWh per FU (bottle). Conversion of electrical energy to kg CO_2e used the emission factor from Defra (2007), which resulted in the juice bottling process contributing 0.061 kg CO_2e/FU. Most of this was from the pasteurisers.

Two categories of waste were generated; waste water from cleaning and washing operations, and apple pulp from milling and pressing.

Waste water is gravity fed to a reed bed, which removes much of the organic matter, and fixes the carbon and nitrogen within the plant material. It is arguable that within the 100 year life cycle suggested by PAS 2050, all of the organic carbon and nitrogen will end up as gases, and in doing so contribute to GHG emissions. This is not considered during this study because no data is available on the quantities of organic materials in the waste water. No caustic or detergents are used for the cleaning operation.

Apple pulp is fed to the pigs that live on the farm. This is a carbon zero activity.

Transport

Estimations were made for the distances travelled in delivering the raw materials to the farm, and for the number of journeys made. Greenhouse gas emissions for these deliveries are shown in Table 111.

Table 111 Greenhouse gas emissions (kg CO_2e) for transportation of the raw materials used for 75 cL bottles of apple juice.

Component	**GHG value (kg CO_2e/bottle)**
Wooden bins of apples	0.0092
Glass bottles	0.0243
Plastic caps	0.0122
Cardboard boxes	0.0110
Total	**0.0566**

Acknowledgements

Jane Clive of Clive's Fruit Farm in Upton upon Severn.

3.2.6 Complex food products

3.2.6.1 Jaffa cake

Product description

The scope of the study was to estimate the embodied GHG emissions of one FU of a single packet (165 g including the packaging) of McVitie's jaffa cakes. The composition of a FU is shown in Table 112.

Table 112 Pack of jaffa cakes composition by mass.

Component	Mass per FU (g)
Jaffa cakes	145
Cardboard box	20
Metallised plastic sleeve	1.2
Total	**164.5**

Process description

The information used in the assessment comprised data provided by the company (primary data), 'book' values (secondary data) from literature sources and results from ADAS. In some cases, assumptions were used to complete missing information.

Jaffa cakes are manufactured in one part of the McVites factory in Manchester. In this area, standard jaffa cakes are produced on one production line, alongside a second line that produces smaller quantities of similar products e.g. Mini jaffa cakes and flavoured jaffa cakes. Data were available for the electricity and water use for this area of the factory. As all of the products produced in the area were similar, data were scaled in the ratio of the product output. Data for gas use were available for the jaffa cake oven.

All of the ingredients have more than one supplier with many different countries of origin. It was not possible to estimate the proportion of time that the ingredients were sourced from each area so values were chosen that represented the 'worst case' value. It is highly complicated to determine the exact transportation route followed by each raw material, as each is sourced from more than one country depending on the season and market circumstances. This imposes a limitation and the need for assumptions in the assessment of product specific GHG emissions from transport operations.

Due to the quantities involved, most of the ingredients were transported in bulk containers that are washed and re- used.

The main stages in the production process were:

1. Mixing of the cake batter
2. Depositing batter onto oven belt
3. Baking of cake base
4. Inversion of the baked base
5. Cooling
6. Depositing of acidified jam (mixed with pectin)
7. Chocolate coating
8. Cooling
9. Sorting
10. Packaging

The system boundary defines which processes in the supply chain were included in the estimation of the GHG emissions and which processes were excluded.

The system boundary for this case study was defined following PAS 2050 specification. The processes included in the system boundary were: the manufacturing of raw and packaging materials, the processing stages at the factory, all transport operations of materials and waste streams and waste disposal operations.

Greenhouse gas emissions

For jaffa cakes, Table 113 shows a breakdown of the estimated embodied GHG emissions of one FU. These results are estimates and the assumptions made through the calculation process could impact on the values obtained. Assumptions are considered later in this assessment. For example, estimated emissions for waste and transport may not represent the total impact of these activities.

Table 113 Breakdown of the estimated GHG emissions (CO_2e) of one 165g functional unit (FU) packet of jaffa cakes.

Category	**GHG emissions (kg CO_2e/FU)**	**Comments**
Raw materials	0.24	
Packaging	0.024	
Transport	0.0018	Where ingredients sources not specified, estimates used. for transport route and transport method
Processing	0.15	Energy used in the factory
Waste disposal	0.0018	Waste product and waste water disposal
Total	**0.42**	

Raw materials

Emissions were calculated for the all of the raw materials

Table 114 GHG emissions attributed to the raw materials, giving a total of 0.24 kg CO_2e/FU. FU = functional unit.

Ingredient	GHG emissions (kg CO_2e/kg)	mass per FU (kg)	CO_2e per FU (kg)
Glucose - Fructose syrup	2.0	0.022	0.04
Sugars solution	0.43	0.022	0.01
Concentrated Orange juice	1.40	0.011	0.02
Eggs per 20 or 1 kg	1.70	0.019	0.03
Water, UK mains	0.000	0.001	0.00
Glucose syrup	2.0	0.002	0.00
Glycerine	2.0	0.001	0.00
Sunflower seed oil	1.00	0.001	0.00
Baking powder	0.69	0.000	0.00
Ammonium Bicarbonate	0.69	0.002	0.00
Powdered whole egg	5.50	0.00	0.00
Dextrose	0.43	0.005	0.00

Ingredient	GHG emissions (kg CO_2e/kg)	mass per FU (kg)	CO_2e per FU (kg)
Milled flour	0.69	0.027	0.02
Sugar	0.43	0.019	0.01
Chocolate	3.40	0.029	0.10
Total, scaled up to 100%			**0.24**

The same GHG emission values were used for sugar, dextrose, glucose and glucose/fructose syrup.

GHG emission value of concentrated orange juice was derived from data for fresh orange juice.

The GHG value for dried egg was scaled up from the dry matter basis of whole egg.

The GHG value for chocolate was taken from publicly available data for milk chocolate.

The GHG value for sunflower oil was taken from the LCD database[64].

Values for minor dry ingredients (e.g. citric acid and baking powder) were estimated to be similar to refined flour.

Packaging

Table 115 presents the breakdown of GHG emissions attributed to the packaging, including both primary and secondary packaging. Total attributed to packaging was 0.024 kg CO_2/FU.

Table 115 GHG emissions attributed to the packaging, including both primary and secondary packaging, giving a total of 0.024 kg CO_2/FU.

Component	GHG emissions (kg CO_2e/kg)	mass per FU (kg)	CO_2e per FU (kg)
Cardboard	1.0	0.02	0.021
LDPE film	2.4	0.0015	0.0036
		Total	**0.024**

Transport

This category cannot be calculated with precision because of the high number of lorry and ship journeys made each year However, each raw material was considered and an estimate made for the number of miles between the specified source and the factory, Total GHG emissions for the transport by road were 0.0018kg CO_2/FU.

Emissions from transport were calculated using Defra Guidelines for Company Reporting on Greenhouse Gas Emissions – Annexes 2008 (Diesel Freight Road Mileage Conversion Factors) and making the following assumptions:

- Average distance from point of origin to delivery point was calculated through Viamichelin. The sea distances were calculated through World Port distances homepage. The speed of the ship was assumed to be 20 knots and time required for shipping was calculated according to this.
- All transport in Europe by road.
- Type of lorry: large rigid, single drop.
- If there was more than one supplier / country of origin of an ingredient, it was assumed that their contribution to the FU was evenly distributed. (e.g. three suppliers, with three different countries of origin, the contributions to the FU were 1/9 from each source).

Processing

Emissions from processing considered the energy used from electricity and gas, together with the water used for factory cleaning (Table 116).

Table 116 GHG emissions attributed to the processing, giving a total of 0.14 kg CO_2/FU.

Component	GHG emissions (kg CO_2e/unit)	kWh or kg per FU	CO_2e per FU (kg)
Electricity	0.43	0.08 kW h	0.03
Gas	0.19	0.62 kW h	0.11
Water	0.00093	0.61 kg	0.00057
Total			**0.14**

Electrical energy and water usage data was available for the jaffa cake production area, an area that comprised of 2 production lines, designated jaffa 17 and jaffa 18. Jaffa 17 was the main jaffa cake production line that was operated on a continuous basis. Jaffa 18 was a smaller line that could be used to make standard jaffa cakes if needed but was normally used to make jaffa cake variations e.g. mini jaffa cakes or flavoured cakes. The annual production figures from both production lines were available and so the energy and water usage figures were divided between the two lines in the proportion of annual production. Figures were available for the gas consumption of the jaffa 17 oven and these were divided by the annual production of the oven.

Emissions from refrigerant leakage were not assessed.

Waste

Figures were provided for annual water input to the factory and water that was included in the product. The remaining water was assumed to be sent to drain. These figures were converted to GHG emissions per FU using the same approach as described in section 7.4.

A figure of 10% for product waste was supplied. Waste has an impact on all of the categories of raw materials, packaging, transportation and processing, in effect by increasing the GHG emissions by 10%[65]. Table 117 presents the GHG emissions for waste categories.

10% waste was estimated for manufacture of this product. Emissions from waste water disposed through the drain was calculated from figures for factory waste water.

Table 117 GHG emissions attributed to waste (FU=functional unit).

Component	**GHG emissions (kg CO_2e/kg)**	**kg per FU**	**GHG emissions (kg CO_2e/FU)**
Water, waste	0.00041	0.61	0.00025
Waste (raw materials, packaging, transportation and processing)	0.12	0.015	0.0018
Total			**0.0021**

Acknowledgements

Dave Brown, United Biscuits, Manchester.

3.2.6.2 Duck in Hoisin Sauce

Product description

The scope of the study was to estimate the embodied GHG emissions of one FU of a shredded duck with pak choi in Hoisin dressing. The composition of a FU is shown in Table 118.

Table 118 FU composition by mass.

Component	**Mass per FU (g)**
Cooked free range egg noodles	140
Hoisin dressing	85
Shredded duck	53
Chinese leaf	23
Pak choi	23
Other	37
(Total food material)	**(360)**
PET tray	21
PET film lid	1.0
Cardboard sleeve	18
Cardboard outer case (apportioned)	31
Paper label (apportioned)	0.25
Total packaging	70
Total	**430**

Process description

The shredded duck product is manufactured in a factory that produces a large number of different products. There are differences in the way the range of products are manufactured. However, in general, components are received, stored, cleaned or washed, assembled by hand and packed. The factory monitors energy and water use only at a factory level and differentiation of use by production lines or at a product level cannot be done at present. This imposes a limitation on the calculation of product specific GHG emissions from processing operations.

Greenhouse gas emissions

For the shredded duck ready meal, Table 119 shows a breakdown of the estimated embodied GHG emissions of one FU. These results are estimates and the assumptions made through the calculation process could impact on the values obtained. The assumptions made for each set of calculations are discussed.

Table 119 Breakdown of the estimated GHG emissions for one functional unit (FU).

Category	GHG emissions (kg CO_2e/FU)	Comments
Raw materials - Food	0.55	Emissions estimated for components accounting for 96.8% by mass of food raw materials. Calculated value was scaled up to 100%. Some components present in very small amounts were disregarded.
Raw materials - Packaging	0.16	Calculation accounted for primary and secondary packaging: PET tray and film, cardboard sleeve, cardboard outer case, and paper label.

Category	GHG emissions ($kg\ CO_2e/FU$)	Comments
Transport - materials in	0.018	Transport of main food components (noodles, hoisin dressing, duck, red chilli and water chestnuts) considered. Precise source data for other main components (pak choi, Chinese leaf) not available but considered local to factory and therefore disregarded.
Transport - product out	0.0087	Uniform distribution to each retail distribution centre considered. Final value is the average emissions resulting from transportation to each centre.
Processing - electricity	0.14	Target product accounts for 0.42% of factory resource use.
Processing - gas	0.000004	
Processing - water use	0.0018	
Waste - effluent treatment	0.0025	Target product accounts for 0.42% of factory waste production.
Waste - disposal to landfill	0.0072	
Total	**0.88**	

Raw materials

Table 120 presents the breakdown of GHG emissions attributed to the primary production of raw materials. Listed here are the emissions for each ingredient as listed on the product packaging. Many ingredients are composed of several base components, therefore emissions calculations are made up of individual emissions of base components. Some base components were present in very small amounts (<1% by mass) and reliable secondary data was not available for these. Where this was the case the components were disregarded. However, emissions attributable to 96.8% of the mass of the food raw materials were accounted for. The calculated value was corrected by scaling it up proportionally to 100%.

The following assumptions were made:

- For all starches and flours, an emissions factor available for milled flour was used[66]
- For pasteurised free range egg, an emissions factor available for eggs was used[67]
- For salt, potassium carbonate, sodium carbonate, citric acid and beta-carotene, an emissions factor available for salt was used[68]
- For all oils, an emissions factor for vegetable oil was used[64]
- For sugar, an emissions factor for granulated white sugar was used[69]
- For garlic and ginger, an emissions factor for potatoes was used. For purees of garlic and ginger, it was considered that an 8-fold concentration of the initial material takes place, and therefore the emissions factor was multiplied by this amount.
- For shredded duck, an emissions factor for poultry meat was used[70]
- For spring onions, pak choi, Chinese leaf and coriander, an emissions factor for onions was used[71]

Table 120 GHG emissions attributed to the raw materials.

Ingredient	Mass per FU (kg)	CO_2e per FU (kg)
Cooked free range egg noodle mix	0.135	0.18
Hoisin dressing	0.085	0.062
Shredded duck	0.053	0.24
Chinese leaf	0.023	0.0033
Pak choi	0.023	0.0033
Spring onion	0.018	0.0026
Other	0.019	0.040
Total - 96.8% of total raw material input		0.53
Total - Scaled up to 100% (divide by 0.968)		**0.55**

The analysis shows that the main contributors to the GHG emissions of the food-based raw materials are shredded duck and noodles, i.e. largely animal-derived raw materials. This correlates well with analysis from other products, where the primary production of these raw materials tends to be relatively intensive in terms of GHG emissions.

Packaging

Table 121 presents the breakdown of GHG emissions attributed to the packaging, including both primary and secondary packaging.

The following assumptions were made:

- For PET-based materials, an emissions factor for PET was used
- For cardboard-based materials, an emissions factor for cardboard was used[72]
- For paper label, an emissions factor for paper was used[73]

Table 121 GHG emissions attributed to the packaging, including both primary and secondary packaging.

Component	**Mass per FU (kg)**	**GHG emissions (kg CO_2e/kg)**	**GHG emissions (kg CO_2e/FU)**
PET tray	0.0206	5.4	0.11
PET film	0.001	5.4	0.0054
Cardboard sleeve	0.0176	0.83	0.015
Cardboard outer case	0.031	0.83	0.026
Paper label	0.00025	2.0	0.0005
Total			**0.16**

Transport

Emissions from the transportation of raw materials was particularly complex. However, the total of GHG emissions for transport was 0.027 kg CO_2e/FU, only 0.03% of the total (Table 119). The ingredients contain a large number of individual components sourced from many different international locations. Without precise knowledge of the logistics of how these components are brought together, a number of assumptions were made in order to make a reasonable estimate of the transport emissions. The aim of these assumptions was to account for the major ingredients in terms of mass and to consider the largest distances that they could possibly be transported:

- Wheat flour for the noodles was assumed to be shipped from the United States (New York - Southampton), then transported by road to the factory. Other noodle components were assumed to be transported by road from the supplier.

- Hoisin sauce was considered to be shipped from Japan (Tokyo - Southampton) and transported by road to the factory. The soy sauce component was considered to be shipped from Hong Kong (Hong Kong - Southampton) and transported by road to the factory.

- Shredded duck was considered to be transported by road from the supplier to the factory.

- Packaging was considered to be transported by road to the factory from each of the named suppliers.

- Suppliers for the remaining major components (spring onion, pak choi and Chinese leaf) were not named. However, it was established that these were produced within a relatively short distance of the factory and transported by road. It was considered therefore that the emissions from their transport could be disregarded in comparison to the other components.

- A list of retailer distribution centres was provided for the final product. It was assumed that with uniform distribution of the product to each of these, an average emissions value for products going to each centre would be a good estimation.

- Emissions factors were taken from Defra guidelines. For shipping emissions, the mode of transport was assumed to be LARGE SHIP RO-RO. For road transportation, the mode of transport was considered to be LARGE LORRY, RIGID.

- Shipping distances were obtained from an online marine transport information resource (www.maritimechain.com). Road distances were obtained from an online route finder for motorists (www.theaa.com).

Processing

Emissions from processing considered the energy used from electricity and gas, together with the water used in the factory (Table 122). A lack of sub-metering within the factory prevents precise data on the specific consumption of these resources through the processing of the target product. However, factory level data for electricity, gas and water consumption was available. In addition, production data for the target product and for the factory as a whole was provided. The target product was calculated to account for 0.42% of the total output of the factory. It was considered, therefore, to apportion the factory resource use data to the target product at this percentage. This allowed processing GHG emissions to be estimated per FU.

Emissions factors for electricity and gas consumption were obtained from Defra Guidelines, and for water consumption from the UK water industry levy organisation, Water UK.

Table 122 GHG emissions attributed to the processing.

Component and units	**Apportioned quantity per FU**	**GHG emissions (kg CO_2e/unit)**	**GHG emissions (kg CO_2e per FU)**
Electricity (kWh)	0.268	0.52	0.14
Gas (therms)	5.91×10^{-7}	6.0	0.000004
Water (kg)	6.080	0.00029	0.002
Total			**0.14**

Waste

Similarly for processing emissions, data on waste and effluent production at a product level was not available. However, factory level data were provided. GHG emissions for waste treatment and disposal are summarised in Table 123.

An emissions factor for effluent treatment was obtained from the UK water industry levy organisation, Water UK[13].

Table 123 GHG emissions attributed to waste.

Component and units	Apportioned quantity per FU	GHG emissions (kg CO_2e/unit)	GHG emissions (kg CO_2e per FU)
Effluent treatment	6.073 L	410	0.0025
Landfill disposal	0.044 kg	0.16	0.0072
Total			**0.0097**

Acknowledgements

David Savage (Bakkavor) and colleagues.

3.2.6.3 Lamb Shanks and roasted potatoes chilled ready meal

Product description

The scope of the study was to estimate the embodied GHG emissions of one FU of lamb shank, sold as a chilled ready meal. The composition of a FU is shown in Table 124.

Table 124 Composition of the FU; 1,300g lamb shank ready meal.

Component	Mass per FU (g)
Lamb shank with sauce	1,150
Aluminium tray	108
Cardboard lid	12
Cardboard sleeve	27
Total	**1,297**

Process description

The lamb shank product is manufactured in a factory that produces a number of different products. Differences in the characteristics and processing steps required for these products are significant. Some products require cooking operations while some do not; some products are frozen while some are chilled. However, the factory monitors energy and water use only at a factory level and differentiation of use by production lines or at a product level cannot be done at present.

The product recipe contains a high proportion of marinated lamb shank (51.69%).

Food waste generated in the factory is classified as category three food waste and is sent to land injection/composting with a previous heat treatment stage. Packaging waste is recycled although a minor part is sent to landfill. One of the direct impacts of product waste is the need to use proportionally more raw materials, with a proportional increase in the GHG emissions.

Greenhouse gas emissions

Total GHG emissions for the lamb shanks chilled ready meal are calculated to be 25 kg CO_2e. Data and sources on the GHG emissions for each stage of the process are given in Table 125.

Table 125 Breakdown of GHG emissions

Category	kg CO_2e/FU	Data values and sources
RAW MATERIALS – INC. TRANSPORT		
Lamb	19	value from ADAS, calculated 24.78 kg CO_2/kg as average UK lowland and NZ lamb
Carrot	0.015	value from ADAS
Parsnip	0.012	Assume as for carrots
Onion, including red onion	0.010	value from ADAS
Vegetable oil	0.031	LCA database, 3.63 kg CO_2/kg
Tomato puree	2.4	9.4 kg CO_2/kg for tomatoes, but 8x concentrated to Puree[70]
Salt	0.007	Assume as for sugar
Sugar	0.005	[69] 0.6 kg CO_2/kg
Cornflour	0.009	Assume wheat flour ex-mill, LCA database, 1.01 kg CO_2/kg
Glucose syrup	0.006	Assume as for sugar
Garlic Puree	0.001	Assume as for onions
Water	0.000	0.289 tonne CO_2e/ML
Aluminium foil tray	1.2	[74]
Cardboard lid, sleeve and case	0.060	
Other raw materials	0.91	-
Transport of above raw materials to processing unit	0.55	[75] Various journeys, including refrigeration losses.
TOTAL RAW MATERIALS – INC. TRANSPORT	24	

Category	kg CO_2e/FU	Data values and sources
PROCESSING		
Electricity	0.47	0.537 kg CO_2/kWh
Gas	0.029	0.206 kg CO_2/kWh
Water, mains	0.004	0.289 tonne CO_2e/ML
Water, waste	0.004	0.406 tonne CO_2e/ML
Waste	0.73	Assumed 3% of raw materials and transport wasted, 0.03 x 23.71 kg CO_2/kg
TOTAL PROCESSING	1.2	
TOTAL FOR LAMB SHANKS	25	

Raw materials

Emissions were calculated for the main raw materials, which were lamb, carrots, parsnip, onion, vegetable oil, tomato puree, salt, sugar, cornflour, glucose syrup, garlic puree and water (97.9% in mass of total raw materials. The following assumptions were made:

- It was assumed that 50% of lamb was from UK and 50% was New Zealand lamb[20]. The UK lamb was assumed to be lowland lamb.
- GHG emissions of carrot and parsnip were assumed to be similar to potato.
- Emissions from different types of onions (onion, red onion, garlic) were assumed to be the same.
- GHG value of corn flour was assumed to be similar to wheat flour (ex-mill).
- 35-40% tomato puree was assumed to be 8 fold concentration of tomatoes.
- The same GHG emission values were used for sugar and glucose syrup.

- GHG emission value of salt was assumed to be similar to that for sugar.

To estimate the correspondent GHG emissions of the rest of materials, emissions were scaled by calculating the average emissions from the known materials and adjusting by mass.

Processes

The main stages in the production process are the lamb shank preparation (including tumbling it with various herbs and spices, and steaming), gravy preparation, parsnip, carrot and onion mix preparation (including mixing with various herbs and spices, steaming and roasting), assembly and packing.

3% waste was estimated for manufacture of this type of chilled ready meal.

Emissions from waste water disposed through the drain were calculated from figures for factory waste water.

Transport

The main ingredients have more than one supplier with many different countries of origin. The country of origin of the rest of the products is known to some extent (raw material specifications provide this information) but it is highly complicated to determine the exact transportation route followed by each raw material, as each is sourced from more than one country depending on the season and market circumstances. This imposes a limitation and the need for assumptions in the assessment of product specific GHG emissions from transport operations. However, each raw material was considered and an estimate made for the number of miles between source and the factory, together with the number of journeys per year. These were then proportioned to the lamb shank product.

Acknowledgements

James Cherry, Greencore, and colleagues at Greencore in Wisbech.

3.2.6.4 Thai chicken chilled pizza

Product description

The scope of the study was to estimate the embodied GHG emissions of one FU of Thai chicken pizza, sold as a chilled product. The composition of a FU is shown in Table 126.

Table 126 Thai Chicken Pizza composition by mass.

Component	Mass per FU (g)
Thai chicken Pizza	346
Polystyrene disk	10
Plastic sleeve	5
Cardboard box	55
Total	416

Process description

The Thai chicken pizza is manufactured in two main stages. The first stage is the baking of the pizza base. This is done in a factory in Ireland and then this is frozen and shipped to the factory in Nottingham. This is then stored and when needed is defrosted and made into the finished pizza. Both of the factories produce a range of other pizza base and pizza products. It was assumed that the water and energy consumed and waste generated in the manufacture of all products would be broadly similar. It was therefore valid to divide that data supplied for energy, water consumption and waste generation by the overall factory output.

Greenhouse gas emissions

For the Thai chicken pizza, Table 127 shows a breakdown of the estimated embodied GHG emissions of one FU. These results are estimates and the assumptions made through the calculation process could impact on the values obtained. Assumptions are considered in Section 9. For example, estimated emissions for waste and transport may not represent the total impact of these activities. Emissions were calculated for the food raw materials, (97.7% in mass of total raw materials). The emission values were then scaled up to account for the rest of materials for which GHG emission data were not available.

Table 127 Breakdown of the estimated GHG emissions (CO_2e) of one 416 g functional unit (FU) of Thai Chicken Pizza.

Category	**GHG emissions (kg CO_2e/FU)**	**Comments**
Raw Materials	0.81	Scaled up to account for minor raw materials
Packaging	0.13	
Transport	0.044	
Processing	0.63	Gas, electricity and water use
Waste	0.0003	Water, and factory waste
Total	1.6	

Raw materials

It was assumed that the emissions factors used for UK produced ingredients would be similar to the true ingredients that were sourced from a variety of countries including China and Thailand.

- Emissions from different types of onions (onion, red onion, garlic) were assumed to be the same.
- GHG value of corn flour was assumed to be similar to wheat flour (ex-mill).
- It was assumed 35-40% tomato puree was eight-fold concentration of tomatoes.

To estimate the correspondent GHG emissions of the rest of materials, emissions were scaled by calculating the average emissions from the known materials and adjusting by mass. This was the approach recommended in PAS 2050.

Table 128 presents the breakdown of GHG emissions attributed to the raw materials, giving a total of 0.81 kg CO_2e/FU. Some ingredients, such as were used for several ingredients, and appear in Table 129 as separate values.

Table 128 GHG emissions attributed to the raw materials (FU=functional unit).

Ingredient	**GHG emissions (kg CO_2e/kg)**	**mass per FU (kg)**	**GHG emissions (kg CO_2e/FU)**
Mozzarella cheese	4.9	0.045	0.22
Milled flour	0.69	0.043	0.029
Water, UK mains	0.0003	0.040	0.000
Chicken breast strips	2.8	0.035	0.10
Coconut milk	1.0	0.027	0.027
pure dried vacuum salt	0.25	0.024	0.006
Starter culture	1.0	0.024	0.024
Vegetable oil	3.6	0.023	0.084
Red pepper	9.4	0.022	0.20
Olive oil	3.6	0.021	0.077
Yeast	1.0000	0.016	0.016
Onion	0.2410	0.010	0.002
Spring onion	0.2300	0.006	0.001
Cornflour	0.6930	0.003	0.002
97.7% of total raw material input			**0.79**
Total, scaled up to 100%			**0.81**

Table 129 presents the breakdown of GHG emissions attributed to the packaging, including both primary and secondary packaging. Total attributed to packaging was 0.128 kg CO_2e/FU.

Table 129 GHG emissions attributed to the packaging, including both primary and secondary packaging (FU=functional unit).

Component	**GHG emissions (kg CO_2e/kg)**	**mass per FU (kg)**	**GHG emissions (kg CO_2e/FU)**
Polystyrene disk	3.4	0.005	0.017
Plastic sleeve	5.4	0.01	0.054
Cardboard outer	1.0	0.055	0.057
Total			**0.13**

Transport

Emissions from transport were calculated using Defra Guidelines for Company Reporting on Greenhouse Gas Emissions – Annexes 2008 (Diesel Freight Road Mileage Conversion Factors) and making the following assumptions:

- Average distance from point of origin to delivery point was calculated through Viamichelin. The sea distances were calculated through World Port distances homepage. The speed of the ship was assumed to be 20 knots and time required for shipping was calculated according to this.
- All transport in Europe by road; transport from far east by ship.
- Type of lorry: large rigid, single drop.
- If there was more than one supplier / country of origin of an ingredient, it assumed that their contribution to the FU was evenly distributed. (e.g. 3 suppliers, with 3 different countries of origin, the contributions to the FU were 1/9 from each source).

This category cannot be calculated because of a number of journeys made in the supply chain. However, each raw material was considered and an estimate made for the number of miles between source and the factory. Total GHG emissions for the transport 0.044 kg CO_2/FU.

Processes

Emissions were calculated at a factory level basis and divided by the total site production. This did not allow product differentiated results and might imply some error in the results. Emissions from refrigerant leakage were not assessed.

Emissions from processing considered the energy used from electricity and gas, together with the water used for factory cleaning (Table 130).

Table 130 GHG emissions attributed to the processing (FU=functional unit).

Component	**GHG emissions (kg CO_2e/kg)**	**kWh or kg per FU**	**GHG emissions (kg CO_2e/FU)**
Electricity	0.537	0.888 kW h	0.48
Gas	0.206	0.722 kW h	0.15
Water	0.000289	0.005 kg	0
Total			**0.63**

Waste

Figures were provided for annual waste water produced. Figures for other waste categories were not available and so an estimated 3% waste was assumed. This percentage was used for a previous GHG study with a similar product. Waste has an impact on raw materials, packaging, transportation and processing, in effect increasing the GHG emissions by 3%. Table 131 presents the GHG emissions for waste categories.

Table 131 GHG emissions attributed to waste (FU=functional unit).

Component	GHG emissions (kg CO_2e/kg)	kWh or kg per FU	GHG emissions (kg CO_2e/FU)
Water, waste	0.00041	0.0054	0.0000022
Waste (raw materials, packaging, transportation and processing)	0.12	0.0024	0.00029
Total			**0.00029**

Acknowledgements

Gus Atri, Northern Foods, and colleagues at Northern Foods, Nottingham.

3.2.7 <u>Major ingredients for complex food products</u>

3.2.7.1 Spring onion

Product description

The FU was 1 tonne of conventional, UK-produced, field-grown spring onions.

Process description

UK conventional spring onions were grown from seed in fields that had previously been ploughed, destoned and bed formed. Fertiliser applications and pesticides were applied as per standard farm practice on our reference farm. Some weed control was provided through precision hoeing. Spring onions were harvested by hand before being transported to a pack house where they were mechanically trimmed and washed (no data was available for washing and trimming). Once washed spring onions were then transported to the distributer.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 132. Raw materials were the greatest component (due predominantly to nitrogen manufacture).

Table 132 GHG emissions (kg CO_2e) per functional unit (FU; 1 t spring onions).

Category		GHG emissions (kg CO_2e/FU)
Raw Materials		**100**
Processes		
	Energy	77
	waste	<1
	Soil emissions	46
	total	**120**
Transport		**9.4**
Total		**230**

Raw materials

Nitrogen was the major contributor to the GHG emissions of raw materials (Table 133).

Table 133 GHG emissions (kg CO_2e) per functional unit (FU; 1 t spring onions) from raw materials

Category	GHG emissions (kg CO_2e/FU)
N	40
P_2O_5	21
K_2O	10
Lime	-
Other	12
(Total Nutrients)	**(84)**
Pesticides	6.5
Packaging	1.4
Seed	8.2
Total	**100**

Processes

Soil emissions (N_2O from N application) were the major contributors to the GHG emissions of processes (Table 134).

Table 134 GHG emissions (kg CO_2e) per functional unit (FU; 1 t spring onions) from processes.

Category	GHG emissions (kg CO_2e/FU)
Total energy (Diesel)	**77**
Total waste (inc plastics)	**<0.001**
N_2O emissions from N application	35
Emissions from residue incorporation (inc out grades)	11
(Total soil emissions)	**(46)**
Total for processes	**120**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yield was 13.2 t/ha.

Acknowledgements

D and M Gedney Ltd, Court Lodge Farm, Southfleet, Kent DA13 9NQ.

3.2.7.2 Carrot

Product description

The FU was 1 tonne of conventional, UK-produced, field-grown carrots.

Process description

This system was based on a crop of processing carrots, half of which were stored in the field under straw to last through the winter until March. Carrots were drilled into soil which had had stubble cultivations, been sub-soiled, destoned, deep ridged and bed-formed. Applications of fertilisers and pesticides occurred as per standard practice on the reference farm. Weed control was provided through a combination of precision hoeing and herbicides. Carrots were irrigated 4 times per season. Half of the carrots were assumed to be harvested directly in the autumn, whilst the other half were covered with straw and black plastic to protect them from the frost to enable storage over winter in the field. Carrots were topped and harvested and then graded and washed before being transported to the distributer.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 135. Soil emissions & refrigeration were the greatest component (due predominantly to refrigeration).

Table 135 GHG emissions (kg CO_2e) per functional unit (FU; 1 t clean carrots).

Category	GHG emissions (kg CO_2e/FU)
Raw Materials	**57**
Processes	
Energy	29
waste	<0.001
Soil emissions	17
Emissions from refrigeration	220
(Total processes)	**(260)**
Transport	**41**
Total	**350**

Raw materials

The straw and black plastic used in mulching the winter stored crop were the major contributors to the GHG emissions of raw materials (Table 136).

Table 136 GHG emissions (kg CO_2e) per functional unit (FU; 1 t clean carrots) from raw materials

Category	GHG emissions (kg CO_2e/FU)
N	7.8
P_2O_5	2.2
K_2O	2.6
Other	0.35
(Total nutrients)	**(13)**
Pesticides	0.52
Straw mulch*	21
Black plastic**	21
Seed	0.73
Total	**57**

* Emissions factor calculated by ADAS from wheat co-products

** Emissions factor available[76]

Processes

Energy use in refrigeration was the major contributor to the GHG emissions of processes (Table 137).

Table 137 GHG emissions (kg CO_2e) per functional unit (FU; 1 t clean carrots) from processes.

Category	GHG emissions (kg CO_2e/FU)
Electricity	3.9
Diesel	26
(Total energy)	**(30)**
Total waste (inc. plastics)	**<0.001**
N_2O emissions from N application	6.8
Emission from lime application	-
Emissions from residue incorporation (inc out grades)	11
(Total soil emissions)	**(17)**
Emissions from refrigeration	220
Total for processes	**260**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yield was 86 t/ha.

Acknowledgements

Watton Produce Co Ltd, Hargham Road, Shropham, Attleborough, Norfolk, NR17 1DT.

Knights Farms Ltd, Lower Farm, Narborough, Swaffham, Norfolk, PE23 1JB.

3.2.7.3 Garlic

Product description

The FU was 1 tonne of conventional UK field grown garlic.

Process description

This system was based on 1 ha of garlic, although in actual practice garlic would be grown on a smaller scale. Prior to planting fields were ploughed and then power harrowed. Bulbs saved from the previous harvest were then planted and fertilisers and pesticides were applied as per standard practice on our reference farm. Bulbs were under cut and lifted at harvest, before being transported to the pack house for grading and drying. Once dried bulbs were dried they were transported to the distributer.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 138. raw materials were the greatest component (due predominantly to nitrogen manufacture).

Table 138 GHG emissions (kg CO_2e) per functional unit (FU; 1 t garlic).

Category		**GHG emissions (kg CO_2e/FU)**
Raw Materials		**290**
Processes		
	Energy	140
	waste	<0.001
	Soil emissions	130
(Total processes)		**(270)**
Transport		**21**
Total		**570**

Raw materials

Nitrogen was the major contributor to the GHG emissions of raw materials (Table 136).

Table 139 GHG emissions (kg CO_2e) per functional unit (FU; 1 t garlic) from raw materials.

Category		**GHG emissions (kg CO_2e/FU)**
	N	130
	P_2O_5	33
	K_2O	25
	Lime	-
	Other	29
(Total Nutrients)		**(220)**
	Pesticides	8.8
	Seed (bulbs)	62
Total		**290**

Processes

Soil emissions (from Nitrogen application) and diesel usage on farm were the major contributor to the GHG emissions of processes (Table 140).

Table 140 GHG emissions (kg CO_2e) per functional unit (FU; 1 t garlic) from processes.

Category	**GHG emissions (kg CO_2e/FU)**
Electricity	9.4
Diesel	120
LPG	13
(Total energy)	**(140)**
Total waste, inc. plastics	**<0.001**
N_2O emissions from N application	110
Emission from lime application	-
Emissions from residue incorporation (inc out grades)	21
(Total soil emissions)	**(130)**
Total for processes	**270**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yield was 7 t/ha.

Acknowledgements

The Garlic Farm, Newchurch, Isle of Wight, PO36 0NR.

3.2.7.4 Maize (for cornflour)

Product description

The FU was 1 tonne of conventional grain maize produced in the UK.

Process description

The grain maize crop was drilled after two passes with a disc cultivator, once drilled it was rolled to compress the seed bed. Fertiliser and pesticide applications were made as per standard practice on the reference farm. The crop was then harvested using an adapted combine with a maize header, with the stems left as trash in the field. Once harvested the grain maize was dried down15% before being transported to the distributer.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 141. Raw materials and soil emissions were the greatest component (due predominantly to nitrogen manufacture and application).

Table 141 GHG emissions (kg CO_2e) for 1 tonne grain maize.

Category	GHG emissions (kg CO_2e/FU)
Raw Materials	**140**
Processes	
Energy	82
Waste	<0.001
Soil emissions	120
(Total processes)	**(200)**
Transport	**4.7**
Total	**340**

Raw materials

Nitrogen was the major contributor to the GHG emissions of raw materials (Table 142).

Table 142 GHG emissions (kg CO_2e) from 1 t grain maize.

Category		GHG emissions (kg CO_2e/FU)
	N	110
	P_2O_5	30
	K_2O	-
	Lime	-
	Other	-
(Total Nutrients)		**(140)**
	Pesticides	**1.0**
	Seed	**1.0**
Total		**140**

Processes

Soil emissions (N_2O from N application) were major contributors to the GHG emissions of processes (Table 143).

Table 143 GHG emissions (kg CO_2e) from processes for 1 tonne grain maize.

Category	GHG emissions (kg CO_2e/FU)
Total energy	**82**
Total waste (inc. plastics)	**<0.001**
N_2O emissions from N application	92
Emissions from lime application	-
Emissions from residue incorporation	30
(Total soil emissions)	**(120)**
Total for processes	**200**

Co-products and yields

No co-products were allocated emissions as part of this assessment. The yield was 8.5 t/ha.

Acknowledgements

Ben Lintott, L&D Farm Services Ltd, Somerset – Grain maize production system.

3.2.7.5 Egg

Product description

The FU was 1 dozen (12) eggs produced in an intensive egg production system.

Process description

The egg production system was based on a standard UK battery egg production cycle. Birds were produced from a breeding flock, the eggs were then hatched at a hatchery and the female chicks were raised in a rearing flock for 16 weeks. Once pullets reached point of lay they were transported to the egg production farm. This system used a 100,000 bird egg producing flock. The birds were housed 100% of the time and fed a predominantly cereal based diet. The birds produced eggs from 16 weeks through until 72 weeks, before all birds were slaughtered for low grade meat, the houses were cleaned and disinfected and the cycle started again.

Co-products included the whole eggs, plus lower grade eggs that were sold for processing, cull meat from the end of the cycle and layer litter.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 144. Raw materials were the greatest component of the system.

Table 144 GHG emissions (kg CO_2e) per functional unit (FU; 1 dozen eggs)

Category	GHG emissions (kg CO_2e/FU)
Raw Materials	**1.4**
Processes	
Energy	0.11
Waste	0.08
Animal & soil emissions	0.23
Refrigeration of cull meat (inc. electricity & leakage))	0.009
(Total processes)	**(0.42)**
Transport	**0.03**
Total	**1.8**

Raw materials

Feed was the major contributor to the GHG emissions of raw materials (Table 145).

Table 145 GHG emissions (kg CO_2e) per functional unit (FU; 1 dozen eggs) from raw materials.

Category	GHG emissions (kg CO_2e/FU)
Wheat	0.50
Wheat feed	0.027
Soya meal	0.45
Limestone	0.14
Vitamins & Minerals	<0.001
(Total feed & bedding)	**(1.1)**
Replacements from outside cycle	**0.24**
Veterinary medications	**<0.001**
Total	**1.4**

Processes

Soil emissions & refrigeration (N_2O) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 146).

Table 146 GHG emissions (kg CO_2e) per functional unit (FU; 1 dozen eggs) from processes.

Category	GHG emissions (kg CO_2e/FU)
Electricity	0.034
Diesel	0.071
Petrol	<0.001
(Total energy)	**(0.11)**
Plastics (land-filled)	<0.001
Animal waste (incineration of dead stock & slaughter house waste)	0.11
Other waste disposal	<0.001
(Total waste)	**(0.11)**
N_2O emissions	0.20
CH_4 emissions	0.032
(Total soil emissions)	**(0.23)**
Refrigeration of cull meat (inc. electricity & leakage))	0.009
Total for processes	**0.42**

Co-products and yields

In Table 147 details of co-products are given to show how GHG emissions were allocated, by percentage of emissions and by emissions per FU. Allocation of emissions to eggs was 92% of total emissions.

Table 147 Egg production – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Whole eggs	2,300,000	dozen	£0.55	92.0	1.8
Eggs for processing	280,000	dozen	£0.35	7.1	1.2
Litter	2,500	t	£3.00	0.5	1.0
Cull meat	120,000	kg	£0.03	0.4	0.15

3.2.7.6 Duck

Product description

The FU was 1 kg of oven ready bird produced in an intensive indoor duck meat production system.

Process description

This system was based on a duck flock of 20,000 birds with a survival rate of 95%. Eggs were produced by a rearing flock and then transported to the farm for hatching, the day old chicks were then moved to the meat production sheds where they were housed until they reached slaughter weight. All birds were fed a predominantly cereal based diet. At slaughter the carcass weight of each bird was an average of 2.6kg. At the end of each cycle houses were washed down and disinfected before re-stocking occurred.

Greenhouse gas emissions

Emissions of GHGs during production are shown in Table 144. Raw materials were the greatest component of the system.

Table 148 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg oven ready bird).

Category	GHG emissions (kg CO_2e/FU)
Raw Materials	**2.0**
Processes	
Energy (exc. refrigeration)	0.35
waste	0.96
Animal & soil emissions	0.62
Refrigeration (inc. electricity & leakage)	0.090
(Total processes)	**(2.0)**
Transport	**0.059**
Total	**4.1**

Raw materials

Feed was the major contributor to the GHG emissions of raw materials (Table 149).

Table 149 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg oven ready bird) from raw materials.

Category	GHG emissions (kg CO_2e/FU)
Wheat	1.2
Soya meal	0.67
Beans	0.013
Vitamins & Minerals	<0.001
Straw	0.056
(Total feed & bedding)	**(1.9)**
Replacements from outside cycle	0.11
Veterinary medications	0.001
Total	**2.0**

Processes

Animal and soil emissions (N_2O) and waste (animal remains) were major contributors to the GHG emissions of processes (Table 150).

Table 150 GHG emissions (kg CO_2e) per functional unit (FU; 1 kg oven ready bird) from processes.

Category	GHG emissions (kg CO_2e/FU)
Electricity	0.004
Diesel	0.018
LPG	0.12
Other	0.20
(Total energy)	**(0.35)**
Plastics (land-filled)	<0.001
Animal waste (incineration of dead stock & slaughter house waste)	0.96
Other waste disposal	<0.001
(Total waste)	**(0.96)**
N2O emissions	0.59
CH4 emissions	0.032
(Total Animal & soil emissions)	**(0.62)**
Refrigeration (inc. electricity & leakage)	0.090
Total for processes	**2.0**

Co-products and yields

In Table 151 details of co-products are given to show how GHG emissions were allocated, by percentage of emissions and by emissions per FU. Allocation of emissions to duck meat was 99.5% of total emissions.

Table 151 Duck meat production – co-products. FU = functional unit.

Co-Product	Yield / cycle	FU	Value (£/FU)	% allocation of CO_2e emissions	kg CO_2e / FU
Duck meat	49,400	kg	£2.00	99.5	3.9
FYM	400	t	£0.65	0.23	0.0013
Pet food	3,800	kg	£0.07	0.27	0.14

3.3 Discussion

3.3.1 Crop and livestock commodities

3.3.1.1 Use of model systems

Some assessments were made for model businesses defined by the project team. In these cases, activity data came from a variety of sources, often weighted for the size of the model processes, and in some cases relying on expert knowledge for process information. This work was done to test PAS 2050, not to produce values that represent an average for UK production. Therefore, results should not be interpreted as benchmarks.

3.3.1.2 Hotspots

For livestock commodities, large GHG emissions values were associated with raw materials, which in turn were dominated by emissions from production of feed crops. Another important hotspot was emissions from soil and animals, which included methane from enteric fermentation (ruminant animals) and manures, and nitrous oxide from soil and manures, including from soil during production of feed crops.

Soil emissions and emissions from fertiliser manufacture dominated emissions from crop production (including feed crops for animals). For crops that were stored using refrigeration, such as potato, onion and apple, emissions from energy consumption were greater than form other crops (e.g. 36% of the total for pre-pack potatoes, but 6% of the total for conventional winter bread wheat).

3.3.1.3 *Comparisons between production systems*

The assessment of differing production systems for some livestock and crop commodities (specifically: beef, lamb, pig meat, chicken, milk, bread wheat, potato, tomato, apple, onion) showed that in general, emissions of GHGs were of the same order for production systems that differed in level of intensification. Compared with intensive production systems, more extensive systems have lower emissions associated with inputs and processes per area of land, but also have lower yields per area of land, with the result that emissions per FU are often similar. For example, organic production systems generally had emissions that were of the same order as more intensive conventional systems. In some cases, emissions values for organic systems were higher than for conventional (chicken, pig meat, wheat, onion, apple) and in other cases emissions values for organic systems were lower than for conventional (beef and potato).

Tomato stands out as a commodity with widely differing emissions values between production systems. Spanish tomatoes (1.8 kg CO_2e/kg) had lower emissions than conventional UK crop with a traditional heating method (2.3 kg CO_2e/kg), but conventional UK crop that utilised waste heat from another process had emissions (0.39 kg CO_2e/kg), that were only 23% of those from Spanish production.

3.3.1.4 *Soil emissions*

The 2006 IPCC tier 1 method does not include calculations to estimate the N_2O emissions from soil arising from residues as a result of either pruning (i.e. where the crop is still growing) or from vegetable/fruit out grades (i.e. just the vegetable/fruit and not any associated roots or foliage). Emissions from pruning and out grades were calculated using the simpler tier 1 method in the revised 1996 method.

The calculation of N_2O emissions from soil following the incorporation of crop residues from many products originating in the UK or overseas was highly problematic. The IPCC 2006 method using the tier 1 approach is complicated and uses many default values for specific crops or crop group e.g. grains. A large number of products (even common UK crops such as oilseed rape) were not represented in the IPCC method and therefore default data were not available. None of the residues produced from the overseas crops or from the horticultural crops were represented.

This is a major problem for the UK and carbon accounting of UK products, particularly as there is a large change in the calculations used to calculate N_2O emissions from soil following the incorporation of crop residues between the revised 1996 IPCC method (used to calculate the UK inventory) and the 2006 IPCC method (used in the PAS specification). Some UK dry matter values used in the revised 1996 IPCC method (Choudrie et al., 2008) can be used in the 2006 method and these were used as necessary. The necessary UK default data is not easily available in one document. It is assumed that this is because it is not yet required for calculation of the agricultural greenhouse gas inventory.

In the published report of the New Zealand (an 'Annex 1' country) agricultural greenhouse gas inventory, not all the necessary information was provided in order to fully calculate emissions from rearing lamb using the New Zealand tier 2/3 methods. Where data was missing, UK values were substituted.

No guidance is given in the 2006 IPCC method for glasshouse farming. The revised 1996 IPCC method states that 'N_2O emissions from glasshouse agriculture should be included only in the total fertiliser nitrogen consumed within each country', Nitrogen use in glasshouses and the subsequent N_2O emissions are, however, not included in the current UK agricultural GHG inventory (Pers. Comm. Laura Cardenas, compiler of UK agricultural GHG inventory).

3.3.1.5 Availability of emission factors and primary data

Availability of emission factors and values for GHG emissions is limited for minor raw processes and raw materials. Many secondary data values that are available have not been calculated using the PAS 2050 method. In many cases the workings are not clear as to what is or is not included so these values are subject to change.

3.3.1.6 Interaction with other environmental impact categories

Our discussions with producers identified a concern about other environmental impact categories in addition to global warming potential. Life cycle assessment of a wider range of environmental impacts can help give assurance that recommendations for decreasing greenhouse gas emissions will not increase some other environmental impact. It is important to notice that GHG emissions expressed on an area basis give a different picture compared to values per product unit. Emissions expressed per product unit encourage intensification to decrease emissions, whilst area values are likely to support extensification. Emissions expressed per product unit may encourage farming systems that have other negative effects on the environment – higher fertiliser and pesticide usage, poorer welfare conditions for livestock etc. These arguments are entwined with the issue of indirect land use change resulting from changes to systems for GHG emissions improvement.

3.3.2 Overseas products

The assessments of coffee, tea, cocoa, cane sugar and pineapple were included in this project to test the application of PAS 2050 for commodities from developing countries. These products were assessed with varying success, and some important lessons have been learned.

Because of budget constraints the assessments of the agricultural component for coffee, tea, cocoa and cane sugar, were made without visiting production sites. A visit was made to a pineapple producer in Ghana, and the same visit was used to meet experts in cocoa production.

Some features of these assessments are given below, followed by some general discussion points relating to application of PAS 2050 for foods from developing countries.

3.3.2.1 Coffee

The product was a 100 g glass jar of freeze-dried, instant coffee. Instant coffee is usually produced using coffee beans of lower value than more expensive coffee products. Early in this assessment it became clear that the coffee beans used for instant coffee were not from developing countries such as Kenya (small-scale production), but were more likely to be sourced from South America. To achieve the objective of testing PAS 2050 for foods from developing countries, it was decided to assess coffee production in Kenya, and instant coffee manufacture in the UK. Although the production and manufacturing stages are linked in our summary of the assessment (see 3.2.4.1), this is not a real reflection of instant coffee production.

Primary data for a coffee plantation in Kenya was not found, so the production of cherries was assessed using published information on production in Kenya.

A further difficulty was encountered in the assessment of the UK processing and manufacturing activities: manufacturers were protective of information about processes because they wished to maintain competitive advantage associated with brands and did not wish to provide primary data that could be used by a competitor to understand details of the process. However, a detailed description of the instant coffee production process was provided, allowing for theoretical energy and water consumption values to be calculated from thermodynamic principles.

3.3.2.2 Tea

The agricultural product was black leaf tea, and the final product was tea bags in a carton. The tea was grown on plantations in Kenya and packaged in the UK. Expert knowledge of the processes, and activity data were provided by Unilever. The involvement of experts from the tea industry overcame the disadvantage of not visiting the production sites.

3.3.2.3 Cocoa

The product was 100 g of cocoa powder in a glass jar. The cocoa was grown in Ghana. Cocoa production in Ghana involves a large number of small cocoa farmers. There is variation between farms in the detail of the production processes and in many cases records of inputs are not available.

We obtained data from the International Institute of Tropical Agriculture (IITA) in Accra, Ghana. These data provided for the agricultural part of this assessment were secondary, using the knowledge of experts at IITA, so the assessment does not comply with PAS 2050 if the primary production processes can be considered to be “owned, operated or controlled by the organization [*sic*] implementing this PAS” (see PAS 2050 section 7.3). In this assessment the PAS was not implemented by a cocoa powder producer, but if it had been then it would need to be determined whether the primary production processes were owned, operated or controlled by that company. If not, the use of secondary data might be defended successfully.

Whatever the conclusion about use of secondary data and compliance with PAS 2050, it was the view of the experts at IITA that good primary data were not available. There is good knowledge of recommended growing practices and many growers can give an account of their production process and inputs, but there is no certainty that actual production processes and inputs would be similar to information obtained in this way.

Clearly the cocoa assessment is dominated by land use change and the land use change data must be secondary, with large uncertainty both in the extent of the land use change and the emissions resulting.

3.3.2.4 Cane sugar

The product was a 1 kg paper bag of granulated sugar, made from sugar cane in Zambia. As for the tea assessment, the agricultural production assessment for sugar relied on expert knowledge and data from industry. These were provided by British Sugar, which holds a 51% stake in Illovo Sugar Limited, the largest cane sugar producer in Africa. As for the tea assessment, the involvement of experts from the industry overcame the disadvantage, at least to some extent, of not visiting the production sites.

The main difficulty in the sugar assessment related to processing in the UK: detailed refining and processing information and data on energy and resource use were not obtained.

3.3.2.5 Pineapple

The product was whole, fresh pineapple produced in Ghana. A pineapple farm in Ghana co-operated with this project and provided primary data for the production and packing operations. Identification of the farm, location, and many details of crop husbandry and transport distances are withheld to preserve confidentiality as requested by the company that has provided the information. Further secondary data were provided by West Africa Fair Fruit Company in Accra.

A visit was made to the pineapple farm and to the port of Tema from where pineapples are exported to Europe. The visit to the farm helped to ensure that the process description was complete to maximise subsequent collection of primary activity data. There were some farm activities that a life cycle practitioner would not have been aware of without visiting the farm. Similarly, there were some farm activities that a pineapple agronomist would not have expected to be relevant to global warming potential if they did not have detailed knowledge of the assessment method and underlying principles. This illustrates that completeness of a PAS 2050 assessment is more likely if practitioners have knowledge of the assessment method and production processes.

3.3.2.6 Emissions from soil

For overseas products from developing countries, it was not possible to find a published report of the relevant greenhouse gas inventory in order to establish the tier and country specific data to use. It was assumed that this was because countries which are not classed within Kyoto as ‘Annex 1’ countries do not have to compile and publish a national inventory. For these products the IPCC tier 1 and IPCC default data were followed and used.

3.3.2.7 Conclusions

Engagement of producers

Engagement of producers is essential for collection of complete process information and primary activity data. This is less likely to be a difficulty in application of PAS 2050 by the food industry, compared with the situation faced by the researchers in this project. In applications of PAS 2050 by the food industry the producers will have reasons for doing the work, otherwise they would not be doing it. In the work reported here the researchers relied on the goodwill of the producers, and in developing countries there was some suspicion of the motives for the work. Comparative assessments involving different producers are likely to be difficult because engagement of the producers is not likely to be equally enthusiastic.

Our experience of working with producers is that engagement is easier to obtain if the practitioner shows to the producer the likely benefits to their business. Such benefits could include marketing advantage, protection of existing markets, identification of cost saving or efficiency improvement opportunities, or more radical industry restructuring to improve business and environmental performance.

Confidentiality

Confidentiality can be an obstacle to assessments. If the producers are not fully engaged in the assessment then confidentiality can make a PAS 2050 compliant assessment impossible. As noted above, engagement is less likely to be a difficulty in application of PAS 2050 by the food industry, compared with the situation faced by the researchers in this project. However, in some cases confidentiality is still likely to be a difficulty for communication of results outside of the producing organisation. Our experience of the pineapple assessment suggests that confidentiality may be attached to parts of processes that the practitioner would not expect. It is possible that there will be a greater tendency for this problem to occur in developing countries, where details of production processes are not well known to European consumers.

Data availability

The cocoa assessment illustrates the difficulty that in some cases it will be difficult to obtain accurate process information and primary data.

Logistical challenges

Visits to producers in developing countries are likely to improve completeness of assessments, but would make such assessments expensive if they are not done by local practitioners. Completeness of a PAS 2050 assessment is more likely if practitioners have knowledge of the assessment method and production processes.

Interaction with other environmental impact categories

Our discussions with producers identified a concern about other environmental impact categories in addition to global warming potential. Life cycle assessment of a wider range of environmental impacts can help give assurance that recommendations for decreasing greenhouse gas emissions will not increase some other environmental impact.

Hotspots

For all of the overseas products assessed, emissions were dominated by agricultural emissions. For coffee tea and sugar, emissions from fertiliser manufacture and from soil were the major hotspots. For sugar, processing and transport emissions were also important. Hotspots for these products were similar to UK-produced crop products.

Cocoa was the only product that had a land use change component to the GHG emissions and this was the major source of emissions (98%).

Pineapple had significant emissions associated with refrigeration (47%), around 20% each for soil emissions and transport.

3.3.3 Comparisons of the application of PAS 2050 with LCA

3.3.3.1 Introduction

The calculation of carbon footprints following the method of PAS 2050 is an example of the application of life cycle assessment (LCA); this much is stated in the first sentence of Clause 4.1 of PAS 2050. The work done to calculate the carbon footprints of the various products covered by this project has indeed closely resembled the work that would be carried out in an LCA. In this section of the report we consider the application of PAS 2050 to these products through the lens of three of the four stages of an LCA: setting the goal and scope, life cycle inventory compilation, life cycle impact assessment and interpretation.

3.3.3.2 Goal and Scope

The standards that set out Life Cycle Assessment (LCA) methodology, ISO 14040 (2006) & ISO 14044 (2006) deliberately allow considerable flexibility to accommodate the desire of commissioners and practitioners to apply LCA in a range of different situations and to support a variety of decisions.

In order to compare the work done applying PAS 2050 to the approach that might be taken in a (or a series of) life cycle assessment(s), it's necessary to narrow down the choices available in the hypothetical LCA by assuming a certain goal and scope for it (them). The PAS hints at what the goal should be in Clause 1 -

"It is one of the intentions of this PAS to allow for the comparison of GHG emissions between products, and to enable the communication of this information." - and provides more detailed guidance about the goal in Clause 4. Overall, it seems that a PAS 2050-compliant carbon footprint study is analogous to an LCA undertaken with the objective of its being verifiable by a third party and of allowing comparisons with other products providing the same function. Both whole-life studies and cradle-to-gate studies are permitted. The coverage of the impact assessment stage of the hypothetical LCA is, of course, restricted to the impact category of global warming potential.

ISO 14044 clause 4.2.3.1 calls for consideration of a number of aspects of the proposed study in setting its scope. PAS 2050 takes many of these decisions out of the hands of the practitioner through the stipulations of Clauses 5 to 9. An approximate correspondence is as follows:

ISO 14044 4.3.2.1 item	PAS 2050 clause
Product system to be studied	4.1
Function of the product system	No specific reference
Functional unit	5.8
System boundary	5, 6
Allocation procedures	8
LCIA methodology	9
Interpretation	No specific reference
Data requirements	7
Value choices and optional elements	e.g. 6.2, 6.4.8, 7.10
Limitations	Various, e.g. 7.10, 7.11
Data quality requirements	7
Type of critical review (if any)	10
Type and format of report	No specific reference (documentation requirements in 6 & 7)

The practical cases undertaken in this project prompt further comment on some of these points:

Revision of goal and scope

ISO14044 4.3.2.1 allows for the revision of the goal and scope in the light of additional information that might emerge as the study proceeds. The scope for such revision is limited with PAS 2050 because the goal and scope is more closely specified in the standard. A practitioner might decide that a carbon footprint that could be declared as PAS 2050—compliant cannot be generated in a particular project, for example on the basis of a review of data availability. In such a case, a carbon footprint can still be calculated using the PAS 2050 method as far as possible. This has effectively been done in two cases in this project – the instant coffee and cocoa cases. In the cocoa case, cocoa production contributes overwhelmingly to the overall carbon footprint, and the land use change (LUC) term accounts for most of that. While the cocoa production part of the footprint is clearly based on observation of the cocoa production system, the data used to represent it is (in the reviewer's judgment) mostly secondary in nature (see discussion under Inventory Analysis, below). In any case, one single piece of secondary data dominates the calculation, so even with primary data covering the agricultural part of the cocoa system. Some might dispute whether a PAS-compliant calculation could be "allowed" in such circumstances, because more than 10% of the GHG emissions are related to a secondary data item. However, it probably is permissible given that the last section of clause 7.3 states:

The requirement to obtain primary activity data shall not apply where implementing the requirement would necessitate the physical measurement of the GHG emissions (e.g. measuring CH_4 emissions from livestock or N_2O emissions from fertilizer application). Given that CO_2 from LUC is equally immeasurable, is reasonable to consider that it is equally excluded from this aspect of the 10% requirement. This is covered on more detail in the section on uncertainty.

Peer review

One item that is not required by PAS 2050 is peer review (it is encouraged), although this is required by ISO 14044 for studies whose results are to be disclosed to the public. As a consequence, one question that we try to address throughout this discussion of this project's applications of the PAS 2050 is whether the specifications about scope in PAS 2050 are sufficient to enable this comparability. The work on uncertainty is particularly relevant to this question and is described in a separate section of the report.

Comparative functionality of product systems

PAS 2050 does not contain explicit requirements for a statement of the function of the product system to be made when the footprint is reported. The unit of analysis "product unit" used in early drafts was replaced by "functional unit" in the final version. Discussion of this (Clause 5.8) remains quite brief. Clauses 6.4.8.3 and 6.4.8.4 provide some elaboration of how the use phase should be treated and documented, while 7.11.2 provides for information relating to use-phase calculations to be made available.

In clause 4.2.3.7 ISO 14044 specifies that in comparative studies, “the equivalence of the systems being compared shall be evaluated before interpreting the results”.

Consider the example of two cooking appliances, a microwave oven and a gas cooker. It is well-recognised that cooking appliances provide two functions: the primary one being to heat food, the secondary one being to provide secondary space-heating (of course, in some commercial environments for part or all of the year, inefficient cookers could add to the power demands for ventilation or air conditioning). This secondary function is quantified in “Standard Assessment of Performance” tools designed to evaluate the energy performance of houses and other dwellings in terms of their compliance with building regulations. In a comparative LCA of these two appliances, we would either have to include delivery of both of these functions in equal amounts within its scope (the microwave oven product system would probably need to be expanded to include some provision of space heat from a dedicated appliance or central heating system) or carry out some allocation of the appliances’ energy uses between these two functions within the use phase calculations. ISO14044 would prefer the former approach. PAS 2050 also expresses a general preference for system expansion in Clause 8.1.1., although the implication of Clause 6.4.8.4 seems to be that system expansion should not be employed in use phase calculations, and that these secondary functions are “excluded”.

While this has some obvious advantages in simplifying calculations, there is a danger that if the carbon footprints of these products are *reported* without accompanying statements about the functions embedded in the functional unit and use-phase calculations, the potential for comparability will be considerably reduced. Furthermore, for products for which use phase calculations might be thought inappropriate (e.g. “passive” products such as hammers or chairs), omitting a statement of the lifetime assumed in the functional unit from reporting of carbon footprints could lead to users drawing conclusions contrary to those (presumably) desired by the designers of the PAS. It would therefore be better were a full statement of the functional unit delivered by the product to be required as part of the reporting of any carbon footprint. Introducing this should only involve minor modifications to the wording of PAS2050.

Functionality

For reasons indicated in the discussion of "Goal and Scope" above, some declaration of the function(s) delivered by the analysed systems would be extremely helpful to any interpretation of the results.

3.3.3.3 Agriculture and food-specific aspects

This project focuses on the cradle-to-gate systems for a number of food products, i.e. the generation of Business to Business (B2B) carbon footprints in PAS 2050 terminology. Certain issues related to the scoping phase have arisen from the examples considered. Some of these are a consequence of the nature of LCA and the fact that much of its development has been undertaken with industries using fossil and mineral resources primarily in mind rather than agriculture.

Capital goods in agriculture

Capital items, such as tractors etc have been excluded. Some argue for the inclusion of capital equipment in all LCAs, but Boustead ("Eco-balance methodology for commodity thermoplastics", APME, n.d.) set out a strong argument for discounting it for most industrial processes on the grounds that its significance is generally found to be low. However, the situation is somewhat different for some agricultural activities. From previous work, we know that inclusion of the production of capital items inflates energy use and GHG emissions in activities like crop cultivation by about 25%. At the more general level, we also note that the distinction between capital goods and other material is not entirely clear-cut: machines have wearing parts such as dies, tyres and so on that can have relatively short lives. Presumably the inclusion of such remains at the discretion of the analyst or rests on the outcome of an assessment of their materiality.

Distinguishing co-products & wastes in agriculture and food processing

Agriculture and food processing each produce a complex array of co-products, which some might regard as wastes. The boundary between the two is easily blurred but the decision as to how to classify any given material stream may well affect the results of the carbon footprint calculation. These streams are more numerous in agriculture, but are also found in the food processing cases. As examples, consider straw from wheat growing and apple solids from the conversion of apples into juice. Straw has been treated as a co-product, in some systems (organic & spring wheat) using allocation by economic valuation, but was also re-incorporated in soil (conventional winter wheat) - a form of waste recycled within the “process”. Emissions from incorporation were included in the soil emissions calculations. It could be argued that straw incorporation should be included in the land use calculations. But it is not clear if this would be allowed under PAS 2050. In the apple juice study, it emerged that apple solids were fed to pigs kept on the apple-producing farm. These solids could not, however, be sold as a co-product: if removal from the farm were necessary, they would become waste. Since these apple solids do not fall into the Directive definition of waste included in PAS 2050 (3.50), defining them as a zero-value co-product seemed to be the best option to enable the analysis to proceed. Resource constraints prevented system expansion from being applied in this case, which would require analysis of a combined pig meat and apple-juice system, so the analysts resorted to allocation. But the result is that no emissions are assigned to them and their function (nutrition, or substitution of purposefully-produced pig feed) is not acknowledged in the calculation.

In contrast, manure was originally treated as a waste in that it incurred burdens of emission during storage and spreading, but without being given any credit for its nutrient content (others would claim even more benefits). Dealing with manure was one of many problems to the analysts arising from how a cycle should be treated (involving many products) when analysing one product. Using the final version of PAS 2050 (e.g. for beef), all direct burdens of manure were included in calculating the overall footprint and a small proportion of the total was allocated to manure using economic valuation. In LCA, system expansion could be used to include credits to manure for fertiliser offsetting. This would certainty give a different valuation of manure.

3.3.3.4 System Boundaries & Allocation rules

The general requirements in PAS 2050 concerning system boundaries reflect the general approach taken in any LCA. The practical work in this project has followed that approach, and inevitably run into problems of definition which would also arise in an LCA. The indistinct boundaries between wastes and co-products in agriculture and the fuzziness of the notion of capital equipment have already been mentioned.

LCA would likely take the same approach to excluding minor components of products as that implemented by the project team. Ideally such selection would be done on the basis of environmental significance (effectively the “materiality” approach specified in PAS 2050), but with meaningful data lacking for many materials used as additives at low levels, proportion of mass becomes the screen applied in practice.

The presence of a reed bed for wastewater treatment in the apple juice production facility also raised a boundary-setting problem: should the fate of the organic carbon in the wastewater (originally from the apples) be considered within the calculation, and if so, how? In the absence of clear values from the literature on emissions from reed beds and any knowledge of the fate of the reeds, and on the basis that its contribution to the overall result of the calculation would be small, this was eventually left out of the system.

The difficulty of setting boundaries around single-product systems in the dairy sector for LCA purposes is widely-recognised and was again encountered in this project. In this case the boundary-setting problem arises because the conversion of milk into cheese involves an indivisible unit process which produces cheese (or strictly its precursor, curd) and whey. Butter is a common additional co-product produced in a secondary, also indivisible, unit process. Whey may be sold but is often processed further in the cheese-making facility to produce higher value products, such as whey powder or concentrated derivatives containing whey protein. The problem that arises in conducting an LCA or in following the PAS 2050 method is of deciding where to draw the boundary for the purposes of allocation. This can be around the facility (which may be the unit process as defined in PAS 2050/ISO14044), in which case cheese butter and whey derivatives are the co-products. This will ensure that the practitioner has directly relevant price information available, but has the likely consequence that the cheese carbon footprint will vary from facility to facility according to the extent of post-processing carried out on the whey; the more value is added to the whey in the facility, the higher the share of total system emissions allocated to the whey products, and thus the lower the cheese carbon footprint.

The alternative, adopted in the cheese case study here, is to draw the system boundary for the co-product system(s) at the earliest point(s) downstream of the *indivisible* unit process at which saleable products can be identified and for which price information is available. In the case of cheese, this should lead to more consistency and therefore comparability between the results of different footprint studies. Using this approach introduces some additional constraints on the conduct of studies:

- The collection of market price information for commodities is required in place of collection of price information from a single organisation. In some studies internal transfer prices might be used (for example where indivisible unit processes generate intermediates that are not commonly traded)
- A certain amount of sub-metered data becomes essential if the system boundary is not co-incident with the facility boundary

In terms of the goal of the PAS 2050-analogous LCA introduced at the beginning of this section, the key questions concerning these issues and relating to the definition of scope appear to be:

1. Are the requirements of PAS 2050 sufficient to ensure compliance with the principle of consistency and the implied requirement of comparability in the goal (Clause 4.2)?
2. Is the method set out in PAS 2050 adequate to ensure that the goal covered by PAS 2050's principles of relevance and completeness in Clause 4.2. are met?

Reflecting on the cases in this project, we suggest that the answer to both these questions is "not in all cases". In those cases where the answer is no, the LCA practitioner should revise the goal, acknowledging - for example - its limited potential comparability with other studies.

As a further example consider the calculation of the carbon footprint of a biofuel derived from some field-grown crop. Based on the observation above concerning the significance of capital equipment in some crop-production systems, the LCA practitioner might conclude that a complete GWP-focused LCA could not be completed given the scope imposed by PAS 2050. However, comparison of the results with studies of other biofuels carried out on the same basis might be valid, since all crop-production systems would have been assessed in the same fashion. Comparison with fossil fuels would however be compromised, since the degree of completeness would be different in the two cases. The LCA's goal might then be revised to reflect this.

The PAS 2050 itself appears to need some refinement to ensure that all studies that use it do fulfil its scope. Achieving such general consistency may be impossible, in which case the development of product category rules should ensure consistency among relevant groups of products (it hardly matters whether the carbon footprint of a car is comparable to that of a block of cheese!).

3.3.3.5 Inventory Analysis

This corresponds to the compilation of data on emissions in PAS 2050.

As a general remark, we note that in going through the PAS 2050 process, much work is undertaken to produce an answer, i.e. the embodied GHG emissions of products (quantified in CO_2e). It is a pity that so much else is not required to be reported as the data would already have been collected. Energy use in the system (embodied energy) is the most obvious example. Other items of agricultural interest are land occupation, which must have been calculated for all commodities, but also other items that are often reported in LCA, like water use, potentials for eutrophication and acidification, ozone depletion and photochemical oxidation.

Data and data sources

The rules concerning data quality and data selection in PAS 2050 (Clause 7) are of course compatible with LCA. The primary data sources used in this project are of course those on which an LCA would rely. The project team have also drawn on some of the same secondary data sources that the LCA would use: Plastics Europe eco-profiles, the EU LCA platform, and so on. Data from the Danish LCA Food database has been used in a few instances. This database should be used with care, since the underlying methodology used to develop it is closer to the consequential than the attributional approach, and so is strictly not compliant with the requirements of PAS 2050 (Clause 4.1).

We noted (see the subsection entitled “revision of goal and scope”, above) how a judgement concerning data made in the course of an LCA might affect such a study. The data used to calculate the carbon footprints for the case studies covered by this project varies in nature. Considering that variety applied in the context of the scope of PAS 2050 highlights some issues for consideration. We discuss these below.

Defra factors for fuel & energy emissions

Electricity conversion factors published by Defra for corporate greenhouse gas reporting (http://www.defra.gov.uk/environment/business/envrp/pdf/conversion-factors.pdf) were used; these do not include either the extraction of mineral and/or hydrocarbon resources or the refining of fuels. It is unclear whether Defra's (also used) transport fuels conversion factors include these elements, but it is believed that they do not. Those boundaries make Defra's conversion factors ideal for use in corporate greenhouse gas accounting in accordance with Greenhouse Gas protocol or ISO14064 guidance. In LCA (and therefore by implication for the Purposes of PAS 2050-compliant work, given the wording of clause 6.4.2) failure to include the extraction and refining elements is contrary to the principles underlying the technique, invalidates several Impact Assessment methods and omits a proportion of the inputs and outputs (including some GHG) to and from the system.

If product-based GHG accounting based on PAS 2050 is to become widespread, an additional section may be needed in Defra's fuel and energy conversion factors to enable the earliest stages of the fuel cycles to be taken into account. Good LCA databases incorporate this information already.

Secondary N_2O

Selecting appropriate data to represent secondary N_2O emissions is, like many matters arising in the data compilation stage, is linked to problems of boundary setting and allocation; in this case to the distinction between wastes and co-products. N is lost from agriculture in several forms, some of which contribute to secondary emissions of N_2O, e.g. ammonia, nitrate and NOx. PAS 2050 does not seem to acknowledge these clearly, but they were actually included in the agricultural activities analysed by ADAS.

The nature of primary data

PAS 2050 contains a qualified requirement for the use of primary data (clause 7.3). In the cocoa powder case (see also above) it seems that achieving PAS 2050-compliance would not require the use of data that involves direct emission measurement. This reviewer considered all of the data used in the calculation of the cocoa footprint to be secondary. But it could be argued that in the case of a commodity that is mixed, blended and traded and for which traceability limited, primary data might include data collected by some other means than recording of inputs and/or outputs in a single facility. So for materials or components that can only be traced as far as a country of origin and for which a batch might contain items from more than one source within that country, might national statistical data be considered as primary data – in the sense of being data covering a reasonably representative sample (Clause 7.7)?

Data Quality

As the beef cottage pie and lamb shanks examples illustrate, the quality of the data used affect the use to which any carbon footprint can be put. Some documentation of data quality – particularly the relevance of the data to the exact product under study – would be a valuable part of any report, and again allow sensible interpretation.

The quality of primary data

In the cottage pie and lamb shanks cases, primary activity data was available for the processing stage, but at very poor resolution. Data is only available for the whole facility which produces a wide range of prepared meals, both frozen and chilled. Essentially, the GHG emissions associated with the processing part of all meals produced at the facility under study are considered as being effectively equal. This was probably substantially in part because the analysis was being “imposed” rather than requested.

Because of the dominance of the value for lamb in the overall carbon footprint of the lamb shank product, this assumption and the quality of the processing data used had little bearing on the overall carbon footprint generated in that case. But the assumption is clearly false. The energy used to cool frozen products (chiller exit temperature typically -22°C) *is* greater than the energy used to cool chilled ones (chiller exit temperature typically 4°C).

Looking at these as short (“screening”) LCA studies, one would conclude that:

- They give a general indication of the relative importance of the different stages of the life cycle

- They allow some comparison of the carbon footprints associated with ready meals, as long as the compared products differ considerably in composition

- They do not allow comparisons between ready meals of similar composition in frozen and chilled form, because the data on the processing stage is inadequate to allow any meaningful comparison

- They do not enable meaningful comparisons to be made between the performance of different facilities making ready meals of similar compositions.

- Further investigation is needed of the ranges of emissions associated with raw materials from different locations, and the uncertainty attached to those emissions. These factors are discussed elsewhere in this report.

But these examples probably provide a realistic representation of what a resource-constrained company might do in applying PAS 2050 to generate numbers quickly to feed forward to impatient customers, e.g. retailers. They show that primary data is not necessarily particularly good data in terms of the data quality parameters identified in Clause 7.2 of PAS 2050. So a further important question arises: should *primary* data be required to be of a certain "quality standard" or "resolution" before any calculation of "embedded GHG" can be deemed fully PAS 2050 compliant (i.e. meeting the objectives set down in the scope of the PAS")?

We recognise, of course, that defining such a quality standard in a general way is no easy task, and could place some burden on those using the standard. It would be possible to specify that PAS-compliant calculations must use data from the manufacturing processes for the product under study measured at the level of the indivisible unit process. Direct measurement at this "engineering unit process" level in the kind of facility described in the cottage pie case (or indeed in a large, interconnected chemicals facility) is a large task, and to require it would surely slow down the uptake of the PAS. But this may be necessary to avoid a situation in which flawed comparisons are made on the basis of bad numbers, which is a highly possible outcome of the release of this standard.

Waste data

PAS 2050 contains clear guidance on how emissions from waste processing should be treated. Obtaining data to implement that guidance can be difficult, as the lamb shanks and cottage pie case studies demonstrate. There are two problems, common to both LCA and carbon footprint calculations:

- The first is identifying the amount of waste associated with any given product in a facility producing many different products from a number of modular processes. The easiest, and often the only available, approach is simply to divide the total waste arising between the total amount of production and assume that the wastage rate (i.e. 1 - yield) is the same for all products. This ignores a great deal of process optimisation knowledge which recognises that yield is influenced by run length, the nature of the intermediate products and the potential for their re-use, and so on. But, the data to allow a more sophisticated approach is often lacking. Spoilage in handling or transit may also inflate upstream emissions in the same way, but has not been considered in these case studies; it is likely to be much less significant than wastage in the processing stage. Strictly speaking this should be included in both LCA and carbon footprinting studies. Other products are more prone to wastage, such as some salads and soft fruits. Animal products can suffer bad losses is subject to a loss of refrigeration in the supply chain.

- The second problem is identifying the appropriate emissions from waste treatment.

The second of these is more tractable: managers of UK facilities can identify where their waste goes, how it's treated and how landfill gas is handled (if landfill is the fate of the waste) and models have been developed (for example, to enable the impacts of different waste management scenarios to be compared using the WISARD and WRATE software tools) from which GHG emission factors for classes of waste in different end-of-life "scenarios" might be drawn. The first presents more of a challenge but is perhaps more significant, because the assumed wastage rate inflates all upstream emissions. There is no difference here between LCA and carbon footprinting according to PAS 2050.

Use of mass balances

The example mass balance diagram in the guide to PAS 2050 (P21) is trivial compared with growing wheat let alone producing lambs. Within agriculture, we have several relatively uncontrolled mass flow streams, e.g. water in from rain and out through transpiration or respiration, dry matter accumulation through photosynthesis, N fixing and dry matter loss through respiration. These are generally not easy to quantify and extensive interactions with soil are involved. ADAS did produce process flow charts with some annotated values that could be used in parts of a mass balance. In the latter part of the project, these were refined and important parts made clear. In animal production, for example, head counts were made of herd numbers, culls, breeding replacements and the main outputs. This is good practice. This approach should ensure that the fate of all heads is accounted for.

For crop and livestock production, a mass balance of the main nutrients is feasible, e.g. N, P, K and S, acknowledging that there would be uncertainties involved. Unlike Figure 1 in PAS 2050, accumulation or depletion of soil minerals is possible. The significance of this approach is in ensuring rigour in the approach and highlighting whether a production system, for example, is depleting soil resources. This is clearly worthy of reporting in its own right even though it is not part of PAS 2050 objectives. Resources may not permit all elements to be traced, but if “rationing” is imposed, N must feature owing to its contribution to N_2O emission together with NOx, NO_3^- and NH_3, which contribute to environmental harm in their own rights and to secondary N_2O. The supply of N, especially via synthetic N, manufacture and use also contributes to large amounts of energy use and in some cases specific N_2O emissions.

3.3.3.6 Impact Assessment

The impact assessment method set out in PAS 2050 corresponds to one of the common methods used in LCA. We note that there are other impact assessment methods used in LCA, for example some which follow the chain of cause and effect on from the generation of additional greenhouse gases to their ultimate impacts on human health and ecosystems (e.g. ecoindicator ’99) and others which expresses impacts in monetary terms (e.g. STEPWISE 2006).

3.3.3.7 Interpretation - reporting and documentation

Some points relating to the interpretation of the case study carbon footprint calculations have already been made. This sub-section therefore focuses on reporting and documentation requirements.

PAS 2050 is a method for calculation, and says little about how calculations might be reported or documented. As noted above, ISO14040/44 is clear that LCA studies that are intended to be used for comparison should be peer reviewed.

Clearly if PAS 2050 is to be used to quantify the embedded GHG associated with products in a manner in which their comparability is “auditable”, then some specification concerning the documentation of systems, data, and method will be required. Some such requirements are indeed contained in PAS 2050. ISO14044 contains a more complete list of the types of information that could be needed. Some points that seem of particular importance on the basis of experience in this project are noted below.

Flow diagrams

A reasonable approach for reporting would seem to include the basic calculations used in a summary-like document, but to ensure that a fuller description of measurements, data sources, estimates and assumptions is also included.

The diagrams presented all appear to be PAS 2050 compliant. It seems that flow or process diagrams without numerical annotation help the reader understand what is being analysed. A fuller annotated diagram is of much more use to any verifier or especially interested party and should also be included.

Documentation of any PAS-compliant study would need to provide some commentary about boundaries in addition to the flow diagrams to allow any verifier/reviewer to establish that the data used were appropriate to the system boundaries. Documentation of the boundaries applying to secondary data would be important.

3.3.3.8 Concluding remarks

The work done by the analysts using PAS 2050 has broadly been in line with LCA, given its ability to be widely interpreted. The pre and post-farm-gate circumstances have illustrated different challenges. One general observation is that the application of the PAS has been “imposed” rather than “requested” by farmers and food processors. In some cases, great willingness has been shown, but certainly in the early farm studies, a pragmatic approach was used to provide data for analysis by creating virtual farming systems, not measuring activities on actual farms. This creates a slightly artificial environment in which to apply the PAS and to compare with LCA. In some respects, the ADAS approach has been to much like that applied in the Cranfield LCI models, although there are also very substantial differences.

The results for the PAS2050 analysis of meat differ from those calculated in ISO250 for a number of reasons. The boundary conditions differ, e.g. capital was included in IS0205, but not in this project. The LCI data were different. The data used in IS0205 probably comply with PAS 2050 specifications. As it happens, the models developed in IS0205 have been updated including the use of the ELCD energy carriers, and the values have changed somewhat. PAS2050 allocation rules at the time of the analyses required economic allocation, although this was subsequently made more flexible. Both economic and functional allocation were used in IS0205. When economic allocation has been used, price fluctuation can affect the outcome. The PAS2050 study included the costs of slaughter, which the IS0205 study did not.

The inevitable tension between obtaining sufficient reliability vs. flexibility / cost / accessibility raises a question about whether the PAS is trying to be too ambitious by trying to include the whole life cycle of a product and at the same time aiming to produce a product-differentiated result that allows for comparisons unspecified (even unimagined) by the commissioner of the study.

The same tension applies to LCA: it is impossible to be specific enough in a standard covering all situations to force comparable results to be produced without having either a prescription that does not work in some cases or an unmanageably large document. So the standardisation of LCA allows flexibility in a study's goal and scope, and has led to the development of "product category rules" (PCR) at a lower level than ISO1404x, in which more specific methodological specifications are laid down for certain types of products or for certain sectors. This kind of work is reasonably well-advanced in the construction sector, although neither fully-agreed nor harmonised across Europe yet. We believe that some sector-specific rules or tools will have to be developed. Their application will also need to be mandated by the PAS, e.g. for situations where primary data at the "true" unit process level is not available.

We also reinforce the view that simply to report GHG emissions when other very important environmental factors have been used in the calculations seems like an omission. Apart from energy, important gaseous emission like ammonia for example should be quantified owing to their secondary N_2O emissions. The GWP of NH_3 is not zero, but 1% of NH_3-N is assumed to be converted to N_2O-N by IPCC. The GWP of 1 kg NH_3 is thus 3.86 (1 * 1% * 298 * 44/28 * 14/17). As we have signed up to international agreements to reduce ammonia emissions, it seems a great pity not to include such findings within the PAS.

4 ANALYSIS OF UNCERTAINTIES ASSOCIATED WITH APPLICATION OF PAS 2050 TO COMPARE PRODUCTS

4.1 Introduction

The aim of PAS 2050 is to enable an analyst to undertake an objective calculation of all GHG emissions in the delivery of a product. However, for many reasons, the values used within a Pas 2050 analysis are 'best estimates', and an estimate of this uncertainty should be included in the final result.

This will allow "users" to appreciate that the final result falls within a band of valid results. This will permit comparisons between a product produced by system A and by system B. Whatever the intentions of the authors of PAS 2050, comparisons will be made between rival production systems, e.g. sugar from beet *vs.* cane, lamb from intensive *vs.* extensive systems and bread sold by rival supermarkets. A robust approach to calculating and communicating these uncertainties is essential for PAS 2050 to maintain public acceptance and to avoid unsupportable claims being made in the commercial or "political" world.

Lloyd & Ries (2007) noted that: "Additional research is needed to understand the relative importance of different types of parameter, scenario, and model uncertainty and to determine whether guidelines regarding the types of uncertainty and variability that should be included in [Life Cycle Assessment] LCA can be established."

The clearest uncertainty is in estimating primary data, of which an example is the electricity (or gas) to cook a product in a factory that produced many such products. Very few factories will have sub-metering of electricity at the level of an individual product.

A major concern with field crops is that the large uncertainty of N_2O emissions. N_2O emissions account for about 70% of Global Warming Potential (GWP) from wheat, so not only is the contribution large, but the uncertainty in the estimates is very high. If this outweighs all other uncertainties, it may not be possible to compare systems. Thus, an estimate of GWP saving delivered by a reduction in CO_2 emissions versus one delivered by a reduction in N_2O emissions will be much more reliable and small differences could be significant. It is essential to address and clarify these questions.

More generally an LCA carried out by two analysts on an identical system will obtain different results because of the different assumptions made in the course of modelling the system.

In its simplest form, the estimate of GHG emissions per unit product (*g*) is the sum of products of technical coefficients, *c*, (e.g. litres of diesel) and emission factors, *e*, (e.g. x kg CO_2/l). For n components, we have:

$$g = \sum_{1}^{n} c_j \, e_j$$

For gases other than CO_2, there are additional factors (*w*) to convert the mass of gas to GWP, hence we get the following.

$$g = \sum_{1}^{n} c_j \, e_j \, w_f$$

Each value of *c, e* and *w* has its own uncertainty. Broadly speaking, the technical coefficients are associated with measurement errors (*alpha* uncertainties) and both the emission factors (EF) and GWP factors are associated with the errors in the model used to derive them (*beta* uncertainties). EFs may be derived from simple models (e.g. a linear regression from experimental observations) and include such diverse activities as N_2O from fertiliser application and CO_2 up a chimney from fossil fuel combustion in electricity generation. The GWP factors (and some EFs) may be derived by the IPCC using a mixture of experimental measurements and simulation modelling, all of which have associated uncertainties.

The *beta* uncertainties were further divides into Type 1 and Type 2, where Type 1 uncertainties are generic and not geographically specific while Type 2 uncertainties are those uncertainties affected by widely different climatic regions. So, Type 1 includes all GWP factors and, say, the GHG emission from burning diesel. In contrast, the N_2O emission EF for the UK and, say, Australia, are not likely to be and the same and nor would the uncertainties, so that this is Type 1.

These sets of uncertainties can theoretically be characterised by variances with some form of distribution. If the errors in these variables are not correlated with other variables in the set, then relatively simple formulae can be used to combine variances to generate one variance for the value of *g*, i.e. the error or uncertainty associated with the estimate. There are also cases in which the uncertainties are not known and indeed the value of a parameter may not be known, e.g. because of commercial secrecy or the absence of scientific understanding. In these cases, expert opinion is the only realistic option to use.

In the systems being analysed with the PAS, both in primary production and food processing, the simplifying assumption of uncorrelated variables should apply since these are based on independent data. However, fully defined uncertainties will not generally apply owing to, for example:

- large uncertainties associated with the emission factors (e.g. N_2O from soils), which contribute to high uncertainty in one part of the estimate of *g*, so will mean *g* has a high uncertainty, but these emission factors are present in both systems under comparison and therefore should not affect that comparison

- variances being very hard to estimate, e.g. where an absence of data requires expert opinion to ascribe a value or where an input has no declared variance. Note that many standard emission factors do not as yet have publically accessible, defined associated variances.

4.2 Aims

The work was aimed at defining a framework as follows

- Define and utilise uncertainty in technical coefficients, emission and GWP factors.

- Combine these uncertainties in an analysis and enable presentation as a single result (together with as many parameters that are needed to define the uncertainty).

- Define how to compare two results using the uncertainties.

4.3 Exclusions

This does not (and cannot) address such matters as:

- miscalculation by practitioner

- errors in selecting source data

- errors in the source data.

These are areas that should be addressed by internal and / or external peer review.

4.4 Approach

The project proposal divided the work into four phases, as summarised below, although the actuality of the work meant that the order and priorities of these phases were altered. Other matters also arose, such as data sourcing and effects of land use change, which are also reported below.

4.4.1 Phase 1

The first phase was to analyse the nature of uncertainties likely to be encountered when applying PAS 2050, focussing on systematic correlations. Particular attention was paid to the concept that uncertainty in emission factor models (alpha uncertainties) can be “cancelled out” when comparing two similar systems of production, through the uncertainties (rather than the *variables*) being highly correlated. A theoretical framework was produced from this analysis. It considered how the 'average' concept for a product footprint (representing an average over time and across different geographical and technical supply chains) influences how we identify or measure sources of variability or uncertainty.

4.4.2 Phase 2

The second phase used data collected during the project by analysts from ADAS and Campden BRI, together with input from those analysts, to test the applicability of the framework for typical production systems. It was applied mainly to aspects of apple production and juicing.

This phase also included comparisons of how the same production system changed by using more renewable electricity (as might happen as the national grid changed over time). The cases of well and poorly sub-metered production were considered.

The aim was to identify similarities and differences between the systems and hence how a protocol might be needed for particular types of analysis. For example with apple juice production, there are two separate stages of producing the apples and then juice extraction (juicing). If the juicing process is improved and you are comparing two juicing methods, the apple production system is not changed and hence the apple production uncertainty is not relevant for that comparison. Similarly, different amounts apples from the same source are used, the uncertainty from apple production is irrelevant, but if the source of the apples is changed then it is relevant.

4.4.3 Phase 3

The third phase addressed whether and how a readily available existing software package can deal with the scale of problem that confronts us. This included using a package for carrying out the Monte Carlo simulations in assessments of comparisons.

4.4.4 Phase 4

The last phase developed guidelines for the statistical analysis of the food products that are evaluated with PAS 2050. This was accompanied by guidance on how to report and explain the statistical output so that communication will be unambiguous.

Some aspects of the uncertainties from land use change (LUC) were also addressed, although not in the original proposal.

4.5 Outcomes

In considering phase 1, it quickly became apparent that phase 3 needed addressing at the same time. The estimation of uncertainty of any particular system was carried out using Monte Carlo (MC) techniques – these enable a large number of simulations to be performed where the input parameters and emission factors are selected from the probability distributions defined and predictions of the GHG emissions made. Two software packages were applied during preliminary investigation of the test studies applied the Markov Chain Monte Carlo Simulation tool *WinBUGS* and the commercial add-on to *Microsoft Excel*, *@Risk*. Both were capable of being applied to the sort of analyses required. Most analysts collate and process their data in a spreadsheet (usually *Microsoft Excel*, hence an add-on that is easy to use and is versatile was considered to be the more suitable tool. *@Risk* was selected, but its use by us does not imply commercial endorsement or that other tools are inadequate. We were bound to try an add-on and *@Risk* was the first on considered. It must be stressed, however, that it is a tool that requires a good understanding of statistics to be applied reliably. It generates random numbers, but the user must take great care to avoid generating random results. We note, for example, that there are open source or freeware Monte Carlo simulation packages, listed here: http://www.mathtools.net/Excel/Simulation/ but none were tried here.

Much of Phase 1 addressed the nature of uncertainties and the correlation between them (as opposed to [and as well as] the correlation between variables) and how a framework could be developed to meet the different needs of analysts and sponsors.

The framework is presented in the following section. A discussion of aspects of land use change follows. The framework is applied to a set of case studies (using ADAS and Campden BRI data) and the description of reporting guidelines are in the Appendix (Section 4.14.1).

4.6 A framework for estimating uncertainty of the GHG emissions calculated using PAS 2050

The purpose of the calculating the uncertainty of the GHG emissions derived with PAS 2050 is to allow comparisons to be made between the estimated mean values of GHG emissions for a product created either by different organisations and/or for different production systems. The uncertainty of an estimate of GHG emissions can be used in several different ways:

1. To enable the GHG emission of one product from one organisation to be compared with the carbon footprint of the same product from another organisation. For example 1kg of white sliced premium bread sold by Supermarkets A and B using different sources of wheat or baking methods.

2. To enable the GHG emission of one product produced under one production system to be compared to that of the same product produced under a different production system within the same organisation, for example 1kg of white sliced premium bread using Canadian or French wheat.

The detail required by any analysts modelling these systems varies between these as well as the detail in reporting the findings. What is possible to achieve depends on the access that analysts have to the same original data and /or to the detailed reporting by other organisations.

4.6.1 Definitions

An estimate of the GHG emissions is created using **input data** and **factors** as follows.

- **Input data** (primary activity data) are values which can be measured or estimated from measurements. Typical examples are kWh of electricity consumed, fuel used, distance travelled or hours of use of a machine. The associated uncertainties are termed **alpha uncertainties**.

- **Factors** (secondary data) are values which are taken from a source such as an LCA database (e.g. kg CO2e per unit process) or IPCC guidelines (e.g. kg CO2e per unit N applied). They may come from simulation models or be rule-based or be a mixture of experimental data and modelling. The associated uncertainties are termed **beta uncertainties**.

- In some cases, expert judgment is used in the production of primary or secondary data, e.g. in allocating fuel used between several processes or indeed several factors (or their uncertainties) in the IPCC Guidelines. Expert judgment itself has some uncertainty.

- Expert judgement is also required in cases requiring economic allocation between co-products. For example, with rape oil and rape meal, the prices are rarely stable. In some cases, a price for a co-product at the point of division is not readily available, e.g. straw behind the combine is the point of division, but the usual prices refer to straw *after* it is baled. This also applies to whey in cheese-making where it may be dewatered or dried before sale.

The estimate of GHG emission is typically the sum of a set of primary and secondary factors multiplied together, although the arithmetic may be complex. Further complexity may be introduced by applying allocation or other features.

In a typical GHG assessment, many variables will be correlated. In the implementation of the uncertainty assessment using Monte Carlo simulations, this becomes built-in wherever an arithmetic relationship applies between two variables. In some biophysical systems, other variables might be implicated and should possibly be correlated with another variable. For example, nitrate leaching on a fertilised crop is a function of at least N application rate, yield, soil texture and rainfall.

If leaching was calculated by the IPCC default formula (leached N 30% of the applied N), then yield should not be correlated with N leaching, even though it is in reality, because the model used to calculate leaching does not include it. If leaching was calculated by a model that included yield, it should be correlated. In @Risk, there is a matrix to enable these correlations to be established.

Given the measurement orientation of PAS 2050, we feel that the default assumption about correlated variables is simply that no additional correlation is required in the uncertainty assessment than that which arises from arithmetic operations.

4.6.2 Methods

The process that needs to be followed to estimate the uncertainty in GHG emissions is shown in Figure 6. Each step in the process is detailed in this section.

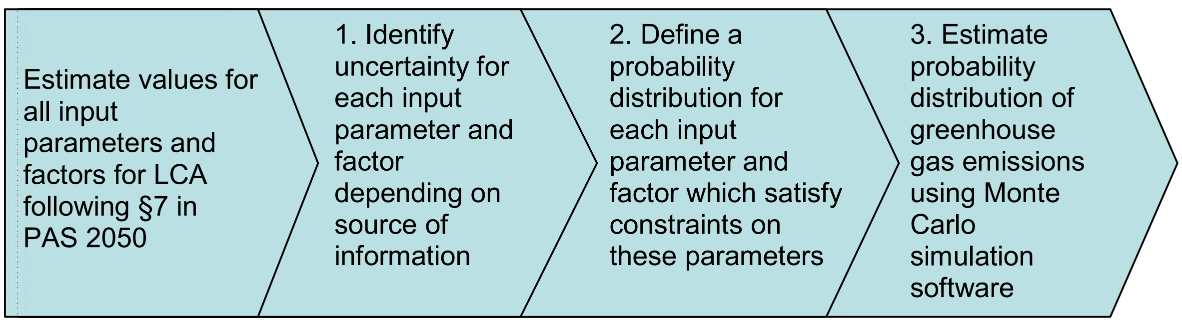

Figure 6 A general process map for estimation of uncertainty in LCA.

Identify uncertainty for each input parameter and factor depending on source of information

Data to be used as input parameters in the LCA will be either primary activity data or secondary data as defined by PAS 2050. The emission factors will be secondary data.

Uncertainty in any parameter or factor can come from two sources. One is the "natural" variation in the parameter or factor, for example, wheat comes into a factory from many farms, the soil on these farms varies from light to heavy and hence the fuel use per tonne covers a range due to the soil type. The other is the error in the measurement system, for example the gas meter, weighing scales, electricity meter, weight of feed arriving in a lorry. Some of the measurement errors are fairly small, for example utility meters, but in other cases errors could be larger, for example estimating dry weight of waste tomato haulm in trailer loads when no scales are available and the moisture content is very variable. Any estimation of variation from sampled data will include both these sources of error.

a) Primary activity data (alpha uncertainties)

Estimation of uncertainty from primary data will usually be straightforward as data will have been collected to estimate the average value of the input parameter so the full dataset can be used to estimate the standard error of that mean input parameter using sampling theory. This requires repeated observations.

However, in some cases, (repeated) data on primary activities is not available and expert judgement and/or allocation must be used. This applies more to food processing than primary production, as the typical food processor has several lines and several processes. A typical problem is that there is one gas and electricity meter, but several machines (although this can apply on farms where the commercial and domestic bill is one). The energy use allocated to the product under investigation thus depends on expert judgment. This can happen in a very simple case, e.g. in the apple juicing example analysed, an electric motor is used, but with no sub-meter. The upper estimate of electricity usage is nominal motor power multiplied by the time used. The expert needs to estimate what fraction of this is reasonable to use, because the motor is very unlikely to run at full load all the time. Estimation of the variability in this situation is more problematical and some rules for assigning variability in these types of situation will be set out.

A similar issue occurs in agriculture because of the long-term nature of farming. Thus an operation such as sub-soiling is carried out on, say, a 1 in 5 year cycle and benefits all subsequent crops. It may not have occurred in cultivation of a crop under analysis but it should not be neglected. The converse may occur when a herbicide is not applied to one crop and so causes a build up of weeds in later years. Thus even apparently accurate primary data can be inaccurate in LCA terms.

b) Secondary data (beta uncertainties)

There are several sources of secondary data that could be used and the identification of uncertainty will differ for each of these sources.

i) Other GHG emissions assessments that used PAS 2050

At this stage, the data from another GHG emissions assessment will not necessarily include an estimation of uncertainty but once these guidelines have been included into PAS 2050 then an estimation of uncertainty will be able to be provided.

ii) Peer reviewed publications

Many peer reviewed publications will include some measure of uncertainty

iii) National government, the EU, official UN publications and other publications from UN-supported organisations.

Similarly, official publications should include a measure of uncertainty, however, this is not uniformly true. For example, the EFs used for business reporting on Defra's web site do not, see: (http://www.defra.gov.uk/environment/business/envrp/pdf/conversion-factors.pdf) and this was verified with Defra's contractor who handles these data.

The UK GHG inventory does include them, although not necessarily in the most accessible form for use by analysts:

http://www.airquality.co.uk/archive/reports/reports.php?action=category&section_id=7

iv) ELCD core database.

The core database is still under development and at present does not seem to include any measures of uncertainty. It should be a priority that pressure is applied to the developers of this database that it should include uncertainty in the future.

v) Commercial databases

These normally include an estimate of uncertainty, e.g. the widely used *Ecoinvent*.

vi) Expert opinion

Experts will be required to estimate values. They also thus need to give a range of possible values as well as the single value given for the LCA. This could, for example, be based on the maximum and minimum values experienced by the expert in that context.

vii) Emission factors

Most are covered by the IPCC reporting guidelines for national inventories which do give a measure of uncertainty. It is clear, however, that some interpretation of the actual type of probability function (PDF) is needed.

viii) Simulation models

These could be things like the RothC soil C model for land use and land use changes (LULUC) or SUNDIAL for nitrate leaching. Uncertainties have been derived by the project team for SUNDIAL.

ix) Global Warming Potential Factors

These come from a mixture of experimental science and modelling. One part is relatively easy, i.e. how much radiation is absorbed by a particular gas. This should have a very low uncertainty. The more complex part is modelling the decay of a gas over time and dealing with any breakdown products. The rates of decay typically depend on temperature, radiation level, other species that might catalyse decay rates, take up by sinks like the soil or sea. Estimates are given in

http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch02.pdf.

Suggestions for values to be used for the uncertainties of a number of input parameters and factors are given in the Appendix (Section 4.14.1). These estimates should only be used when measured data are not available.

Define a probability distribution for each input parameter and factor which satisfy constraints on these parameters.

For each input parameter, it should be possible, given the uncertainty for that parameter and knowledge of the range and possible distribution, to define a probability distribution for that parameter (or factor). A probability distribution describes the range of possible values that a random variable can attain and the probability that the value of the random variable is within any (measurable) subset of that range. This probability distribution could be a very simple uniform distribution where the parameter value is equally likely to fall anywhere between an upper and lower limit, or a classic normal distribution or a more complex distribution such as a lognormal distribution which is a skewed distribution. The latter is often applied to avoid generating negative numbers of variables that have high uncertainties, e.g. GWP from N_2O. Any probability distribution is usually defined by two parameters, for a uniform distribution the two parameters are the maximum and minimum, for a normal distribution the two parameters are the mean (or most likely value) and the standard deviation, which is a measure of the spread of the distribution. In the situation where the distribution to be represented is skewed to the left it is best to use a lognormal distribution. A lognormal distribution can be specified by two parameters which are usually the mean and standard deviation of the data. For example, the @Risk function Risklognorm uses the mean and standard error as parameters – this will give a skewed distribution with the specified mean and standard error.

Some parameters must be constrained to be positive in this case a lognormal distribution can also be used as the range of values for this probability distribution are from zero to infinity. To generate this distribution in @Risk, use the Risklognorm2 function and give the mean and standard deviation of the required distribution. The mean value of this distribution will not be the same as that inputted but the distribution will represent the original distribution with the property that the parameter values will always be greater than zero. If the standard deviation of the data is small compared to the mean the lognormal distribution will tend towards a normal distribution but with the property that the parameter is always greater than zero.

For some parameters only a mean, maximum and minimum are given – so there is no direct estimate of variance. It is important to establish if the maximum and minimum are literally maximum or minimum or just that the parameter has only a small probability of being larger or smaller than these limits. We have found that the Max and Min given for a some parameters in the IPCC guidelines are actually 95% confidence intervals and that a lognormal distribution can be used to represent the probability density function for these factors.

Some more commonly used probability distributions for IPCC factors are in Table 152 with all the information needed to define the probability distribution.

Table 152 Probability distributions that are recommended to be used for a range of commonly used input parameters and factors from the IPCC Guidelines.

Emission factor	Default mean value	Min (or lower 95%CI)	Max (or upper 95%CI)	PDF
EF_1 for N additions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon [kg N_2O–N (kg N)$^{-1}$]	0.01	0.003	0.03	Lognormal
$EF1_{FR}$ for flooded rice fields [kg N_2O–N (kg N)$^{-1}$]	0.003	0	0.006	Lognormal
$EF2_{CG}$, Temp for temperate organic crop and grassland soils (kg N_2O–N ha^{-1})	8	2	24	Lognormal
$EF_{3PRP, CPP}$ for cattle (dairy, non-dairy and buffalo), poultry and pigs [kg N_2O–N (kg N)$^{-1}$]	0.02	0.007	0.06	Lognormal
$EF_{3PRP, SO}$ for sheep and 'other animals' [kg N_2O–N (kg N)$^{-1}$]	0.01	0.003	0.03	Lognormal
EF_4 [N volatilisation and re-deposition], kg N_2O–N (kg NH_3–N + NO_x–N volatilised)-1 22	0.01	0.002	0.05	Lognormal
EF_5 [leaching/runoff], kg N_2O–N (kg N leaching/runoff) $^{-1}$	0.0075	0.0005	0.025	Lognormal
$Frac_{GASF}$ [Volatilisation from synthetic fertiliser], (kg NH_3–N + NO_x–N) (kg N applied) $^{-1}$	0.1	0.03	0.3	Lognormal
$Frac_{GASM}$ [Volatilisation from all organic N fertilisers applied , and dung and urine deposited by grazing animals], (kg NH_3–N + NOx–N) (kg N applied or deposited)$^{-1}$	0.2	0.05	0.5	Lognormal
$Frac_{LEACH-(H)}$ [N losses by leaching/runoff for regions where Σ(rain in rainy season) - Σ (PE in same period) > soil water holding capacity, OR where irrigation (except drip irrigation) is employed], kg N (kg N additions or deposition by grazing animals)$^{-1}$	0.3	0.1	0.8	Lognormal

Estimate uncertainty in greenhouse gas emissions using Monte Carlo simulation software

The estimate of uncertainty in GHG emissions can be used for several different scenarios. In agricultural production, in particular, a large and very uncertain term is often GWP from N_2O. This can easily dominate the overall uncertainty. If the only approach taken is to consider the overall uncertainty of the production system up to the farm gate, thus including all uncertainties, those from N_2O may be so big that a measurable difference, e.g. from reducing fuel use, may not apparently have a significant effect. Different approaches are thus needed to address this:

If the estimation of uncertainty is to be used to compare production methods within an organisation then the uncertainties associated with primary data (alpha uncertainties) should be applied, but the secondary data (EF, GWP etc, i.e. beta uncertainties) should have the uncertainties set to zero (unless an exception applies as in agricultural production in disparate climatic zones (Table 153).

The reasoning is that the uncertainties for each factor in the secondary data are the same for each system. It is reasonable to assume that the emission of N_2O from x kg N applied to a UK soil will be the “same” as any other in the UK, in that the climate is generally similar, exactly the same model is used from IPCC and that the uncertainties are the same. This assumption could not be made if say comparing N use in the UK and Australia. Because the same model would probably not apply with such a different climate, it cannot be assumed that the uncertainties would be the same and thus the beta uncertainties would need to be retained in a comparison.

If the estimate of uncertainty is to be reported so that a product system can be compared across organisations the secondary data that would be common to the two organisations (that is from the same source) should have the uncertainties fixed at zero to allow a valid comparison to be made (these are Type 1 *beta* uncertainties). I

This approach thus focuses only on the measurement uncertainties associated with the primary data and those secondary data that are relevant and the significance of the difference between these is tested. Table 153 shows the Type 2 *beta* uncertainties that should be retained if the two systems are in different climatic regions (this table assumes one organisation is in NW Europe). Note however that if one system was lowland England and the comparator was upland Scotland then the climate-based, Type 2 *beta* uncertainties should be retained.

Table 153 Type 2 beta uncertainties that should be retained in a comparison between two locations, where one is always the UK.

Activity	**Other locations**			
	NW Europe	Other Europe	Temperate zones on other continents	Non-temperate zones on other continents
N leached (if IPCC)	N	N	N	N
N from housed livestock	N	N	N	Y
N from grazing livestock	N	Y	Y	Y
Enteric CH_4	N	N	N	Y
CH_4 from manure management	N	Y	N	Y

The estimation of uncertainty of any particular system will be carried out using Monte Carlo (MC) techniques – these enable a large number of simulations to be performed where the input parameters and emission factors are selected from the probability distributions defined and predictions of the GHG emissions made. This builds up a distribution of possible results. As long as enough simulations are carried out (we recommend at least 10,000) this distribution can be assumed to be a Normal distribution whatever the original input distributions. This distribution can therefore be characterised by its mean (*m*) and coefficient of variation (*CV*). The CV is defined as the standard deviation divided by the mean expressed as a percentage. In @Risk, *m* and *CV* are obtained from the Riskmean() function and RiskStdDev()/Riskmean() respectively.

For a single GHG emission estimate of a system reported by an organisation using PAS 2050, three CVs should be calculated and reported. The three CVs are:

- with alpha uncertainties only
- with alpha and type 1 beta uncertainties
- and alpha, type 1 beta and type 2 beta uncertainties.

This will enable later analyses to be compared with these results.

For two systems within an organisation it is possible to calculate the **difference** between the values for each simulated set as the individual estimates for each simulation will be available. In this case, the distribution generated by the MC software will be the distribution of the differences which can also be characterised by a mean and coefficient of variation.

4.7 Procedure to test the significance of differences

Once the uncertainties have been estimated it is important to use the correct statistics to compare the distributions or assess if the distribution of differences is significantly different to zero.

For two systems (A and B) from different organisations (in which each have not had access to the original data), to determine whether the two GHG emission estimates are significantly different calculate z using Equation 1.

$$z = \frac{100 \times |m_A - m_B|}{\sqrt{CV_A^2 \times m_A^2 + CV_B^2 \times m_B^2}} \qquad \text{Equation 1}$$

Here, m_A and m_B, are the mean values and CV_A and CV_B are the coefficients of variation for the two systems respectively. If the value of z is greater than $z_{\alpha/2}$ then the two means are significantly different at the 100(1-α) confidence level. α is the probability level for applying the test expressed as a decimal, e.g. 0.05 for a 95% test. The reason α/2 is used is that this is a two-sided test as the alternative hypothesis to equal mean values is non-equal mean values i.e. m_A less than m_B or m_A greater than m_B. It is important that the CV's for each system have been determined with the same factors fixed.

For two systems (A and B) within an organisation for which estimates of the mean and CV for the distribution of differences have been calculated, to test the hypothesis that this mean value is significantly different to zero calculate

$$z = \frac{100}{|CV_{A-B}|} \qquad \text{Equation 2}$$

If the value of z is greater than $z_{\alpha/2}$ then the mean difference in the systems can be considered significantly different to zero with a confidence of 100(1-α)%. This is also a two sided test as we are concerned with whether the mean difference is greater or less than zero.

The standard normal variate (z) for a specified probability can be found in Excel by using the NORMSINV function with the probability you require as the parameter. For example in Equation 1 the z value for α=0.05 is returned from NORMSINV(1-0.05/2) and is 1.96. So any z value from equation 2 or 3 which is greater than 1.96 will be significant at the 95% confidence level.

4.8 Examples applying this framework

A simple example is shown below to illustrate the principles.

The example compares two hypothetical arable systems (A & B) producing wheat. All the machinery activity has been lumped together and has a relatively low uncertainty of use rates (primary) and emission factors and GWP factors combined (secondary). The fertiliser part relates to N fertilisation, which has a relatively low uncertainty of use rate (primary) but very high combined emission and GWP factors (secondary). The basic systems are summarised below (Table 154) and we wish to compare them. They had the same fertiliser inputs and crop yields, but different machinery inputs. Two variations were also considered in System B with a reduced yield (from reducing machinery input) and then further reduction in machinery input, but without a further reduction in yield. The two systems were analysed separately so that the only statistics available for comparison were the mean and CVs for each system.

When including all uncertainties in the simulations, the comparison of the two systems showed that no significant difference between the estimates of GWP was detectable (Table 155). This is established using Equation. 1 as the only statistics available were the mean and CV   There was also no apparent difference with either system. Assuming the systems were in the same general location, the beta uncertainties were set to zero with both simulations and the results can be compared again (Table 156). This time, the difference was significant at the 95% level between the two original systems. Reducing the yield to 9.5 from 10 t/ha in system B made the difference from A non-significant, while reducing the machinery input further without loss of yield in system B made the systems significantly different again at the 95% level.

Table 154   Two simplified wheat production systems for uncertainty analysis.

	Primary units	**CV %**	**Secondary (EF & GWP)**	**CV %**	**GWP, kg CO_2e/ unit**
System A					
Machinery (Fuel) per ha	10	2.5%	1.2	5%	12
Fertilisation (N_2O) per ha	100	2.5%	0.5	30%	50
Total per unit area					62
Yield, t/ha	10.0	0			
GWP per t					**6.20**
System B					
Machinery (Fuel) per ha	7	2.5%	1.2	5%	8
Fertilisation (N_2O) per ha	100	2.5%	0.5	30%	50
Total per unit area					58
Yield, t/ha	10.0	0			
GWP per t					**5.84**

Table 155 Comparison of two wheat systems with beta uncertainties applied.

System	A	B	A	B	A	B
Machinery (Fuel) per ha	10	7	10	7	10	5
Fertilisation (N_2O) per ha	100	100	100	100	100	100
Yield	10.0	10.0	10.0	9.5	10.0	9.5
GWP per t (mean of simulated distribution)	6.2	5.8	6.2	6.1	6.2	5.9
CV of simulated distribution	28%	30%	28%	30%	28%	32%
Z	0.14		0.02		0.15	
Significantly different at 95% level?	N		N		N	

Table 156 Comparison of two wheat systems with beta uncertainties set to zero.

System	A	B	A	B	A	B
Machinery (Fuel) per ha	10	7	10	7	10	5
Fertilisation (N_2O) per ha	100	100	100	100	100	100
Yield	10.0	10.0	10.0	9.5	10.0	9.5
GWP per t (mean of simulated distribution)	6.2	5.8	6.2	6.1	6.2	5.9
CV of simulated distribution	2.1%	2.2%	2.1%	2.2%	2.1%	2.3%
Z	1.99		0.29		1.99	
Significantly different at 95% level?	Y		N		Y	

It cannot be stressed too highly, that removing all the beta uncertainties will not apply in all cases, e.g. different countries.

4.9 Processing Allocation and Sub metering

The problem of energy use without sub-metering was considered for a hypothetical food production factory. It was assumed that there were 10 main energy using processes, in which the power use per unit process varied from 1 to 0.1 in steps of 0.1. It was also assumed that 100 products were procured in the same factory. Energy use for each food item could vary from 1 to 0.2 in steps of 0.2 (the turndown ratio). This could occur if the same process was applied at the same energy rate (e.g. x kW/kg), but the time varied in steps of 0.2 from 0.2 to 1.

The 10 main energy using processes were:

1. Washing
2. Chopping

3. Mixing
4. Boiling
5. Microwave heating
6. Oven heating
7. Chilling to 4°C
8. Chilling to -25°C
9. Packing
10. Heating, lighting and ventilation

This was analysed by simulation modelling as follows. For each of 100 product lines, the energy per unit process was allocated randomly and the sum for each functional unit (FU) was calculated. The number of product lines was also allocated randomly. For each iteration, the sum of energy was calculated and the mean energy per FU together with the difference (error) between the actual individual FU energy and the mean that would be calculated as if there was no knowledge at all of the inner workings of the factory. The average root mean squared error was calculated and plotted. 1000 iterations were made, although little would differ after 50.

The results show that the error increases along with the turndown ratio, which is not surprising. It also tends towards an asymptote, which is probably below 25% (Figure 7). So, it is reasonable to speculate that the worst case error of no attempt at proper allocation is about 25%.

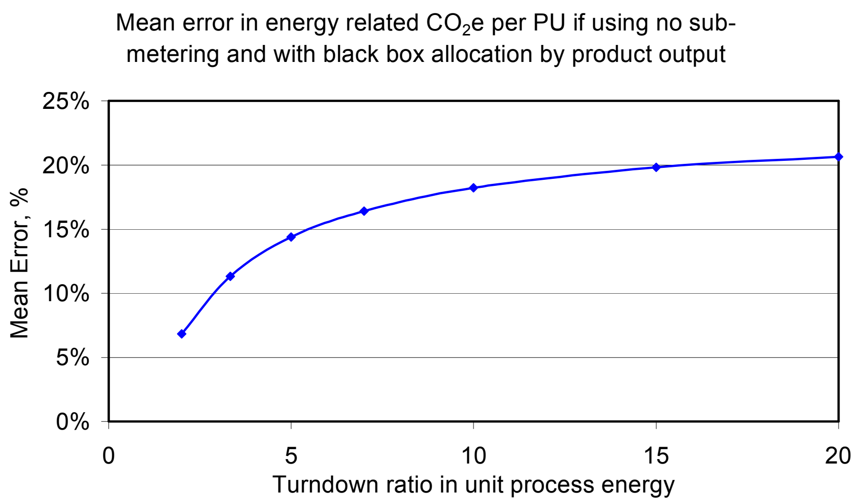

Figure 7 Errors simulated in factory with no sub-metering.

4.10 Material contribution

PAS 2050 has this text in 3.33 and 6.3 (combined for convenience).

A materiality threshold of 1% has been established to ensure that very minor sources of life cycle GHG emissions do not require the same treatment as more significant sources. A preliminary assessment of the sources of GHG emissions in the life cycle of a product may be undertaken using secondary data or through an EEIO approach. This preliminary assessment could provide an overview of the key sources of GHG emissions within the life cycle of the product and identify major contributors to the GHG emissions assessment.

This was examined using the beef cottage pie as an example together with limited access to proxy data. The pie has 23 food ingredients (including water) together with two energy sources, three types of packaging, process water and some wastes. Campden-BRI applied PAS 2050 to this product and had to scale up the material contribution of some food ingredients for which no GWP data were available and were physically small in scale. These gaps were plugged with expert judgment and other sources of proxy data to produce the "true" total.

The proxy data was assembled from PAS 2050 assessments done by ADAS in this project together with other LCA data from other Defra-funded work and the literature.

The set was not exhaustive, but covered a disparate range. The data were sorted in sets including, temperate crops, temperate fruits, meats, animal products, field vegetables, salads and tropical beverages (tea, coffee[1] and cocoa). It was assumed that spices (white pepper in this case) were the mean of the beverages and simple assumptions were made to convert raw ingredients like tomatoes into tomato purée. Some sets were also converted to averages to deal with unknowns, e.g. all meats, to allow proxy data to be used with different levels of detail. These were:

Level 1. All data items available to the analyst

Level 2. Grouped into semi-targeted means, e.g. all beef, all field vegetables, all salads, the mean of all proxies for use with unknowns

Level 3. More widespread use of the mean of all proxies and a mean of all plant product proxies and a mean of all meats (together with the simplifying assumption that a meat derivative, like stock, would have the same values as the meat itself).

The data reflected the differing degrees with which data are available and the sub-divisions that are possible. Data from three studies were used and included prime suckler beef, dairy cull beef and Brazilian prime beef. Potatoes included UK, Israeli, early and maincrop.

The data were used as follows. The materiality of each ingredient was tested using proxy data, as would happen with a preliminary assessment. Those falling below the 1% materiality threshold were excluded and the recipe scaled up from the remaining ingredients. The energy and packaging inputs were assumed to be well known and constant. Where several choices were "available" to analysts, a choice was made using randomisation. This was repeated 100 times and the mean calculated. The total GWP per FU was then calculated using the materiality rule to exclude minor ingredients, but using the actual "true" values of GWP per unit FU (rather than those from the simulated screening). The resulting estimates were then scaled up by mass in order to obtain the best estimated and these were then compared with the "true"

[1] The coffee value has been revised since this work was done, but the updated value was not used here. This does not influence the conclusions of the work on analysis of uncertainties.

value. This was repeated with the contribution of packaging and direct energy being scaled by factors of 0 to 1 in order to change the weighting of the food ingredients.

4.10.1 Results

Two ingredients clearly dominated – beef and potatoes. Although varying with the proxy level, few other ingredients rose above the 1% threshold. These typically included tomato purée, skimmed milk and buttermilk powder, but this meant that about 17 of the 23 ingredients were excluded. The importance of the two dominant ingredients in scaling up the results was thus large.

Results (Table 157) show that the errors caused by the 1% materiality rule were apparently, generally relatively small. It must be remembered that the 1% rule was used to screen out small components and then the coefficients that were actually used in the “true” case were applied to the remaining unscreened ingredients. As the proportion of GWP from the other processes fell, the estimate, not surprisingly, got worse. This approach gives an underestimate because the proportion of weight of potato (low GWP per unit weight) has a large effect because of its weight being scaled up to compensate for the weight of filtered-out ingredients.

Although the errors introduced by this approach were relatively small on average, the Level 1 approach was applied 100 times and the CV was about 30%. The level 1 data was analysed further to show how variable the outcome can be by calculating the proportion of estimates made with errors of >5% to >20% (Table 158). This analysis showed that the probability of the error in the final analysis being more that 5% was around 80% (depending on the level of other contributing processes). The probability of error decreased as the level of error increased to 20%.

Table 157 Effects of applying the 1% materiality rule to screen out individual ingredients in the beef cottage pie.

Contribution of other process to total GWP per FU.	"Screened" / "true" total GWP per FU		
	Proxy Level 1	Proxy Level 2	Proxy Level 3
0%	86%	93%	93%
8%	91%	94%	94%
17%	96%	94%	94%
25%	92%	95%	95%
33%	95%	101%	101%

Table 158 Errors when applying the level 1 approach.

Contribution of other process to total GWP per FU.	Proportion of results with errors above four thresholds			
	> 5%	> 10%	> 15%	> 20%
0%	90%	70%	55%	49%
8%	83%	67%	57%	50%
17%	85%	76%	62%	53%
25%	80%	67%	61%	54%
33%	73%	63%	55%	39%

Now, this is only one example and it was necessary to project an idea of the availability of data into the mindset of an unknown analyst, with an unknown ability to discriminate between data sources. What is demonstrates is that the materiality rule can clearly introduce additional error. Part of this will be a consequence of the range of proxy data that is available to analysts (the wider the better) and the skill and experience of any analyst in applying the PAS.

It may be that the materiality rule for products with so many ingredients may be better applied to functional groups, e.g. all vegetables (other than potatoes) grouped together. Furthermore, guidance about the applicability of the data would help considerably (e.g. ensuring that system boundaries are described, such as to farm gate or regional distribution centre (RDC), whether food processers are more likely to use prime suckler beef, cull cow or possibly imported Brazilian).

The ability to source proxy data that is suitable for use with PAS 2050 in this screening phase must be limited initially to LCA data that has been applied with different rules. As time proceeds, more data will become available that the process will be self-improving.

The data used in the analysis (Table 159) shows a wide range of values for raw ingredients. It must be stressed that it is not a definitive list, but a guide. Air freighting from Africa, for example, could add about 10 kg CO_2e/kg to a vegetable. Spices were assumed to be the mean of tea, coffee and cocoa (but without land use change).

Table 159 Grouped data used in the analysis of the beef cottage pie.

Type of ingredient	Mean GWP, kg CO_2e/kg	s.d.	CV	n
All plant products	2.0	2.6	130%	27
Temperate Fruit	1.9	3.0	163%	7
All Fruit	2.7	4.0	146%	4
Salad	2.5	2.0	81%	6
Veg (European)	0.58	0.4	65%	10
Cereals & Pulses	0.65	0.2	33%	2
"Spices"	6.7	2.3	34%	3
All plants & meat	3.6	6.0	165%	31
Meat *	15	12	76%	4
Beef	24	10	42%	10

* Mean of poultry, port, beef and lamb

4.11 Land use change

Land use change (LUC) can have major effects on GHG emissions from crops, especially if tropical rain forest is converted to cropland. PAS 2050 specifies a method to use, which is clear for some situations, but not for all. The uncertainties associated with LUC are also large. This section considers the effects if including LUC both on the uncertainty that is derived when applying formulae derived directly from the IPCC and when following PAS 2050. Two crops were selected to represent broad types: cocoa and soy, as examples of perennial and annual crops respectively.

It is first noted that the table on LUC in Annex E in PAS 2050 was taken from guidance on renewable fuel use and it does not define exactly what method was used and nor does it quote any uncertainty. It was clearly derived from *IPCC 2006 Guidelines for National Greenhouse Gas Inventories*, with particular reference to Chapter 5, Section 3.

Different possible methods of establishing what was used in the source for PAS 2050 were tried to illustrate the examples of LUC, because this situation arose with cocoa and Ghana is not listed. Thus, PAS 2050 instructs the analyst in Annex E, Note 3 as follows:

For emissions from land use change in countries not listed in this Annex, refer to IPCC Guidelines for National Greenhouse Gas Inventories (see Clause 2), with particular reference to Chapter 5, Section 3 of IPCC 2006 Guidelines for National Greenhouse Gas Inventories which provides details on how to apply the standard methodology to calculate the carbon lost when land is converted to cropland.

The assumptions made were as follows.

- Above ground biomass (AGB) is 310 (150-510) t dm/ha (IPCC 2006, Table 4.7) and C is 50% of dry matter (CDM).
- Assume dead organic matter (DOM) is 2.1 (1 – 3) t C/ha (IPCC 2006, Table 2.2)
- Soil C (SC) is between 44 and 66 t C/ha (IPCC table 2.3, assuming not volcanic at 130), error is 90%. Note that the IPCC error is defined as 2 * standard deviation / mean.

- The fate of cleared forest must vary depending on actual useful logging rates vs burning etc. We assumed no logging and that all combustion is converted only to CO_2.
- Assume all dead organic matter is burned or lost soon.
- Tillage could be plough based, reduced tillage or direct drilling. We assumed plough based was used to derive the values.

For a perennial forest crop like cocoa, the soil C loss could be small and replacement of above ground biomass could be reasonably large, although probably not returning to the equilibrium of virgin forest.

The cultivation changes are given by three factors for land use (F_{LU}), crop management (F_{MG}) and cultivation intensity (F_I) that are applied to the soil C density (SCD), which was assumed to be 55 t C/ha. The terms are all multiplied by the initial soil C stock to estimate the change in soil C stocks over 20 years. For soy in wet tropical area, these are given in Table 160.

Table 160 Soil C change factors used (IPCC 2006, Table 5).

Factor	Value	Error	Comment
F_{LU}	0.48	48%	
F_{MG}	1	N/A	Assume plough based tillage
F_I	0.92	14%	

So the worst case scenario for C loss over 20 years is given by:

(AGB * CDM) + DOM + (0.48 * 1 * 0.92) * SCD

This has numerical values of:

(310 * 50%) + 2.1 + (.48 * 1 * .92) * 55 = 181 t C ha^{-1}

or 9.1 t C ha^{-1} y^{-1} or 33.3 t CO_2e ha^{-1} y^{-1}.

Without soil C (55 t C/ha), which would be an approximation for no further soil change, this gives 28.8 CO_2e ha^{-1} y^{-1}.

Table E1 in PAS 2050 has forest to annual crops at 37 t CO_2e ha^{-1} y^{-1}. For perennial crops, Table E1 has 26 t CO_2e ha^{-1} y^{-1}. It is also possible that the PAS 2050 values included two C flux terms for perennial cropping in that a C accumulation term may have partly offset loss terms. Depending how this was approached, soil C losses could be set to zero and biomass accumulation could be included, depending on the years after initial forest clearance. The tropical rainforest plantation accumulation rate is given as 6 (5 to 8) t dm ha^{-1} y^{-1}or 3 t C ha^{-1} y^{-1}. For the sake of argument, we assume we have used a sufficiently similar procedure to that in PAS 2050.

We also included an arbitrary agricultural activity for either annual or perennial cropping with the GHG emissions set at 3 t CO_2e/ha to assess the effect of LUC on both the overall outcome and the uncertainties of the outcome.

Using these values and the associated errors, the uncertainty in LUC for conversion to arable soy was calculated (Table 161). These suggest an increase in order of magnitude in emission by including LUC. Not only that, but the uncertainties are also greatly increased. Increasing the biomass accumulation to 2 years decreases the mean loss to 14 t CO_2e ha^{-1} y^{-1}. Depending on the approach taken (and the realities of tropical forest crop cultivation), much of the original loss could be recovered through biomass accumulation.

Table 161 Effects of LUC on GHG emission from annual and perennial cropping in a wet tropical area (t CO_2e ha^{-1} y^{-1}).

LUC and agriculture	**PAS 2050**	**Mean**	**CV**	**IPCC Error (2 * sd / mean)**
Agriculture total per ha		**3.0**	15%	30%
All losses (1)	**37**	**36**	36%	73%
Losses without soil (2)		**32**	40%	81%
All losses and 1 year biomass accumulation (3)	**26**	**25**	55%	109%
Losses w/o soil plus biomass accumulation (4)		**21**	64%	129%

(1) as if annual cropping

(2-4) Possible interpretations of IPCC for calculating a change to perennial cropping in a cocoa plantation

The approaches used above may or may not be "correct" and may not be what was used in the values supplied in Table E1 of PAS 2050. The IPCC guidelines are complex documents and offer different tiers of detail. An inconsistent approach to interpretation will not help progress the application of PAS 2050. It may not be possible to deal with all aspects of LUC in the supporting documentation, but it could be made easier. It does not have to be done for all countries, but could be done for all the climatic regions covered by IPCC LUC, together with a reference to identify the climatic region in question.

4.12 Case studies on data from the related studies on apple juicing and the beef cottage pie

4.12.1 Case Studies on Apple Juice Production

This case study was based on data from ADAS on apple production, both intensive and extensive. Apple juice production involves two separate stages of apple production followed by the apple juice extraction (juicing) itself. The data from these two aspects were obtained independently, but were analysed in different scenarios that assumed that the analysts had different levels of knowledge of the apple production and juicing.

The actual juice production data was from Campden BRI including measurements (or estimates) of packaging, waste, water and processing energy. The energy was without sub-metering, although the base cases were analysed with the assumption that it was properly sub-metered and then sub-metering was analysed separately. The FU was 750 ml of bottled juice.

Scenarios investigated

1. Intensive vs. extensive apple production (without juicing)
    a. Both alpha and alpha plus beta uncertainties (types 1 and 2) included (as if both systems were in the same climatic region and analysed by *different organisations*)
    b. Both alpha and alpha plus beta uncertainties (types 1 and 2) included (as if both systems were in the same climatic region and analysed by *the same organisation*)
2. Production and juicing using intensively produced Cox's apples compared to production and juicing using apples from an alternative, extensive. It was assumed that this analysis was from the perspective of the organisation that analysed the juicing, while both the apple sources had been analysed by different organisations.
3. Juicing with intensive apple input compared to juicing with extensive apple input
    a. Alpha and beta uncertainties (as if both systems analysed separately in the same climatic region)
    b. Alpha uncertainties only (and systems analysed by different organisations
4. Juicing with a change to a higher proportion of renewable energy input
5. Juicing with different levels of uncertainty about sub-metering

Apple production

The majority of input data (primary data) and factors (secondary data e.g. emission factors) were assumed to be normally distributed with coefficients of variance as given in the Appendix (Section 4.14.2). The exceptions were N_2O emission factors, which were taken as being lognormally distributed, with the parameters in Table 162 .

Table 162 N_2O emission factors and uncertainties from IPPC (2006) used with apple production.

Emission Factor	**Mean**	**Coefficient of Variation**
EF_1	0.01	0.6
EF_4	0.01	0.8
EF_5	0.0075	0.89
$Frac_{LEACH}$	0.3	0.6
$Frac_{GASF}$	0.1	0.6

For example, EF_1 would have a probability distribution function as shown in Figure 8. The blue line shows the theoretical distribution based on the input parameters above, while the red histogram shows the distribution of simulated values.

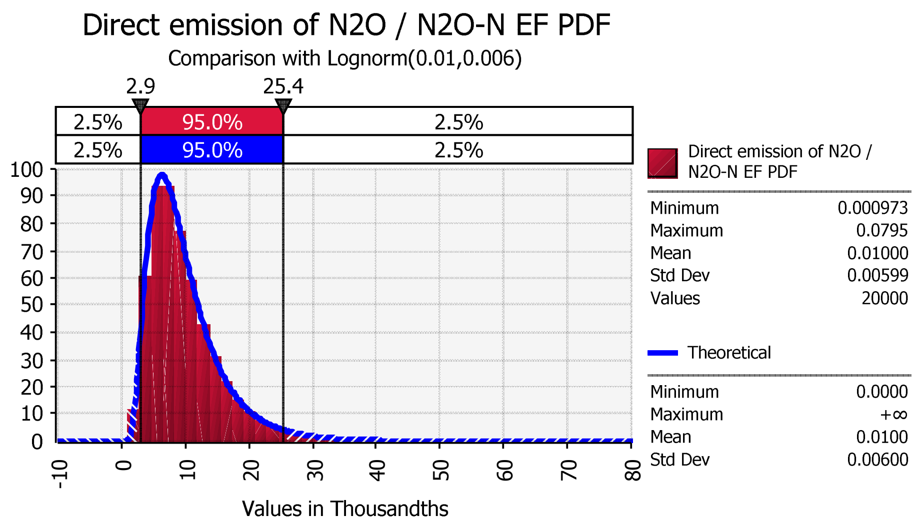

Figure 8 Example of lognormal distribution for EF1 produced by @*Risk*., which automatically generates its own captions.

CO_2 emissions for production, transportation, storage and transfer of pesticides were taken from Lal (2004). In this case, there were assigned lognormal distributions, because of the large range of values (Table 163).

Table 163 Estimates of carbon emission for production, transportation, storage and transfer of agricultural chemicals.

	Equivalent carbon emission (kg CE/kg)	
(B) Pesticides	**Range**	**Mean ± S.D.**
Herbicides	1.7 – 12.6	6.3 ± 2.7
Insecticides	1.2 – 8.1	5.1 ± 3.0
Fungicides	1.2 – 8.0	3.9 ± 2.2

Scenario 1: Comparing intensive and extensive apple production.

The uncertainties for intensive and extensive apple production systems were calculated using the method described in the Appendix (Section 4.14.2) with the option of including the beta uncertainties applied (Table 164).

Table 164 Results of simulations comparing apple production methods under scenarios 1a and 1b. Alpha and beta uncertainties were both included in 1a, while only alpha uncertainties were included in 1b.

Total kg CO_2e/t	Mean	Coefficient of Variation
Extensive (alpha + beta)	91.2	12.1%
Extensive (alpha only)	91.2	11.6%
Intensive (alpha + beta)	66.8	10.9%
Intensive (alpha only)	66.8	9.4%
Difference (ext-int) between extensive & intensive (alpha + beta)	24.5	54.0%
Difference (ext-int) between extensive & intensive (alpha only)	24.45	50.0%

Scenario 1a assumed the uncertainty analysis has been carried out by different organisations both of which generated two estimates of uncertainty, i.e. the alpha uncertainties associated with measurement errors and the beta uncertainties associated with EF and GWP factor errors.

Production methods can be compared using step 3a. That is two systems A and B are considered significantly different (in terms of GHG emissions) if

$z = \frac{100 \times |m_A - m_B|}{\sqrt{CV_A^2 \times m_A^2 + CV_B^2 \times m_B^2}}$ is greater then $z_{\alpha/2}$, where m_A and m_B, are the means and CV_A and CV_B are the coefficients of variation for the two systems respectively and $z_{\alpha/2}$ is the standard Normal variate such that the area under the standard normal probability distribution to the left of z is (1-α/2), with the results in Table 165.

Table 165 Statistical differences between extensive and intensive apple production under scenario 1. Different organisations are assumed to have conducted the uncertainty analyses. $z_{\alpha/2}$ = 95%

Systems analysed separately	Difference in means	z	Significance of difference with 95% confidence
Extensive-intensive (including alpha + beta uncertainties)	24.4	1.85	N
Extensive-intensive (including alpha uncertainties only)	24.4	1.98	Y

Therefore, if alpha and beta uncertainties are used, $z < 1.96$ ($z_{\alpha/2}$ with $\alpha=0.05$) and so the amounts of GHG emitted from the production systems are not significantly different at the 95% confidence level (Figure 9). However if only alpha uncertainties are included, $z > 1.96$ and thus the intensive apple production system produces significantly lower GHG emissions per kg than the extensive system at the 95% confidence level (Figure 10).

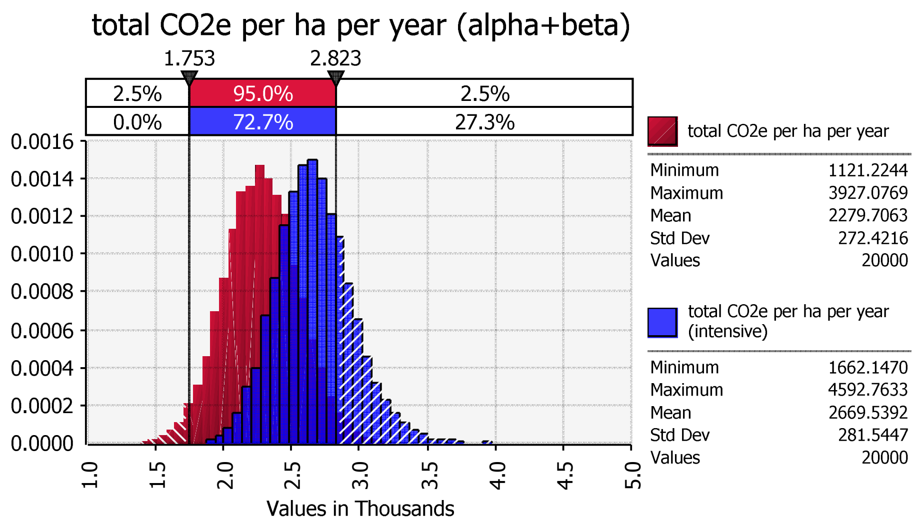

Figure 9 Simulation of the distribution of extensive and intensive apple production using both alpha and beta uncertainties.

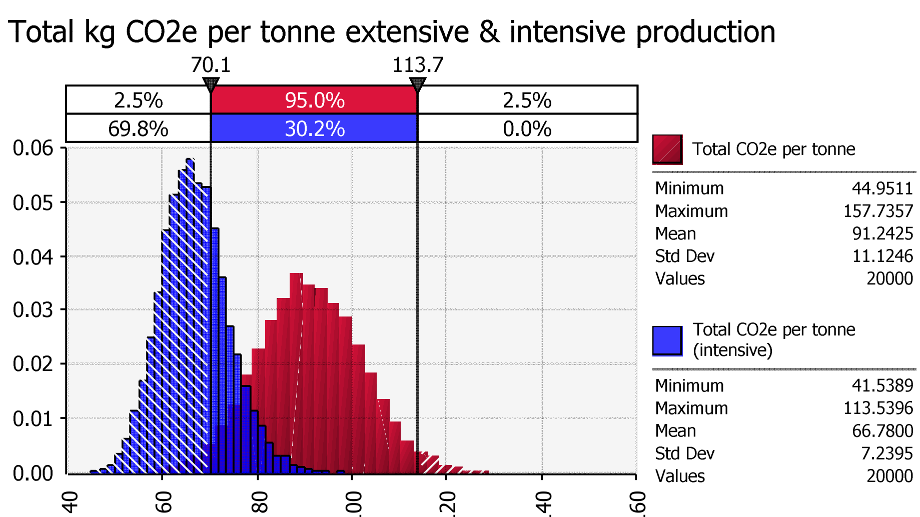

Figure 10 Simulation of the distribution of extensive and intensive apple production using only alpha uncertainties.

Scenario 1b assumed the uncertainty analysis for both systems was carried out within one organisation. The production methods can be compared using step 3a (as data come from the same organisation) and a probability distribution of the difference in means could be generated. That is, two systems A and B are considered significantly different if $z = \frac{100}{|CV_{A-B}|}$ is greater than $z_{\alpha/2}$, where CV_{A-B} is the CV of the distribution of differences and $z_{\alpha/2}$ is the standard normal variate such that the area under the standard normal probability distribution to the left of z is (1-α/2).

In this case, very similar results are produced to those where we assumed the systems were analysed by different organisations so we only had the statistics of the probability distributions to use to compare the systems not the actual distributions. The only difference in this case is that we were able to compute a distribution of differences (Figure 11 and Figure 12). This gave a value of z was slightly larger (i.e. 2.00 rather than 1.98), because we had more detailed information on the comparison (Table 166).

Table 166 Statistical differences between extensive and intensive apple production as if analysed by the same organisation in which the Monte Carlo simulations were conducted simultaneously so that the statistical analysis was on the basis of comparing the uncertainty of the *difference* of means (Scenario 1b). $Z_{\alpha/2}$ = 95%

Systems analysed together	**Mean difference**	**Z**	**Significance of difference with 95% confidence**
Difference (alpha + beta)	24.4	1.85	N
Difference (alpha only)	24.4	2.00	Y

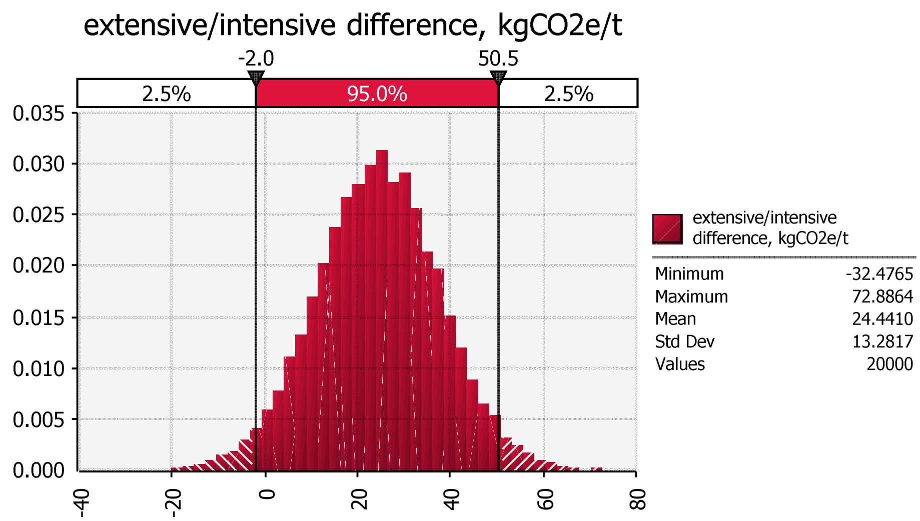

Figure 11 Simulation of the differences between extensive and intensive apple production including both alpha and beta uncertainties (as if both analysed by the same organisation under Scenario 1b).

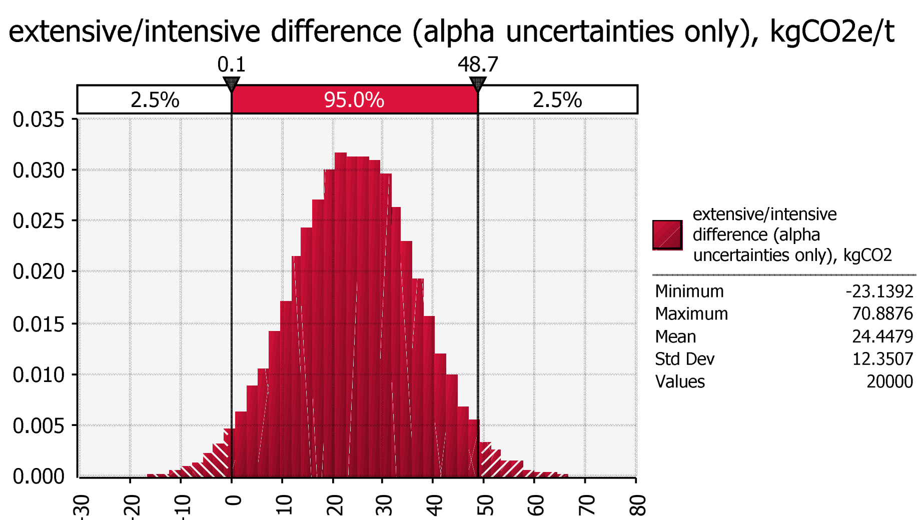

Figure 12 Simulation of the differences between extensive and intensive apple production including only alpha uncertainties (as if both analysed by the same organisation).

Scenario 2. Apple juice processing

Data was taken from the study by Campden BRI that was part of this project on the estimation of the GHG emissions for the manufacture of a 75cl bottle of apple juice made with intensively produced Cox's apples.

Campden BRI provided estimates of input values and measures of uncertainty such as 95% confidence intervals.

The majority of inputs were assigned normal distributions. Power of electric appliances were allocated lognormal probability distribution functions proportional to the variation in mains voltage, which is 240 V (+12%, -6%), with a CV of 6%. Because the standard deviation is small compared to the mean value, many of these distributions tend towards the normal distribution, but do have a slight skew and do force the input value to be positive

The mass of apples used was nominally 1.3 kg/FU, which is one 750 l bottle of apple juice. However depending on 'squashing performance' this could be up to 1.495 kg, and thus this quantity was assigned a triangular distribution (Figure 13).

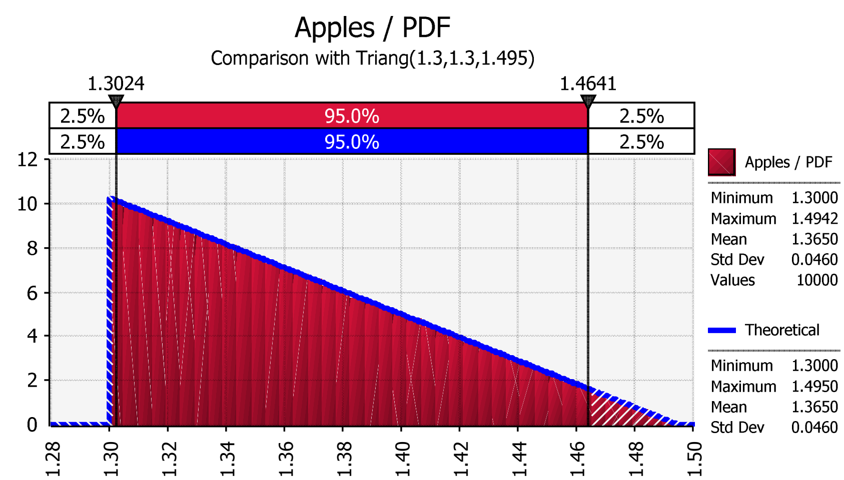

Figure 13 Example of triangular distribution used for raw input of apples, both theoretical and simulated values shown.

The GHG emission value for apples was taken as the intensive system result, with mean value 0.0667 kg CO_2/kg apples and CV of 10.9%.

The emissions from juicing were compared with those where the apples came from an unknown source, where the only known values were a mean of 0.1 kg CO_2e/kg apples input and CV of 10%, Table 167.

Table 167 Results of simulations for apple juice processing for a baseline case and data from an unknown source.

Total kg CO_2e/FU	Mean	Coefficient of Variation
Baseline case, juicing only	0.5196	3.33%
Unknown source, juicing only	0.5650	3.50%

To test for a significant difference between the baseline case and an external source of apples, z must be calculated: $z = \frac{100 \times |m_A - m_B|}{\sqrt{CV_A^2 \times m_A^2 + CV_B^2 \times m_B^2}}$

Z must be greater than $z_{\alpha/2}$ =1.96 to be significant. As Z was 1.727, the alternative, extensive source was not significantly different from the baseline case at the 95% confidence level.

Scenario 3. Juicing using intensively produced apples compared to juicing using extensively produced apples

This was examined from the perspective that the analyst had access to all data about the juicing process, while the alternative apple sources were compared both as if the full data were and were not available to the analyst.

3a Alpha and beta uncertainties included.

The results of the combined apple production and apple juicing from intensively and extensively produced apples were similar in magnitude (Table 168)

Table 168 Comparison of apple juice made from intensively and extensively produced apples with alpha + beta uncertainties included for the extensive apples, as applied under scenario 3a.

Production system	Mean GWP, kg / FU	CV
Intensive apple production	0.520	3.30%
Extensive apple production	0.553	3.74%

To test whether the difference in GHG emissions from apple juice produced using intensively and extensively grown apples is significant, z values should be calculated according to the Appendix (Section 4.14.2), such that if z = $\frac{100 \times |m_A - m_b|}{\sqrt{CV_A^2 \times m_A^2 + CV_B^2 \times m_B^2}}$

is greater that 1.96 then the systems can be considered significantly different at the 95% confidence level. The value of z was 1.244 and being less than $z_{a/2}$ = 1.96, the GHG emissions from production of juice using apples from extensive and intensive systems were not significantly different.

b. Alpha uncertainties only

If only alpha uncertainties are included in apple production, the CVs are reduced slightly (Table 169). Despite this, Z was 1.279 and again there was no significant difference in GHG emissions between juice from the two apple production systems even though all beta uncertainties from apple production were set to zero.

Table 169 Comparison of apple juice made from intensively and extensively produced apples (only alpha uncertainties included for the apple production, as applied under scenario 3b).

Production system	Mean GWP, kg / FU	Coefficient of Variation
Intensive input, total CO2/FU (alpha only)	0.520	3.15%
Extensive input, total CO2/FU (alpha only)	0.553	3.68%

Scenario 4 Juicing with a change to a higher proportion of renewable energy input.

The alternative energy sources were wind and hydro generated electricity. Different levels were tested with wind. This was applied to the juicing stage only, not to the apple production itself. Using all renewable energy significantly reduced the emissions significantly (Table 170), but inclusion of wind energy at 50% of the total electricity mix was not significantly different. The transition to a significant differences appear to be a little under 75%, given that values for Z was 2.00 and significance would apply at Z = 1.96.

Table 170 Effects of changing electricity source when juicing on overall GWP of 1 FU. $Z_{\alpha/2}$ = 1.96.

Electricity type	EF, kg CO_2e /kWh	Mean	Standard Deviation	Coefficient of Variation	z (compared with current)
Current mix	0.537	0.5200	0.0163	3.14%	
25% wind	0.404	0.5040	0.0161	3.19%	0.66
50% wind	0.272	0.4894	0.0161	3.29%	1.32
75% wind	0.139	0.4742	0.0157	3.31%	2.00
100% wind	0.00666	0.4591	0.0158	3.43%	2.67
HEP	0.024	0.4611	0.0157	3.40%	2.58

Scenario 5. Juicing with different levels of uncertainty about sub-metering

In this scenario, an increasing error term was applied to electricity use to allow for the associated error with estimated power use without sub-metering. The results (Table 171) showed no significant effects between no sub-metering and with increasingly uncertain sub-metering. However the overall uncertainty of the analysis increased as indicated by the CV. Part of this was because the mean values were not changed.

Table 171 Effects of applying an extra uncertainty factor to allow for errors in sub-metering during apple juicing. $Z_{\alpha/2}$ = 1.96, so the effects were not statistically significant.

Familiarity with circumstances	Uncertainty of sub-metering (CV)	Mean	Standard Deviation	Coefficient of Variation	z (compared with no sub-metering)
No sub metering	0	0.5196	0.01634	3.14%	
Very familiar	5%	0.5196	0.01663	3.20%	0.0003
Moderately familiar	15%	0.5196	0.01869	3.60%	0.0010
Unfamiliar	25%	0.5196	0.02247	4.33%	0.0005

4.12.2 Beef cottage pie study

The method was applied to the beef cottage pie to consider whether the change in beef sourcing was significant. It had been assumed by CBRI that prime suckler beef would be used, because it was an up-market product. This was compared with cull cow suckler beef and the proportion of beef was varied. The case was dominated by beef, which represented about 65% of the total GWP of the product unit (FU), which contained 400 g cooked ingredients, while being only 7% of the ingredients by weight. The beef characteristics are shown below (Table 172). Because the only changes being investigated relates to the source of beef or the amount, the beta uncertainties of the other ingredients and processing energy could be set to zero as these were assumed not to be affected. If the recipe was changed extensively and say the energy for cooking was altered, then the cooking energy terms would need to include the beta uncertainties.

Table 172 GWP per kg of the two beef sources.

	Alpha Uncertainties Only		Alpha and Beta Uncertainties	
	Prime suckler	Cull Cow	Prime suckler	Cull Cow
Mean	30.6	7.2	30.6	7.2
CV	5.0%	7.0%	9.2%	9.1%

Table 173 Ingredients of the beef cottage pie, GWP per item and the assumed uncertainties. Note that the beta uncertainties were set to zero in these cases, except for the minced beef, which was varied.

	g material / FU	CV for quantities (i.e. Alpha)	g CO_2e / g material	gCO_2e / FU
Water	67.4	1%	0.00029	0.019
Minced Beef	40.9	3%	30.6	1251
Leeks	14.5	3%	0.20	2.9
Carrot	14.5	3%	0.34	4.9
Onion	7.8	3%	0.50	3.9
Celery	5.0	3%	0.50	2.5
Chicken Stock	1.6	3%	0.091	0.14
Wine Red	0.5	3%	2.60	1.2
Beef Juices	4.5	3%	0.77	3.4
Starch	2.5	3%	1.66	4.2
Flour White	1.7	3%	0.69	1.2
Tomato Paste	1.4	3%	18.0	25.3
Salt - Fine Sea	0.8	3%	0.25	0.21
Sugar Syrup Caramel	0.7	3%	0.43	0.29
Oil - Rapeseed	0.5	3%	3.63	1.7
Beef Stock	0.4	3%	0.77	0.34

	g material / FU	CV for quantities (i.e. Alpha)	g CO_2e / g material	gCO_2e / FU
Garlic Puree	0.3	3%	0.88	0.29
Horseradish Puree	0.1	3%	0.88	0.12
Ground White Pepper	0.1	3%	6.74	0.45
Potato	370	3%	0.15	56.8
Skimmed Milk	21.0	3%	1.30	27.3
Buttermilk Powder	10.5	3%	7.15	75.1
Pure Dried Vacuum Salt	0.3	3%	0.25	0.09
Pepper, white	0.1	3%	6.74	0.55
Aluminium tray	27	0%	9.80	7.9
Carton box	7.7	0%	1.03	103
*RM and A packaging	60	0%	1.72	2.4
Water	8408	1%	0.00029	3.2
Transport				0.02
Processing energy		1%		0.4
Total per FU				1848

Changing the beef source to cull cow significantly lowered the GWP of the FU, whether the beta uncertainties for the beef were included or not (Table 174).

Table 174 GWP of cottage pie with two sources of beef (kg CO_2e/FU).

	Alpha only for beef		Alpha and Beta for beef	
Beef Source	Prime suckler	Cull Cow	Prime suckler	Cull Cow
Mean GWP	1.85	0.89	1.85	0.89
sd	0.071	0.022	0.12	0.025
CV	3.8%	2.5%	6.5%	2.9%
Z	12.8		8.1	
Significant at 95% level?	Y		Y`	

Reducing the amount of beef also reduced the GWP of the pie. In this case, the weight of beef was replaced by increasing the weight of potato. The amount of beef, however, had to be reduced to 75% of the original weight before the change became significant, i.e. Z was 2.09 and thus exceed $Z_{\alpha/2}$ = 1.96. (Table 175).

Table 175 Effects of reducing weight of prime suckler beef and replacing it with potato. $Z_{\alpha/2}$ = 1.96.

Beef quantity	100%	90%	80%	75%
Mean GWP	1.85	1.72	1.60	1.54
sd	0.12	0.11	0.095	0.088
CV	6.5%	6.3%	5.9%	5.8%
Z		0.76	1.62	2.09
Significant at 95% level?		N	N	Y

4.13 Discussion

The outcomes of this investigation have been to provide a method that users can apply to estimate the uncertainties when using PAS 2050 and to assess some case studies when using the framework. The framework supplies the basis for comparing results of analyses in a range of circumstances in which differing levels of knowledge are available. Numerical guidance is also provided for values of uncertainty to apply and use. These guidelines are based on the experience of the project team and could well be updated, especially when more assessments are made using the PAS.

Great care is needed when considering the comparisons of products with different levels of information available. The choices required must be made with due diligence.

The approach taken of separating the alpha and beta uncertainties has great power, especially the consideration of N_2O from field crops. It demonstrates that improvements can be made, despite the existence of high uncertainties from N_2O. This was of considerable concern to some representatives of the agricultural industry before the PAS became published.

4.14 Appendix to Section 4

4.14.1 Estimates of uncertainties that can be used for all input parameters and factors when measured data are not available

Error here is nominally a CoV per estimate

1. Direct energy recording
    a. Electricity meter reading 1%
    b. Gas meter reading 1%
    c. Gas calorific value 1%
    d. Diesel pumped supply readings 1%
    e. Petrol pumped supply readings 1%
    f. LPG delivery or pump purchase 1%
2. Combustion emissions per unit energy
    a. Electricity, mains 5%
    b. Gas, mains 1%
    c. Diesel 2%
    d. Petrol 1%
    e. LPG 1%
3. Transport
    a. Distances 2%
    b. Fuel use per t-km or km (if std value) 10%
    c. Fuel use per unit activity if from vehicle refuelling records and odometer 1%
4. Weights and volumes
    a. Weighbridge (e.g. grain), commercial 2.5%
    b. Weighbridge, government 1%
    c. Animal liveweight (on farm), 5%
    d. Animal deadweight, from weighing 2%
    e. Animal deadweight, if estimated from liveweight 5%
    f. Fertiliser as delivered, 1%
    g. Lime as delivered 2%

h. Pesticide as delivered, 1%
i. Weight from on-combine recording, 5%
j. Solid manure by estimation, 25%
k. Weight of heterogeneous material from bulk volume, e.g. compost, trimmings 25%
l. Weight of homogeneous material from bulk volume, e.g. grain 10%
m. Weight of wastes taken away by skip or container load and paid for by the load, not individual weight, 25%
n. Liquid manure from tank of known cross section, 5%
o. Liquid manure from lagoon of irregular cross section, 20%
p. Fertiliser application rate per ha, 2%
q. Water meter, 1%
r. Unmetered irrigation water use per ha, 20%
s. Volume of milk collected by wholesaler, 1%
t. Concentration of N in solid manure, 35%
u. Concentration of N in liquid manure, 15%

5. Use of reference data
    a. Fuel use per unit area, e.g. ploughing, combining instead of actual, 20%
    b. Refrigeration energy per unit time-volume, 20%
    c. Refrigerant loss per annum, 20%
    d. Waste arisings, 25%
    e. Fertiliser application rate, 10%
    f. Pesticide application rate, 10%
    g. Another crop that has a value derived from PAS 2050 or LCA, but without reported uncertainty, 10%
    h. Another animal product that has a value derived from PAS 2050 or LCA, but without reported uncertainty, 15%
    i. Another non-biological product that has a value derived from PAS 2050 or LCA, but without reported uncertainty, 10%

6. Allocation
    a. Economic allocation, slow price changes 5%
    b. Economic allocation, volatile price changes 30%
    c. Allocation of energy partitioning in say factory or farm with no-sub-metering
        i. Very familiar with circumstances, 5%
        ii. Moderately familiar with circumstances, 15%
        iii. Unfamiliar with circumstances, 25%
7. Expert judgment (where not covered elsewhere, .e.g. estimating a food ingredient)
    a. Very familiar with circumstances, 5%
    b. Moderately familiar with circumstances, 15%
    c. Unfamiliar with circumstances, 25%

4.14.2 Procedure for the calculation of uncertainty of greenhouse gas emissions and comparison of systems of production

Definitions

An estimate of the GHG emissions is created using **input data** and **factors**:

- **Input data** (primary activity data) are values which can be measured or estimated from measurements. Typical examples are kWh of electricity consumed, fuel used, distance travelled or hours of use of a machine. The associated uncertainties are termed **alpha uncertainties**.

- **Factors** (secondary data) are values which are taken from a source such as an LCA database (e.g. kg CO2e per unit process) or IPCC guidelines (e.g. kg CO2e per unit N applied). They may come from simulation models or be rule-based or be a mixture of experimental data and modelling. The associated uncertainties are termed **beta uncertainties**.

- In some cases, expert judgment is used in the production of primary or secondary data, e.g. in allocating fuel used between several processes or indeed several factors (or their uncertainties) in the IPCC Guidelines. Expert judgment itself has some uncertainty.

- Expert judgement is also required in cases requiring economic allocation between co-products. For example, with rape oil and rape meal, the prices are rarely stable. In some cases, a price for a co-product at the point of division is not readily available, e.g. straw behind the combine is the point of division, but the usual prices refer to straw *after* it is baled. This also applies to whey in cheese-making where it may be dewatered or dried before sale.

The estimate of GHG emission is typically the sum of a set of primary and secondary factors multiplied together.

Procedure to calculate uncertainties

1. For each input data and factor define:

   - A mean or most likely value
   - A measure of variability, e.g.
     - A variance
     - A confidence interval
     - Maximum and minimum

2. Define a probability distribution for each input data and factor based on:

   - Measured data
   - Expert judgement
   - Tables given in main report.

3. Decide whether the estimation of uncertainty is to be: (a) used to compare production methods within an organisation or (b) reported so that a product can be compared across organisations:

3a. To compare two production methods within an organisation:

Input factors, which are model based such as emission factors should be fixed (i.e. both Type 1 and 2 beta uncertainties are set to zero), as these will be the same under both production systems. If the change in the production method involves sourcing ingredients from a different climatic region it may be necessary to include some type 2 beta uncertainties to ensure a valid comparison is made –

see Table 176 to identify the beta uncertainties that need to be included. Run Monte Carlo simulation software (e.g. using @Risk, Crystal Ball etc) to generate a probability distribution of differences in GHG emissions between two systems. Calculate the mean and coefficient of variation (CV) of this simulated distribution. CV = standard deviation divided by the mean and expressed as a percentage).

3b. To report an analysis so that a product can be compared with that from another organisation, we recommend that any organisation should report three uncertainties as follows.

- One in which all beta uncertainties are set to zero.
- One to use if comparing a system in the same climatic region. The type 1 beta uncertainties associated with the input factors, which are model based and should not vary within a climatic region, should be set to zero.
- One to be used if comparing a system in a different climatic region. All beta uncertainties (Types 1 and 2) should be included.

Table 176 Types of beta uncertainties that should be retained in a comparison between two locations, where one is always the UK.

Activity	**Other locations**			
	NW Europe	Other Europe	Temperate zones on other continents	Non-temperate zones on other continents
N leached (if IPCC)	N	N	N	N
N from housed livestock	N	N	N	Y
N from grazing livestock	N	Y	Y	Y
Enteric CH_4	N	N	N	Y
CH_4 from manure management	N	Y	N	Y

Run Monte Carlo simulation software (e.g. *@Risk, Crystal Ball*) to generate probability distributions for GHG emissions under both scenarios. The GHG emission should be expressed as a mean and two standard deviations.

It must be remembered that only factors with beta uncertainties may be fixed (i.e. model based ones such as emission factors), not alpha uncertainties, which are associated with measurement errors.

The recommended reporting can thus be summarised by Table 177

Table 177 Recommended reporting of GHG assessments and uncertainty using PAS 2050.

Uncertainties included	Application	Mean of simulations	Coefficient of variation
Alpha only	To allow comparison with data from the same organisation in the same climatic region		
Alpha and beta – same climatic region	To allow comparison with data from another organisation in same climatic region		
Alpha and beta – different climatic region	To allow comparison with data from another organisation in another climatic region		

Procedure to test the significance of differences.

1. Comparison of systems of production within an organisation

To test the hypothesis that the mean difference (m_{A-B}) is significantly different to zero calculate

$$z = \frac{100}{|CV_{A-B}|}$$

Where CV_{A-B} is the coefficient of variation (%) of the probability distribution of the differences. If the value of z is greater than $z_{\alpha/2}$ then the mean difference in the systems can be considered significantly different to zero with a confidence of 100(1-α)%. For example if z=1.5 then the difference between the two systems is not significantly different to zero at the 95% confidence level (as 1.5 is less than 1.96). Please not that in these calculations, the formulae are presented as though the numerical value of a CV of say 37.5% is 37.5.

NB if these are applied in *Excel*, and the CV value is put into cells as 37.5%, it will be erroneous by a factor of 100. Similarly, if calculated in an *Excel* cell as sd/m, it may be displayed as a percentage, but is still a decimal fraction.

2. To determine if the two GHG emission estimates are significantly different calculate

$$z = \frac{100 \times |m_A - m_B|}{\sqrt{CV_A^2 \times m_A^2 + CV_B^2 \times m_B^2}}$$

where m_A and m_B, are the means and CV_A and CV_B are the coefficients of variation (%) for the two systems A and B respectively. If the value of z is greater than $z_{\alpha/2,}$ the two means are significantly different at the 100(1-α) confidence level. For example, if a value of 2.56 is calculated for z then as this is greater than 1.96 this will demonstrate that the two systems are significantly different at the 95% confidence level.

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