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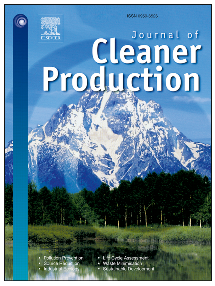

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Systematic review of greenhouse gas emissions for different fresh food categories

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Abstract
This paper presents the results of a systematic literature review of greenhouse gas emissions for different food categories from life cycle assessment (LCA) studies, to enable streamline calculations that could inform dietary choice. The motivation for completing the paper was the inadequate synthesis of food greenhouse gas emissions available in the public domain. The paper reviewed 369 published studies that provided 1,718 global warming potential (GWP) values for 168 varieties of fresh produce. A meta-analysis of the LCA studies was completed for the following categories: fresh vegetables (root vegetables, brassica, leaves and stems); fresh fruits, (pepo, hesperidium, true berries, pomes, aggregates fruits and drupes); staples (grains, legumes, nuts, seeds and rice); dairy (almond/coconut milk, soy milk, dairy milk, butter and cheese); non-ruminant livestock (chicken, fish, pork); and ruminant livestock (lamb and beef). The meta-analysis indicates a clear greenhouse gas hierarchy emerging across the food categories, with grains, fruit and vegetables having the lowest impact and meat from ruminants having the highest impact. The meta-analysis presents the median, mean, standard deviation, upper and lower quartile, minimum and maximum results for each food category. The resultant data enables streamline calculations of the global warming potential of human diets, and is illustrated by a short case study of an Australian family's weekly shop. The database is provided in the Appendix as a resource for practitioners. The paper concludes with recommendations for future LCA studies to focus upon with respect to content and approach.

1 Introduction
The consumption of food contributes to a significant proportion of a person's overall greenhouse gas impact (Dey et al., 2007), with agricultural production accounting for 19%–29% of global anthropogenic greenhouse gas emissions (Vermeulen et al., 2012). Consumers are also displaying 'a moderately high level of concern' for the sustainability with respect to food production (Grunert et al., 2014, p.187). Life cycle assessments (LCAs) of food

ingredients and products provide the primary means to understand a food's environmental impact, discussed in this paper with specific respect to a food's Global Warming Potential (GWP)[1]. While a substantial number of food LCA studies have been completed, comparing food impacts to enable decision making with confidence is difficult at present for four reasons.

First, it is often cited that LCA results should not be compared (Desjardins et al., 2012; Foster et al., 2006; McAuliffe et al., 2016; Röös et al., 2013) due to variation in methodology choices, functional units, as well as temporal and regional differences[2]. Second, no single comprehensive review was identified that adequately covers the breadth of fresh foods available to consumers and caterers. As Helle et al. (2013, p.12643) state 'data availability and quality remain primary obstacles in diet-level environmental impact assessment', while Pulkkinen et al. (2015) calls for the creation of a database that communicates data quality, uncertainty and variability to reliably differentiate between the GWP of food types. Previous studies have compiled LCA data to compare different foods (e.g. Audsley et al., 2009; Berners-Lee et al., 2012; Bradbear and Friel, 2011; de Vries and de Boer, 2010; Foster et al., 2006; Nijdam et al., 2012; Sonesson et al., 2010; Roy et al., 2009). While these are useful attempts, the identified studies are inadequate in the coverage of fresh foods available. Environmental Product Declarations (EPDs) attempt to inform consumers of the environmental impacts (carbon, water and ecological footprint) of specific foods, however they also fall short in breadth of items covered at present. The most comprehensive attempt at carbon footprint labelling was performed by Tesco (2012), however failed to label key categories such as fresh fish, pork, lamb or beef before finishing in 2012 due to the scale of the labelling scheme and a lack of participation from other retailers (Head et al., 2013). Third, studies that do compare results may often present singular figures. Peters et al. (2010) and Röös et al. (2011) argue that a range of impacts should be reported from LCA's to better represent the variety of environmental impacts, as opposed to a singular figure. Finally, there is a lack of synthesised open access LCA data in the public domain available to consumers to inform decision-making.

Therefore this paper presents a systematic literature review and meta-analysis of food LCA studies in the last 15 years to assess the GWP of fresh food. This paper aims to utilise existing GWP values from a variety of LCA studies to generate a database that enables the streamline accounting for individual meals, diets, catering organizations, or nations. The collation and characterisation of data on the GWP values for different food categories is the focus of this paper. The meta-analysis identifies areas where there is strong agreement in the GWP values, a short case study on the use of the GWP data to assess diets is provided in the discussion section, prior to recommendations being provided on how future food LCA studies could be undertaken to enable more direct comparisons.

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1. GWP values (represented as *kg CO_{2}.eq/kg* produce) was selected as an environmental indicator due to the global significance of climate change, and as a consistent metric reported in LCA studies. For example, Renouf and Fujita-Fimas (2013) identified that 92% of Australian food LCA's reported Greenhouse gas emissions. The Life Cycle Impact Assessment guidance flagship project of UNEP/SETAC suggest that the sensitivity of LCA results should be explored to metrics other than GWP, such as fine particulate matter emissions, land and water use, and biodiversity loss (Frischknecht et al., 2016). Using one indicator in GWP only is a limitation of the paper, expanding to include additional indicators is an area for further research.
2. These methodological differences are discussed later in the paper in section 4.1.

2 Method

2.1 Systematic review strategy

The systematic review was completed following the PRISMA Statement protocol to minimize the risk of bias, and increase scientific validity (Moher et al., 2009). The systematic literature search for food LCA studies was completed in February 2015 across three types of literature: peer reviewed scholarly journal papers; conference proceedings; and, EPDs (see Fig. 1). Searches for peer reviewed journals were completed in Sciencedirect using the key words 'LCA + food + CO2'. Conferences proceedings were reviewed from the international conference 'Life Cycle Assessment in the Agri-Food Sector' from 2010-2014. The EPD search was completed in Google using the key words 'environmental product declaration', carbon footprint and carbon label.

The initial studies reviewed identified additional studies for review by two mechanisms; first, scanning the document text and reference list for additional studies, and second, using the cited in function from Google scholar to identify relevant articles for review. Grey literature in the form of industry and government reports were identified through these two mechanisms. The inclusion of grey literature to avoid bias and ensure the systematic review is as thorough as possible is viewed as best practice (Blackhall, 2007). A limited number of targeted food searches were completed to identify foods that were absent. This was completed for almonds, cashews, peanuts, kangaroo, goat, turkey, ostrich, emu, rabbit, and quinoa.

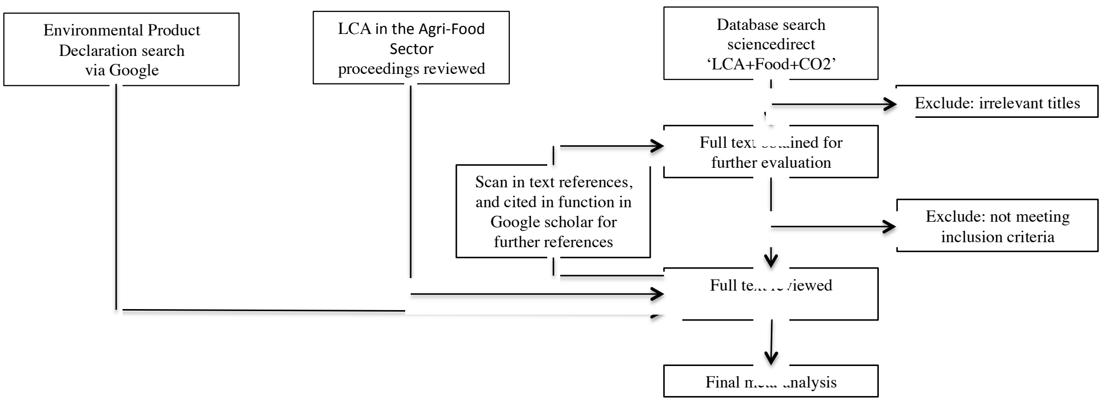

Figure 1 Systematic literature review process

Studies were included in the meta-analysis if they disclosed the LCA results in terms of $CO_{2\text{-}eq}$/mass unit for raw produce, and disclosed the system boundary, functional unit and location of production. Studies were excluded if results were only presented in alternative functional units such as eco-points, percentages, $kg\ CO_{2\text{-}eq}$/ha., live weight gain/year or $kg\ CO_{2\text{-}eq}$/protein. Studies were also excluded if they included cooking, air-freight or canning without disclosing the percentage that these activities accounted for as they significantly alter the results. For example fruit and vegetables studies that cited international airfreight added 9.5 to 10 $kg\ CO_{2\text{-}eq}/kg$ to Milà i Canals et al.'s (2008) study of vegetables and 11 to 12.5 $kg\ CO_{2\text{-}eq}/kg$ from Hofers (2009). Avoiding air freighted produce has been raised in previous studies and is not a focus of the paper (e.g Jungbluth et al., 2000).

2.2 Synthesizing results for comparison

GWP values from the reviewed studies were collated into a database under the following broad category headings: fresh fruits, vegetables and staples; dairy; non-ruminant livestock and ruminant livestock. In addition, data relating to the LCA method were collated including:

- Year of study
- Geographic location of study.
- Original system boundary
- LCA approach utilised (process based or economic input-output or hybrid LCA)
- Unique descriptors (e.g. species, feed type, farming methods etc.)

Each GWP value recorded was converted into a common functional unit and system boundary in kg $CO_{2\text{-}eq}$ /kg bone free meat (BFM) or produce, at the regional distribution centre (RDC).

2.2.1 Conversion of functional units to bone free meat

In LCA, the functional unit is the unit by which all environmental results are reported. The functional unit is typically based on the primary function that a product or service provides. Defining the functional unit for food can be challenging and as such, the functional units can vary between food studies. Functional units reviewed in this study for meat products included:

- Head of animals per year
- Kilogram Live Weight (LW)
- Kilogram Hot Standard Carcass Weight (HSCW)
- Kilogram Carcass Weight (CW)
- Kilogram edible meat from carcass or kg bone free meat (BFM)
- Kilogram of prime retail cut or chicken breast

To enable comparison, the GWP values for meat studies were converted to a common functional unit in *kg* $CO_{2\text{-}eq}$ */kg* BFM. A significant variation in results can occur depending on the functional unit, particularly for meats. For example, only 43% of a live weight (LW) pig is edible meat (Sonesson et al., 2010). Table 1 illustrates the conversion ratios identified in the literature that were utilised to enable the conversions.

Table 1 Conversion of alternate functional units to bone free meat (BFM)

	Beef	Sheep	Pork	Chicken	Fish
Ratio Hot Standard Carcass Weight: Carcass Weight	1:0.98[a]	1:0.98[a]	NA	NA	NA
Ratio Live Weight: Bone Free Meat	1:0.485[b]	1:0.43[c]	1:0.43[d]	1:0.54[d]	1:0.625[e]
Ratio Carcass Weight: Bone Free Meat	1:0.695[f]	1:0.66[c]	1:0.59[d]	1:0.77[d]	

Sources:
a) Average from Pazdiora et al. (2013)
b) Extrapolated from Desjardins et al. (2012)
c) Average from Wilson and Edwards (2008), Liu and Ockerman (2001), and Young and Gregory (2001)
d) From Sonesson et al. (2010)
e) From Food and Agriculture Organization, Fisheries and Aquaculture Department (FAO 2013)
f) From U.S Department of Agriculture (USDA1992)

2.2.2 Accounting for variation in system boundaries

The system boundary used in the food LCA studies also varied, such as:

- Farm to farm gate

- Farm to slaughterhouse
- Farm to regional distribution centre (RDC)
- Farm to point of sale (retail)
- Farm to cooked in home
- Farm to human consumption and excretion

To enable comparison, the GWP values were converted to the system boundary of the Regional Distribution Centre. The system boundaries were recorded in the database. The packaging and transport median figures from Table 2 were added to studies where the system boundary finished at the farm gate.

Table 2 Post farm gate emissions identified from a sample of studies

Life cycle stage post-farm gate	**Number of GWP values**	**Median** ***kg CO_2-eq/kg***	**Mean** ***kg CO_2-eq/kg***	**Stdev**	**Min** ***kg CO_2-eq/kg***	**Max** ***kg CO_2-eq/kg***
Processing meats [a, b, c, d]	5	0.59	0.66	0.14	0.54	0.87
Processing vegetables [d, e, f,]	15	0.06	0.07	0.04	0.01	0.13
Packaging [a, c, d,]	8	0.05	0.06	0.06	0.01	0.21
Transport to RDC [a, b, c, d, e, f,]	21	0.09	0.13	0.19	0.02	0.95
Retail [a, b, d, e,]	20	0.04	0.10	0.25	0.01	1.14

Sources:
a) Eady et al. (2011)
b) Ledgard et al. (2010)
c) Bengtsson and Seddo (2013)
d) Svanes (2008)
e) Yoshikawa et al. (2008)
f) Lantmännen (2010)

The LCA studies typically analysed farm inputs from chemicals and fertilisers; fuel and energy inputs from irrigation and machinery for cultivation, harvesting and processing; and transport and refrigeration to the regional distribution centre. Outputs included emissions released from fertilised soils, plants and animals in fields (see Fig. 2). Nurseries for horticulture, while important are presented outside the simplified system boundary, as Cerutti et al.'s (2014) review stated only 3/19 studies included this stage. Most food LCA's also exclude infrastructure and capital goods (Mungkung and Gheewala, 2007; Roma et al., 2015). Infrastructure and capital goods are also excluded within PAS 2050 (BSI, 2011) and Gabi's LCA software model for Agriculture (Deimling and Rehl, 2016), and presented outside the simplified system boundary.

Human consumption, including how consumers travel to shops, store food, cook, dispose of food and packaging, and excrete were outside the scope of the study, and were excluded from entries entered into the database[3]. Fruits and vegetables that were grown in a greenhouse were analysed in a separate greenhouse category.

[3] The authors acknowledge that consumption, and end-of-life management of food and packaging will alter results. Of particular note is the 30% of purchased food that is not eaten, with a potential causal relationship to packaging design (see for example Wikström et al. 2014). This remains outside the scope of the study.

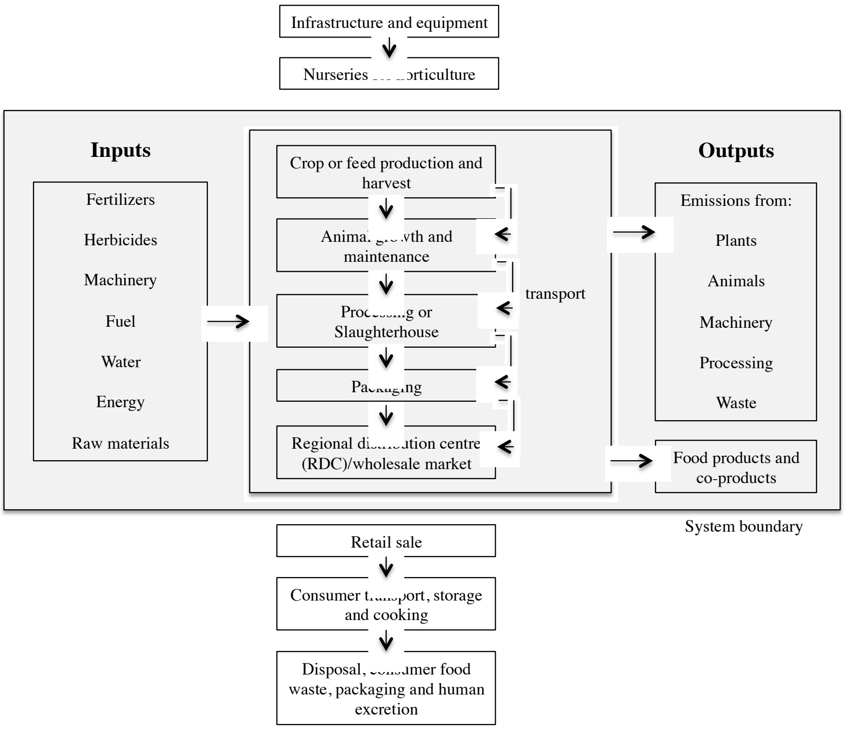

Figure 2 Simplified system boundary

2.3 Meta-analysis of data

The database (see Appendix) was analysed across each food category in Microsoft Excel to calculate statistics, including:

- Number of studies
- Number of GWP scenarios (one study may present multiple comparative results, all results were entered)
- Median, mean, standard deviation, upper and lower quartiles, minimum and maximum

Key statistics were represented schematically using box-whisker plots to assist in understanding the spread and interpretation of the data points. Further analysis was completed on food categories that had multiple data entries to check for correlation between GWP values and geographic locations, farming methods or species.

3 Results of systematic literature review on Food GWP values

3.1 Located literature

The meta-analysis cites 369 published LCA studies that provided 1,718 GWP values for fresh produce from the year 2000 to 2015. 192 journal papers, 80 conference papers, 64 reports (for industry and government), 29 web-based EPDs, and four theses were utilised in total. The majority of GWP values (58%) were from the last five years (see Fig. 3). It is of note that most studies produced multiple GWP values, for example the studies may compare different food types, growing regions, methodological choices or production methods.

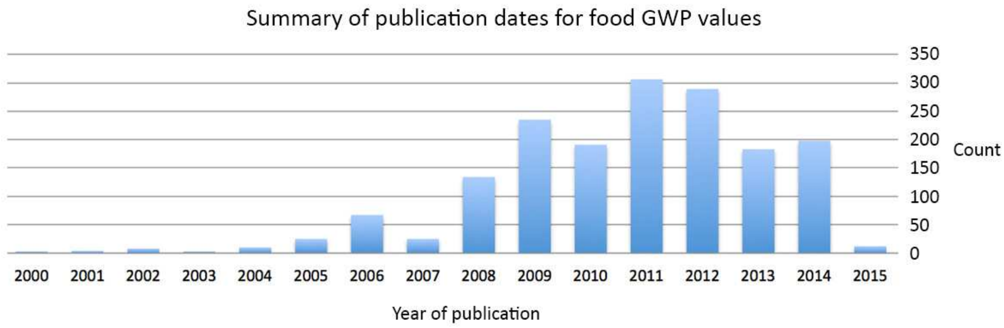

Figure 3 Summary of publication dates for food GWP values

Searching via Sciencedirect produced 3,355 results, the first 1,000 titles were scanned for relevance, of which 113 LCA studies were downloaded for review, 47 being directly used for analysis. Eight studies were used to mine citations. The initial 47 studies identified an additional 64 references to review, which in turn provided further references.

Conference papers from the proceeding from the 'Life Cycle Assessment in the Agri-Food Sector' conferences in 2014 (n = 33), 2012 (n = 20), and 2010 (n = 13) were reviewed. Ruini et al.'s (2014) conference paper 'LCA applied to sustainable diets' and accompanying database was significant in identifying a substantial number of conference and journal articles for review.

EPD studies (n = 29) were primarily identified through the 'international EPD system' webpage (EPD international, 2015) that provided 21 studies. Industry reports (grey literature, n = 64) were identified through in text citations in journal and conferences papers.

The identified literature was predominately European centric (see Fig. 4 and Table 3), with the British Isles (n = 245), and Europe (n = 930) accounting for 68% of the utilised GWP values (n = 1,175), followed by North America (n = 167) and Oceania (n = 143). Asia (n = 77), South America (74) and Africa (n = 23) were less represented. Within Europe, Spain (n = 187) France (n = 173), Sweden (n = 153) and the Netherlands (n = 139) were dominant.

Table 3 Location of food GWP values collated in the database

Region	**Number of recorded GWP values**
Europe	930
British Isles	245
Oceania (Australia and New Zealand)	143
North America	167
Asia	77
South America	74
World	39
Africa	23
Middle East	2
Other (no location specified for 'imported' products)	18
Total	**1718**

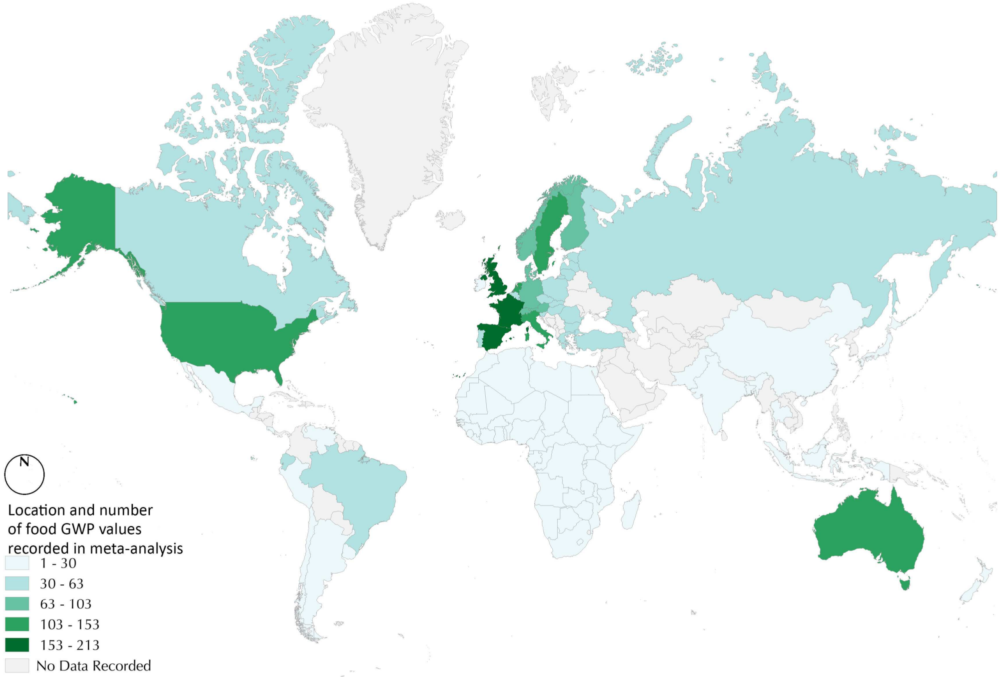

Figure 4 Location and number of food GWP values recorded from reviewed LCA studies

3.2 Overview of results between food categories

The summary of results for the GWP values recorded are presented in Fig. 5 and Table 4, they present a large variation in results between food categories. At the broadest level the lowest median GWP values were for field-grown vegetables (0.37 *kg* $CO_{2\text{-}}eq/kg$), field-grown fruit (0.42 *kg* $CO_{2\text{-}}eq/kg$), cereals (except rice) and pulses (0.50-0.51 *kg* $CO_{2\text{-}}eq/kg$). Slightly higher values for tree nuts were found (1.20 *kg* $CO_{2\text{-}}eq/kg$). Rice had the highest impact of the plant based field grown crops (2.55 *kg* $CO_{2\text{-}}eq/kg$), slightly higher than fruit and vegetables from heated greenhouses (2.13 *kg* $CO_{2\text{-}}eq/kg$).

Non-Ruminant livestock had medium GWP values in fish (3.49 *kg kg* $CO_{2\text{-}}eq/kg$ *BFM*), chicken (3.65 *kg* $CO_{2\text{-}}eq/kg$ *BFM*) and pork (5.77 *kg* $CO_{2\text{-}}eq/kg$ *BFM*). Dairy products (cheese) and butter also shared a medium GWP values.

Ruminant livestock in lamb (25.58 *kg* $CO_{2\text{-}}eq/kg$ *BFM*) and beef (26.61 *kg* $CO_{2\text{-}}eq/kg$ *BFM*) had the highest median GWP values.

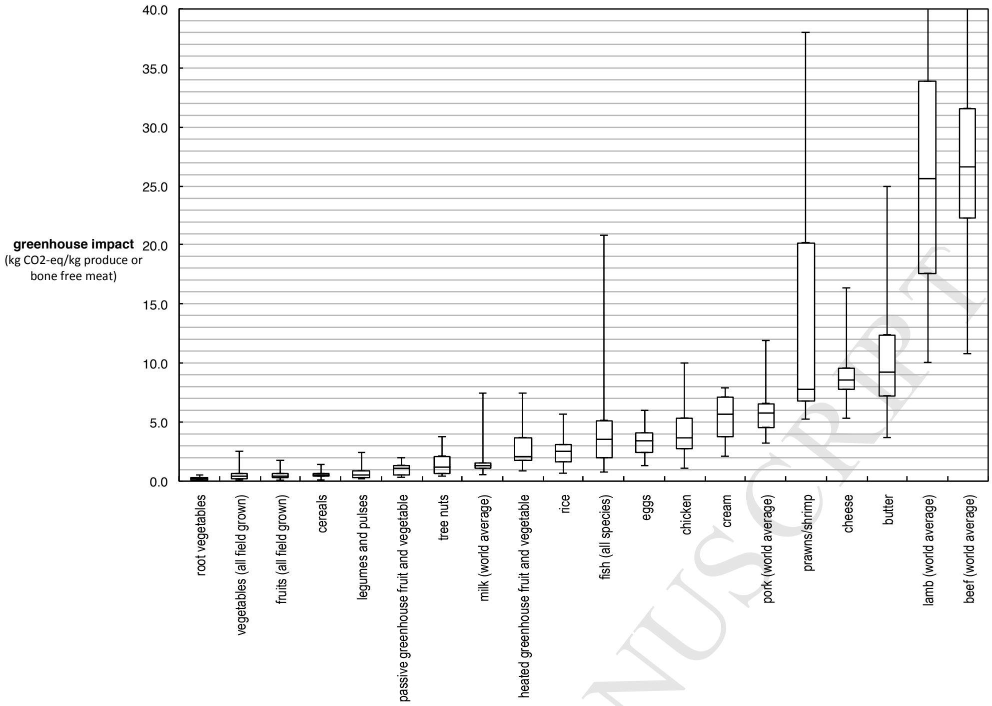

Figure 5 Summary of GWP values (*kg CO_2-eq/kg* produce or bone free meat) across broad food categories

Table 4 Summary of GWP values (*kg CO_2-eq/kg* produce or bone free meat) across broad food categories

Name	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Vegetables (all field grown vegetable)	0.37	0.47	0.39	83%	0.04	2.54	0.19	0.60	33	140
Fruits (all field grown fruit)	0.42	0.50	0.32	64%	0.08	1.78	0.28	0.63	77	250
Cereals	0.50	0.53	0.22	42%	0.11	1.38	0.38	0.63	31	90
Legumes and Pulses	0.51	0.66	0.45	67%	0.15	2.46	0.36	0.83	16	51
Passive greenhouse fruit and vegetable	1.10	1.02	0.49	48%	0.32	1.94	0.54	1.35	5	15
Tree nuts combined	1.20	1.42	0.93	66%	0.43	3.77	0.61	2.13	7	21
Milk world average	1.29	1.39	0.58	41%	0.54	7.50	1.14	1.50	77	262
Heated greenhouse fruit and vegetable	2.13	2.81	1.61	57%	0.84	7.4	1.74	3.7	18	53
Rice	2.55	2.66	1.29	48%	0.66	5.69	1.64	3.08	12	27
Eggs	3.46	3.39	1.21	36%	1.30	6.00	2.45	4.05	19	38
Fish: all species combined	3.49	4.41	3.62	82%	0.78	20.86	1.99	5.16	47	148
Chicken	3.65	4.12	1.72	42%	1.06	9.98	2.77	5.31	29	95
Cream	5.64	5.32	1.62	31%	2.10	7.92	3.82	7.14	3	4
Pork: world average	5.77	5.85	1.63	28%	3.20	11.86	4.50	6.59	38	130
Prawns/shrimp	7.80	14.85	12.37	83%	5.25	38.00	6.76	20.20	7	11
Cheese	8.55	8.86	2.07	23%	5.33	16.35	7.79	9.58	22	38
Butter	9.25	11.52	7.37	64%	3.70	25.00	7.28	12.41	4	8
Lamb: world average	25.58	27.91	11.93	43%	10.05	56.70	17.61	33.85	22	56
Beef: world average	26.61	28.73	12.47	43%	10.74	109. 5	22.26	31.57	49	165
Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and references										

This initial broad overview identifies a clear hierarchy within the GWP values. The above categories are presented in detail in the sub-sections below to identify further trends in the data. Details of the GWP values for individual foods from lowest to highest median values are presented in Table 5.

Table 5 Individual GWP values (*kg CO_2-eq/kg* produce or bone free meat) from low to high

Name	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Onion	0.17	0.18	0.11	60%	0.06	0.37	0.10	0.21	7	9
Celery	0.18								1	1
Potatoes	0.18	0.20	0.08	41%	0.08	0.36	0.16	0.26	16	25
Carrots	0.20	0.22	0.15	65%	0.04	0.50	0.11	0.31	10	13
Zucchini/button squash	0.21	0.42	0.50	121%	0.09	1.17	0.16	0.46	3	4
Cucumber/gherkins	0.23	0.33	0.32	96%	0.13	1.30	0.19	0.31	7	15
Beetroot	0.24	0.23	0.11	50%	0.11	1.61	0.18	0.29	2	3
Pumpkins	0.25	0.33	0.25	74%	0.15	0.73	0.16	0.37	4	8
Rockmelon/cantelope	0.25								1	1
Beans: plake	0.26	0.30	0.12	38%	0.22	0.43	0.24	0.35	1	3
Lemons and limes	0.26	0.30	0.06	19%	0.18	0.45	0.22	0.35	2	3
Mushrooms	0.27	0.27	0.29	110%	0.06	0.48	0.16	0.37	3	2
Guavas	0.28								1	1
Apples	0.29	0.36	0.19	53%	0.18	0.89	0.21	0.47	21	33
Swedes/rutabage	0.29								1	1
Pears	0.31	0.33	0.13	41%	0.19	0.63	0.27	0.33	4	8
Quinces	0.31	0.31	0.01	5%	0.30	0.32	0.31	0.32	2	2
Beans: green	0.31	0.51	0.47	93%	0.24	1.55	0.26	0.46	4	7
Watermelons	0.32	0.32	0.09	29%	0.25	0.38	0.28	0.35	2	2
Dates	0.32								1	1
Orange	0.33	0.35	0.12	34%	0.18	0.59	0.25	0.45	9	20
Kiwi fruit	0.36	0.47	0.26	55%	0.15	0.88	0.29	0.68	5	9
Cauliflowers and broccoli	0.36	0.35	0.06	17%	0.28	0.42	0.32	0.39	4	4
Grapes	0.37	0.41	0.25	60%	0.15	0.88	0.31	0.41	5	6
Oats	0.38	0.44	0.12	26%	0.38	0.67	0.38	0.45	4	6
Rye	0.38	0.41	0.07	17%	0.36	0.49	0.37	0.44	2	3
Peas	0.38	0.60	0.77	128%	0.15	2.46	0.21	0.50	6	8
Cherries	0.39	0.48	0.40	83%	0.26	0.88	0.31	0.56	2	4
Beans: gigante/butter	0.39	0.36	0.09	25%	0.26	0.43	0.32	0.41	1	3
Almond/coconut milk	0.42	0.42	0.03	8%	0.39	0.44	0.39	0.44	1	4
Peaches and Nectarines	0.43	0.54	0.24	44%	0.38	0.81	0.41	0.62	3	3
Figs	0.43								1	1
Barley	0.43	0.49	0.24	49%	0.11	0.98	0.34	0.60	7	13
Apricot	0.43								1	1
Chestnuts	0.43								1	1
Beans	0.43	0.62	0.45	73%	0.22	1.55	0.26	0.72	11	22
Mandarin	0.45								1	1
Tomatoes	0.45	0.46	0.18	39%	0.08	1.00	0.35	0.55	19	56
Maize/corn	0.47	0.63	0.38	60%	0.40	1.38	0.42	0.61	6	6
Fennel	0.48								1	1
Artichokes	0.48								1	1
Cowpeas	0.49	0.48	0.13	28%	0.33	0.61	0.40	0.57	1	4
Soybean	0.49	0.58	0.04	6%	0.38	0.96	0.44	0.62	2	4
Pineapples	0.50	0.72	0.53	74%	0.40	1.78	0.45	0.64	5	6
Melons	0.51	0.88	0.01	2%	0.30	1.74	0.32	1.55	4	5
Grapefruit and pomelo	0.51								2	1
Tangerines/mandarins	0.51								1	1
Tomatoes: passive greenhouse	0.51	0.67	0.34	51%	0.32	1.28	0.44	0.86	5	8
Wheat	0.52	0.51	0.17	33%	0.18	1.10	0.40	0.60	20	51
Spinach	0.54	0.54	0.51	95%	0.18	0.91	0.36	0.73	2	2
Garlic	0.57								1	1
Strawberries	0.58	0.65	0.36	55%	0.20	1.50	0.37	0.84	15	21
Broccoli	0.60	0.70	0.34	48%	0.37	1.73	0.49	0.70	6	17
Olives	0.63	0.56	0.22	38%	0.22	0.85	0.52	0.66	4	8
Capsicums/peppers	0.66	0.60	0.27	44%	0.23	0.87	0.55	0.71	3	4
Beans: pinto USA dried	0.73								1	1

Soy-milk	0.75	0.88	0.27	31%	0.66	1.40	0.70	0.98	2	8
Beans: french and runner	0.75	0.85	0.37	44%	0.52	1.37	0.63	0.97	1	4
Chick peas	0.77	0.67	0.19	29%	0.45	0.80	0.61	0.79	2	3
Asparagus	0.83	0.92	0.49	53%	0.18	2.54	0.60	1.05	5	28
Peanuts	0.83	0.87	0.11	13%	0.80	1.10	0.81	0.87	3	6
Raspberries	0.84								2	1
Currants and gooseberries	0.84								1	1
Sesame seed	0.88								1	1
Ginger	0.88								1	1
Cranberries/blueberries	0.92	0.92	0.07	8%	0.86	0.97	0.89	0.94	2	2
Hazelnuts	0.97	0.97	0.76	78%	0.43	1.50	0.70	1.23	2	2
Ground nuts	0.99	0.99	0.48	49%	0.65	1.33	0.82	1.16	2	2
Lentils	1.03	1.03	0.04	4%	1.00	1.06	1.02	1.05	2	2
Pilchard	1.10	1.10	0.45	41%	0.78	1.41	0.94	1.26	2	2
Peppers: passive and heated greenhouse	1.10	1.08	0.17	16%	0.90	1.25	1.00	1.17	2	3
Quinoa	1.15	1.15	0.07	6%	1.10	1.20	1.13	1.18	2	2
Herring	1.16	1.17	0.17	15%	0.98	1.39	1.09	1.25	3	4
Milk: world average	1.29	1.39	0.58	41%	0.54	7.50	1.14	1.50	77	262
Avocados	1.30								2	1
Yoghurt	1.31	1.43	0.25	18%	1.17	2.00	1.28	1.48	7	11
Eggplants (aubergines)	1.35	1.35	0.07	5%	1.30	1.40	1.33	1.38	1	2
Sunflower seed	1.41								1	1
Cashew nut	1.44	1.55	0.85	55%	1.06	2.27	1.29	1.70	3	4
Melons: passive greenhouse	1.43	1.37	0.11	8%	1.24	1.43	1.33	1.43	1	3
Walnuts	1.51	1.62	1.13	70%	0.50	2.94	1.32	2.54	3	4
Pistachios	1.53	1.53	0.91	60%	0.88	2.17	1.20	1.85	1	2
Almonds	1.54	1.74	1.25	72%	0.51	3.77	0.76	2.33	4	6
Pollock	1.60	1.65	0.47	29%	1.20	2.14	1.40	1.87	2	3
Strawberries: heated greenhouse	1.64	2.56	2.32	91%	0.84	5.20	1.24	3.42	3	3
Carp	1.76	1.80	0.11	6%	1.73	1.93	1.74	1.84	1	3
Zucchini: passive greenhouse	1.77	1.77	0.24	13%	1.60	1.94	1.69	1.86	1	2
Mackerel	1.80	2.00	1.08	54%	0.94	4.50	1.30	2.40	9	21
Rape and mustard seed	2.09								1	1
Cucumbers and gherkins: heated greenhouse	2.10	2.23	0.71	17%	1.68	3.79	1.89	2.12	5	7
Tuna	2.15	2.60	1.45	56%	1.39	6.32	1.75	2.68	4	10
Tomatoes: heated greenhouse	2.20	2.69	1.36	51%	0.92	6.12	1.86	3.65	13	33
Rice	2.55	2.66	1.29	48%	0.66	5.69	1.64	3.08	12	27
Whiting	2.66	2.66	1.59	60%	1.54	3.79	2.10	3.22	2	2
Duck	3.09	3.09	1.44	47%	2.07	4.10	2.58	3.59	2	2
Sea bass	3.27	3.55	1.63	46%	1.91	5.76	2.68	4.14	2	4
Haddock	3.41	3.37	0.08	3%	2.80	3.84	3.03	3.75	2	4
Eggs	3.46	3.39	1.21	36%	1.30	6.00	2.45	4.05	19	38
Salmon	3.47	3.76	1.47	39%	2.04	8.33	2.88	4.13	9	21
Fish: all species	3.49	4.41	3.62	82%	0.78	20.86	1.99	5.16	47	148
Cod	3.51	3.49	1.31	37%	1.58	5.38	2.25	4.50	10	16
Buffalo milk	3.57	3.75	0.86	23%	2.87	5.20	3.14	4.18	1	7
Chicken	3.65	4.12	1.72	42%	1.06	9.98	2.77	5.31	29	95
Lettuce: heated greenhouse	3.70	3.15	1.64	52%	1.30	4.73	1.50	4.51	3	5
Eel	3.88								1	1
Kangaroo	4.10								1	1
Trout	4.20	3.73	1.13	30%	1.37	5.95	3.11	4.33	9	20
Rabbit	4.70	4.70	1.24	26%	3.82	5.58	4.26	5.14	2	2
Cream	5.64	5.32	1.62	31%	2.10	7.92	3.82	7.14	3	4
Pork: world average	5.77	5.85	1.63	28%	3.20	11.86	4.50	6.59	38	130
Ling common	6.45	6.45	4.69	73%	3.13	9.77	4.79	8.11	2	2
Pomfret	6.63	6.63	4.44	67%	3.49	9.77	5.06	8.20	2	2
Rock fish	6.94								1	1
Octopus/squid/cuttlefish	7.13	8.07	2.40	30%	6.39	11.61	6.78	8.42	3	4
Prawns/shrimp	7.80	14.85	12.37	83%	5.25	38.00	6.76	20.20	7	11
Turkey	7.17	6.04	0.66	11%	3.34	8.49	3.82	7.83	3	7
Diamond fish	8.33	8.33	3.27	39%	6.02	10.65	7.17	9.49	2	2
Rhombus	8.41								1	1

Cheese	8.55	8.86	2.07	23%	5.33	16.35	7.79	9.58	22	38
Butter	9.25	11.52	7.37	64%	3.70	25.00	7.28	12.41	4	8
Mussels	9.51	7.54	4.93	65%	1.92	13.90	2.54	9.84	3	5
Hake	9.77	8.98	3.93	44%	2.14	14.15	7.07	11.32	5	7
Porbeagle	11.44								1	1
Shark mako	11.50	11.50	0.09	1%	11.44	11.56	11.47	11.53	2	2
Anglerfish	12.29	12.29	2.63	21%	10.43	14.15	11.36	13.22	2	2
Swordfish	12.84	12.84	1.98	15%	11.44	14.24	12.14	13.54	2	2
Megrim	14.15								1	1
Turbot	14.51	14.51	6.91	48%	9.63	19.40	12.07	16.96	2	2
Sole	20.86								1	1
Lamb: world average	25.58	27.91	11.93	43%	10.05	56.70	17.61	33.85	22	56
Beef: world average	26.61	28.73	12.47	43%	10.74	109.3	22.26	31.57	49	165
Lobster	27.80	21.74	11.7	56%	7.62	28.30	17.71	28.05	3	2
Buffalo	60.43	62.59	20.35	33%	28.78	100.7	43.88	79.14	1	4
Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and references. All fruit and vegetables field grown unless stated, passive greenhouse has no auxiliary heating										

3.3 *Fresh Fruit, Vegetables and Staples*

The meta-analysis for the fruit and vegetable category is drawn from 122 LCA studies that generated 633 GWP values. Typical processes for the fresh vegetable category include farm inputs from chemicals and fertilisers, fuel and energy inputs from irrigation and machinery for cultivation, harvesting and processing, and transport and refrigeration to the regional distribution centre. Outputs included nitrogen released from fertilised soils and emissions released from plants and fields. Maraseni et al. (2010) for example identified on-farm emissions related on average to: energy used for irrigation (54%), Nitrogen emissions from soils after N-fertiliser (17%), energy use for post-harvest storage (11%), fertiliser input (10%) and machinery and fuel use (8%). The size of the farm (Milà i Canals et al., 2008), species requirement for fertiliser use (i.e. beans) or processing (i.e. asparagus) assist to explain the variations between and within the fruit and vegetable category.

The analysis attempts to identify the values for individual foods (Table 5) as well as trends across the data. The fresh fruits and vegetables results were analysed further in four broad categories: vegetables, fruits, staples and greenhouse fruit and vegetables. These four categories were broken down further into botanical classifications in an attempt to identify key trends within the data, presented below in Table 6 and Fig. 6.

Table 6 Fruit, vegetable and staples GWP values (*kg CO_2.eq/kg* produce)

Group	Classification	Foods included	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values[a]
Vegetables field grown	Brassica	Cabbages, other brassicas	0.23	0.32	0.30	94%	0.12	0.64	0.22	0.38	4	5
	Bulbs, roots and tubers	Onions, garlic, beetroot, swedes and carrots	0.18	0.21	0.12	55%	0.04	0.57	0.14	0.29	21	53
	Leaves	Varieties of lettuce	0.37	0.38	0.14	38%	0.13	0.62	0.27	0.46		26
	Vegetables	Vegetables (all field grown vegetable)	0.37	0.47	0.39	83%	0.04	2.54	0.19	0.60	33	140
	Stem shoots	Asparagus	0.83	0.92	0.49	53%	0.18	2.54	0.60	1.05	5	28
	Brassica	Broccoli and cabbage	0.50	0.57	0.33	58%	0.12	1.73	0.38	0.69	1	26
Fruits field grown	Pome	Apples, pears and quinces	0.29	0.34	0.18	52%	0.18	0.89	0.22	0.38	22	40
	Pepo	Fruit of the gourd family including cucumber, gherkins, zucchini, papaya and melons etc	0.30	0.34	0.29	85%	0.08	1.30	0.18	0.32	13	32
	Hesperidium	Fruits of the citrus family including oranges, mandarins, lemons and limes	0.33	0.35	0.12	34%	0.22	0.59	0.25	0.46	10	28
	Fruit	Fruits (all field grown fruit)	0.42	0.50	0.32	64%	0.08	1.78	0.28	0.63	77	250

	Drupe	Stones fruits including cherries, dates, plumbs, apricots, peach, olives, and coconuts.	0.45	0.57	0.36	63%	0.22	1.78	0.32	0.67	1	19
	Multiple fruit	Pineapples and figs	0.45	0.68	0.50	73%	0.40	1.78	0.44	0.61	5	7
	True berry	Tomatoes, grapes, avocado, peppers, kiwi fruits, guava etc.	0.45	0.52	0.26	50%	0.08	1.40	0.35	0.66	24	83
	Aggregate fruit	Strawberries and raspberries	0.60	0.66	0.35	53%	0.20	1.50	0.38	0.84	15	22
	Musa	Bananas	0.72	0.79	0.30	38%	0.42	1.37	0.48	1.04	10	17
Staples	Cereal	Barley, maize, oats, rye, corn and wheat	0.50	0.53	0.22	42%	0.11	1.38	0.38	0.63	31	90
	Legume	Peas, beans, peanuts, ground nuts, and lentils	0.51	0.66	0.45	67%	0.15	2.46	0.36	0.83	16	51
	Tree nuts	Chestnuts, almonds, hazelnuts, palm nuts-kernels, pistachios, cashew nuts and walnuts	1.20	1.42	0.93	66%	0.43	3.77	0.61	2.13	7	21
	Seeds	Rapeseed (canola), mustard seed, sesame seed and sunflower seed	1.41	1.46	3.70	61%	0.88	2.09	1.15	1.75	1	3
	Cereal	Rice	2.55	2.66	1.29	48%	0.66	5.69	1.64	3.08	12	27
Greenhouse Fruit and vegetables[c]	No auxiliary heating (passive)	Melons, peppers, tomatoes and zucchini	1.10	1.02	0.49	48%	0.32	1.94	0.54	1.35	5	15
	Natural gas heated greenhouse	Lettuce, strawberries and tomatoes	2.07	2.58	1.35	52%	1.16	5.90	1.72	2.88	8	25
	Fuel/oil heated greenhouse	Cucumbers, lettuce, peppers and tomatoes	2.82	2.77	1.17	42%	0.90	4.51	2.01	3.65	3	8
	LPG heated greenhouse	Tomatoes	3.40	2.59	0.42	16%	3.10	3.70	3.25	3.55	2	2
	Average from all heated greenhouse[b]	Cucumber, melons, lettuce, peppers, strawberries, raspberries, tomatoes and zucchini	2.13	2.81	1.61	57%	0.84	7.4	1.74	3.7	18	53

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.

a) The number of LCA studies and GWP values column from table 5 does not correlate to tables 6, 7 and 8, as one LCA study may provide multiple GWP values for multiple food categories, or provide a singular GWP value for multiple food types e.g. ‘apples and pears’ (counted as separate GWP values under apples, and pears in table 5, and once only as Pome in table 6).

b) The ‘average from all heated greenhouse’ includes LCA values for heating generated by natural gas, oil, LPG, coal, electricity, and CHP, as well as 14 GWP values that came from studies with an unspecified heating source.

c) Fruit and vegetables grown in different greenhouses in the above table is indicative only of reviewed studies, and not what may be grown in different green house types.

The broad level GWP values within the fruits and vegetables see root vegetables with the lowest median value in 0.18 $kg\ CO_{2\text{-}eq}/kg$, field-grown vegetables (0.37 $kg\ CO_{2\text{-}eq}/kg$), field-grown fruit (0.42 $kg\ CO_{2\text{-}eq}/kg$), cereals (except rice) (0.50 $kg\ CO_{2\text{-}eq}/kg$) and pulses (0.51 $kg\ CO_{2\text{-}eq}/kg$). Slightly higher values were found for tree nuts (1.20 $kg\ CO_{2\text{-}eq}/kg$) and seeds (1.41 $kg\ CO_{2\text{-}eq}/kg$). Rice had the highest impact of the plant based filed grown crops (2.55 $kg\ CO_{2\text{-}eq}/kg$). The meta-analysis presents further granularity within the results with minor variations between the botanical classifications, however the majority fall within a narrow band of median figures from 0.29-0.60 $kg\ CO_{2\text{-}eq}/kg$ for pome, pepo, leaves, brassica, hesperidium, drupes, multiple fruits, grains, legumes, true berries, and aggregate fruits. This band is small in comparison to the variation in results in the livestock groups. Figures for musa (bananas) would likely join this grouping, however most studies noted production in South America, and shipping to a RDC in Europe (e.g. Iriarte et al., 2014; Lescot, 2012). The number of studies utilised for seeds were under represented and draw on one study only by Audsley et al. (2009).

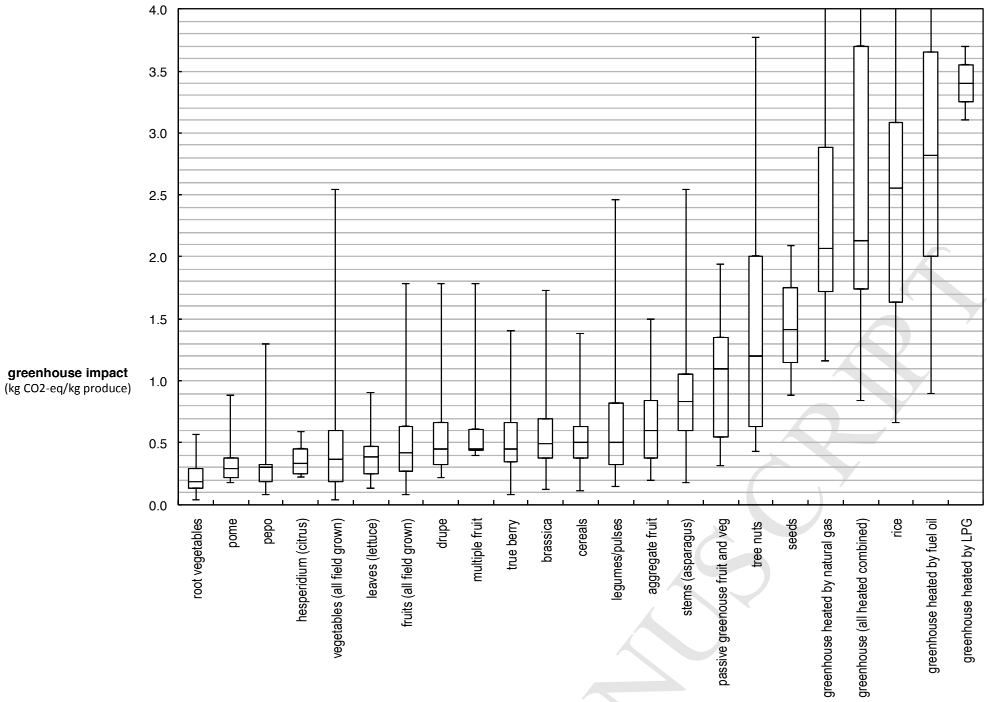

Figure 6 Comparisons of synthesized GWP values across fruit, vegetables and staples classifications

Greenhouse fruit and vegetables from heated greenhouses were notably higher than field-grown equivalents, with a median of 2.13 *kg CO_{2}-eq/kg*. Passive greenhouses with no auxillary heating had GWP figures comparable with the upper quartile of some field grown fruit and vegetables (1.10 *kg CO_{2}-eq/kg*). The energy source used to heat the greenhouse, local climate and the thermal efficiency of the greenhouse has an impact on the GWP values (e.g. Page et al., 2012; Torrellas et al., 2012), as heating is responsible for the majority of greenhouse gas emissions in heated greenhouses (Boulard et al., 2011).

3.4 Non-ruminant livestock: fish, poultry and pork

The non-ruminant livestock category analysed LCA studies including fish, poultry and pork. 108 LCA studies were reviewed resulting in 446 GWP values. Processes for non-ruminant livestock typically include breeding, feed production, fertiliser use, farm/broiler energy use including heating, as well as transport, processing and refrigeration. Farmed fish share largely these same processes, while wild fish processes largely relate to fuel consumption and emissions from refrigeration during the catch. The results of the non-ruminant livestock category are presented in Table 7 and Figure 7.

Table 7 Non-ruminant livestock: fish, poultry and pork GWP values (*kg CO_{2}-eq/kg bone free meat*)

Classification	Foods included	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Fish	Pilchard	1.10	1.10	0.45	41%	0.78	1.41	0.94	1.26	2	2
	Herring	1.16	1.17	0.17	15%	0.98	1.39	1.09	1.25	3	4
	Pollock	1.60	1.65	0.47	29%	1.20	2.14	1.40	1.87	2	3
	Carp	1.76	1.80	0.11	6%	1.73	1.93	1.74	1.84	1	3
	Mackerel	1.80	2.00	1.08	54%	0.94	4.50	1.30	2.40	9	21
	Tuna	2.15	2.60	1.45	56%	1.39	6.32	1.75	2.68	4	10
	Whiting	2.66	2.66	1.59	60%	1.54	3.79	2.10	3.22	2	2

	Sea bass	3.27	3.55	1.63	46%	1.91	5.76	2.68	4.14	2	4
	Haddock	3.41	3.37	0.08	3%	2.80	3.84	3.03	3.75	2	4
	Salmon	3.47	3.76	1.47	39%	2.04	8.33	2.88	4.13	9	21
	Fish (all species)	3.49	4.41	3.62	82%	0.78	20.86	1.99	5.16	47	148
	Cod	3.51	3.49	1.31	37%	1.58	5.38	2.25	4.50	10	16
	Trout	4.20	3.73	1.13	30%	1.37	5.95	3.11	4.33	9	20
	Diamond fish	8.33	8.33	3.27	39%	6.02	10.65	7.17	9.49	2	2
	Ling common	6.45	6.45	4.69	73%	3.13	9.77	4.79	8.11	2	2
	Pomfret	6.63	6.63	4.44	67%	3.49	9.77	5.06	8.20	2	2
	Octopus, squid, cuttlefish	7.13	8.07	2.40	30%	6.39	11.61	6.78	8.42	3	4
	Hake	9.77	8.98	3.93	44%	2.14	14.15	7.07	11.32	5	7
	Shark mako	11.50	11.50	0.09	1%	11.44	11.56	11.47	11.53	2	2
	Anglerfish	12.29	12.29	2.63	21%	10.43	14.15	11.36	13.22	2	2
	Swordfish	12.84	12.84	1.98	15%	11.44	14.24	12.14	13.54	2	2
	Turbot	14.51	14.51	6.91	48%	9.63	19.40	12.07	16.96	2	2
Shellfish	Prawns, shrimp	7.80	14.85	12.37	83%	5.25	38.00	6.76	20.20	7	11
	Mussels	9.51	7.54	4.93	65%	1.92	13.90	2.54	9.84	3	5
	Lobster	27.80	21.74	11.7	56%	7.62	28.30	17.71	28.05	3	2
Poultry	Duck	3.09	3.09	1.44	47%	2.07	4.10	2.58	3.59	2	2
	Eggs	3.46	3.39	1.21	36%	1.30	6.00	2.45	4.05	19	38
	Chicken	3.65	4.12	1.72	42%	1.06	9.98	2.77	5.31	29	95
	Turkey	7.17	6.04	0.66	11%	3.34	8.49	3.82	7.83	3	7
Rabbit	Rabbit	4.70	4.70	1.24	26%	3.82	5.58	4.26	5.14	2	2
Kangaroo	Kangaroo	4.1								1	1
Pork	Pork EU	5.39	5.60	1.51	27%	3.20	10.25	4.31	6.45	24	91
	Pork world average[a]	5.74	5.85	1.63	28%	3.20	11.86	4.50	6.60	38	129
	Pork Nth America	6.00	6.24	1.46	23%	4.30	8.53	4.97	7.58	6	9
	Pork UK	6.11	5.57	1.13	20%	3.50	6.92	4.54	6.34	5	13
	Pork AU	7.65	7.12	1.81	25%	3.90	9.49	5.83	8.46	3	11

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.

a) Pork world average includes one additional LCA value from Asia, two from South America and two unspecified world figures.

Fish and chicken had similar median GWP values, 3.49 *kg* $CO_{2\text{-}eq}$*/kg BFM* for all species of fish and 3.65 *kg* $CO_{2\text{-}eq}$*/kg BFM* for chicken. The world average for pork was slightly higher with 5.77 *kg* $CO_{2\text{-}eq}$*/kg BFM*. Within this data, a large variation in results were identified and further analysed by segregating individual species of fish, and the geographic location of pork production.

The analysis of fish was further broken down between different species of fish (see figure 5). Within the results of specific species of fish, pilchards, pollock, carp, herring and mackerel presented low GWP values comparable with some plant based categories in tree-nuts and rice. Medium values were identified for salmon, cod and trout, while hake, anglerfish, swordfish and turbot had high GWP values. The higher values are for species caught offshore by trawling and long line fishing fleets that have significantly higher fuel consumption than coastal fishing fleets (Iribarren et al., 2010a; Iribarren et al., 2010b; Vázquez-Rowe et al., 2012; Vázquez-Rowe et al., 2010). Shell-fish in prawn and shrimps displayed very high variations in GWP values, while lobster had the highest median GWP value in the category with a median value of 27.80 *kg* $CO_{2\text{-}eq}$*/kg BFM*, which is in part due to the high cost of lobster and the economic allocation method used (Iribarren et al., 2010b).

Chicken (3.65 *kg* $CO_{2\text{-}eq}$*/kg BFM)* and eggs (3.46 *kg* $CO_{2\text{-}eq}$*/kg eggs)* displayed similar median values. The type of protein used as feed (Pelletier et al., 2013) and farming methods

(Bengtsson and Seddon, 2013; Leinonen et al., 2012) have previously been identified as significant indicators of GWP values for chicken.

With respect to pork, a notable variation in GWP values was evident when geography was considered, with European pork displaying a lower median value (5.50 *kg* $CO_{2\text{-}eq}$*/kg BFM*) than the UK (6.00 *kg* $CO_{2\text{-}eq}$*/kg BFM*), North America (6.11 *kg* $CO_{2\text{-}eq}$*/kg BFM)*, and Australia (7.65 *kg* $CO_{2\text{-}eq}$*/kg BFM)*.

Limited GWP values were identified for duck, turkey, rabbit, and kangaroo. Therefore comparison with other food groups should be viewed tentatively, however the results are consistent with mid range figures for non-ruminant livestock.

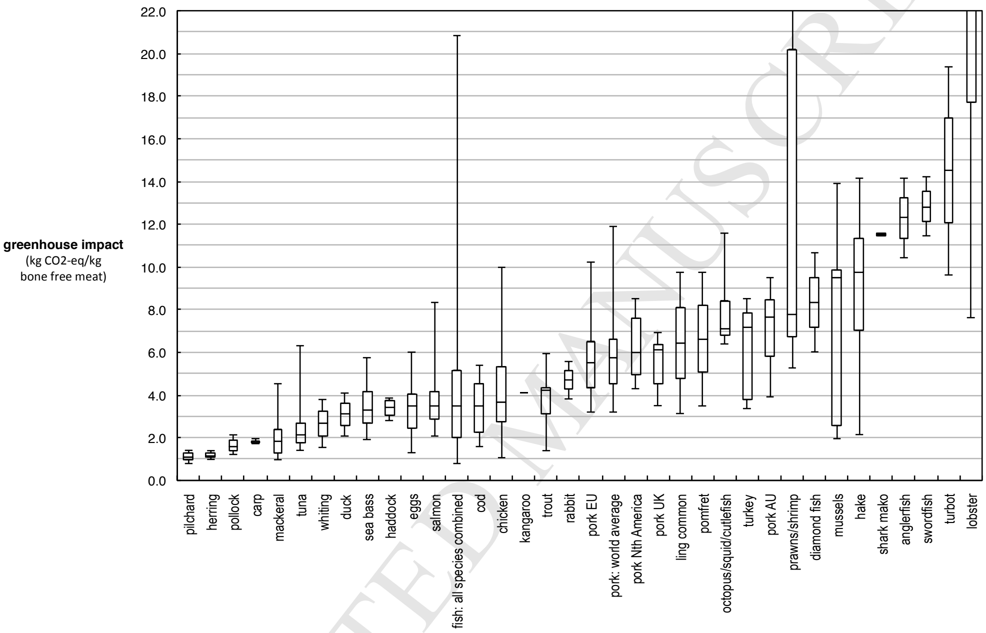

Figure 7 Comparisons of synthesized GWP values (*kg* $CO_{2\text{-}eq}$*/kg* bone free meat) for non-ruminant livestock (fish, poultry and pork)

3.5 Ruminant Livestock: Lamb and Beef

The ruminant livestock category included lamb, beef and buffalo and was compiled from 64 LCA studies resulting in 230 GWP values. The farm processes included inputs associated with breeding, feed production, fertilliser use, farm energy and transport, as well as processing at the slaughter house; the main output was the enteric fermentation process from the livestock. Ruminant livestock are separated from non-ruminants by their multiple guts, whereby the ruminants produce methane as a result of the enteric fermentation process where bacteria converts feed to energy. This process is estimated to account for between 55-92% of the greenhouse profile of cattle (Vergé et al., 2008). The results for the ruminant livestock category are presented in Table 8 and Fig. 8. The geographic location of lamb and beef appear to have an influence on the resultant GWP values (see table 8), as identified by Ledgard et al. (2010).

The median world average for lamb was 25.58 *kg* $CO_{2\text{-}eq}$*/kg* BFM. Australian and New Zealand lamb appeared significantly lower with a median of 17.63 *kg* $CO_{2\text{-}eq}$*/kg* BFM, where as EU lambs median GWP value was substantially higher at 32.70 *kg* $CO_{2\text{-}eq}$*/kg* BFM.

Table 8 Ruminant GWP values (*kg CO_{2}-eq/kg* BFM)

Classification	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Lamb AU & NZ	17.63	19.01	6.57	35%	10.05	33.49	16.30	21.06	9	19
Lamb UK	24.48	25.84	9.43	36%	11.04	43.17	21.48	30.07	7	12
Lamb world average[a]	25.58	27.91	11.93	43%	10.05	56.70	17.61	33.85	22	56
Lamb EU	32.70	33.84	13.06	39%	14.72	56.70	25.95	41.23	4	16
Beef Australia	22.88	23.06	4.79	21%	14.38	34.53	21.64	25.41	8	24
Beef EU	24.96	26.05	6.78	26%	10.74	42.30	21.69	29.07	25	75
Beef UK	26.57	25.76	6.27	24%	12.37	37.92	21.05	29.22	12	26
Beef world average[b]	26.61	28.73	12.47	43%	10.74	109.35	22.26	31.57	49	165
Beef Nth America	26.82	28.55	6.48	23%	19.60	41.73	23.41	30.53	9	13
Beef Sth America	34.10	38.33	12.48	33%	22.00	69.06	30.03	42.00	14	21
Buffalo	60.43	62.59	20.35	33%	28.78	100.72	43.88	79.14	1	4

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.

a) The lamb world average includes four additional LCA vales from North America, two from Asia, two from Africa, and one from South America.

b) The beef world average includes four additional LCA values from Asia, and two from Africa.

The world average for beef was 26.61 *kg CO_{2}-eq/kg* BFM. When geographic locations were compared for beef, South American beef had the highest median greenhouse gas profile with 34.10 *kg CO_{2}-eq/kg* BFM. Australian beef had the lowest median greenhouse gas profile with 22.88 *kg CO_{2}-eq/kg* BFM. The higher South American figure could be attributed to the inclusion of land-use change in the system boundary (Cederberg et al., 2011 p. 1773). Buffalo had the highest median greenhouse gas profile of all food analysed with a median of 60.43 *kg CO_{2}-eq/kg* BFM, identified in one study only. In Australia and the UK, the median value for lamb was less than beef; this trend was reversed in the European studies.

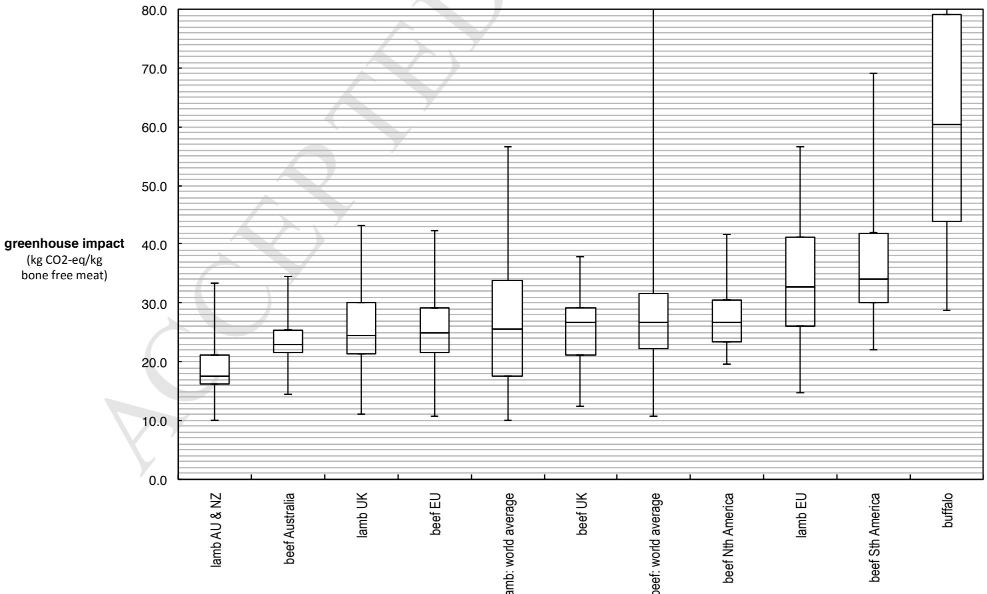

Figure 8 Comparisons of synthesized GWP values for ruminant livestock

3.6 Dairy

The dairy category was developed from reviewing 90 LCA studies that generated 341 GWP values. Milk had the highest number of GWP values (n = 262) identified from all the food categories. Within the dairy category, plant based milk substitutes in almond and soy-milk presented a lower median GWP value (0.42 and 0.75 *kg $CO_{2-}eq/kg$*) than dairy milk (1.29 *kg $CO_{2-}eq/kg$*). Yoghurt had a similar value to milk, with cream (5.64 *kg $CO_{2-}eq/kg$*), cheese (8.55 *kg $CO_{2-}eq/kg$*) and butter (9.25 *kg $CO_{2-}eq/kg$)* having higher median values (see Table 9 and Fig. 9) due to the high concentration of milk used per kg in their production. As with ruminant livestock, the geographic location had an impact on the GWP value for dairy. This could be expected given dairy is a product of ruminant livestock, mirroring the location-based impacts of beef.

Table 9 Dairy and dairy substitute GWP values (*kg $CO_{2-}eq/kg$* or L)

Product	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Almond, coconut milk	0.42	0.42	0.03	8%	0.39	0.44	0.39	0.44	1	4
Soy-milk	0.75	0.88	0.27	31%	0.66	1.40	0.70	0.98	2	8
Milk: AU & NZ	1.14	1.19	0.15	13%	0.94	1.40	1.11	1.32	10	10
Milk: Nth America	1.16	1.34	0.40	30%	0.94	2.06	1.05	1.55	11	19
Milk: British Isles	1.23	1.26	0.23	19%	0.88	1.99	1.12	1.30	16	35
Milk: World average	1.29	1.39	0.58	41%	0.54	7.50	1.14	1.50	77	262
Milk: Europe	1.30	1.32	0.29	22%	0.54	2.39	1.14	1.48	52	175
Milk: Central and Sth America	1.55	1.69	0.61	36%	1.14	3.30	1.41	1.68	5	10
Milk: Asia	2.02	2.53	1.09	43%	1.38	4.60	1.94	2.92	2	7
Milk: Africa	2.50	3.34	1.90	57%	1.02	7.50	1.98	3.70	2	5
Buffalo milk	3.57	3.75	0.86	23%	2.87	5.20	3.14	4.18	1	7
Yoghurt	1.31	1.43	0.25	18%	1.17	2.00	1.28	1.48	7	11
Cheese	8.55	8.86	2.07	23%	5.33	16.35	7.79	9.58	22	38
Cream	5.64	5.32	1.62	31%	2.10	7.92	3.82	7.14	3	4
Butter	9.25	11.52	7.37	64%	3.70	25.00	7.28	12.1	4	8

Source: generated by the authors from the analysis of data collated through the meta-analysis. See Appendix 1 for the compilation of raw values and full references.
a) Milk world average includes one additional LCA value from Belerus, not counted in the EU

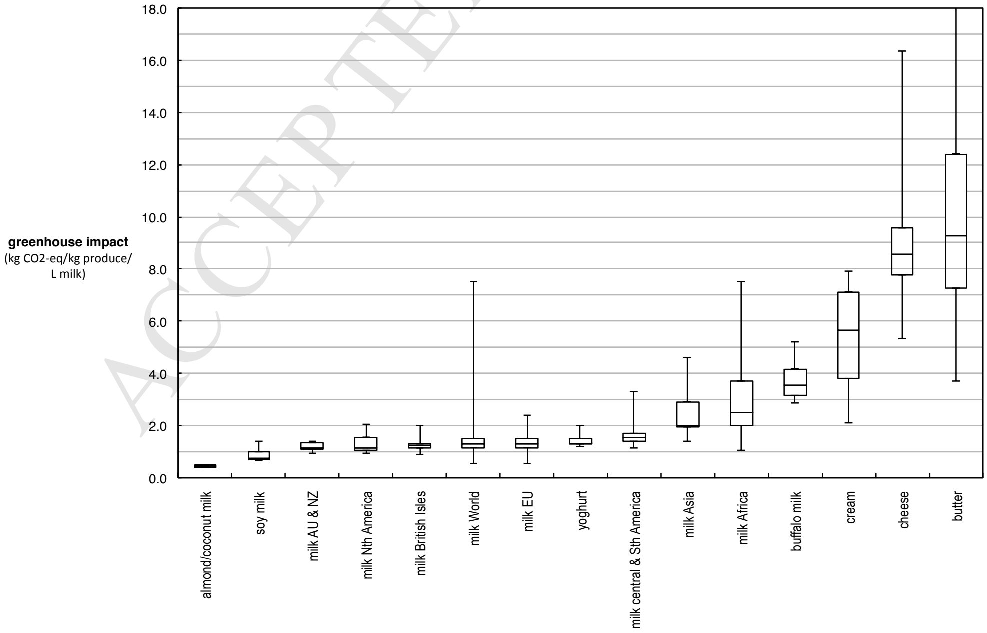

Figure 9 Comparisons of synthesized GWP values for dairy and dairy substitutes

4 Discussion

4.1 Key Trends identified from the meta-analysis

The meta-analysis confirms several existing trends previously identified in the LCA literature including the GWP hierarchy between broad food categories (e.g Head et al., 2013; Niggli et al., 2007)[4]; the hierarchy within plant based foods (Nemecek et al., 2012); and the importance of geographical location for ruminant livestock (e.g. Cederberg et al., 2011; Ledgard et al., 2010). The meta-analysis is also suggestive of new findings including the broad variation in GWP values between species for the fish category; an unequal representation of food types in LCA studies that require further attention (discussed in section 5.1); and the dominance of Europe in LCA publications.

4.2 Attributing the variation between studies and the risk of bias

To assess potential bias within studies, comparisons between methodological choices and publication type were completed for the beef and dairy categories only. Beef and dairy were selected as the category has a substantial number of LCA studies to enable comparison. For the Beef category, results from European LCA studies that used economic-input output (EIO) modelling (top down studies) were compared against studies that used process-based modelling (bottom up studies). In theory, these two approaches should correlate. The review of EIO studies from Lesschen et al. (2011) and others (n = 27 GWP values) when compared to process-based studies (n = 48 GWP values) illustrates that a strong correlation exists between methodological choices (see Figure 9). A very minor variation in median values of 2.6% was identified with respect to beef production and LCA methodological choices (see Fig. 10 and Table 10).

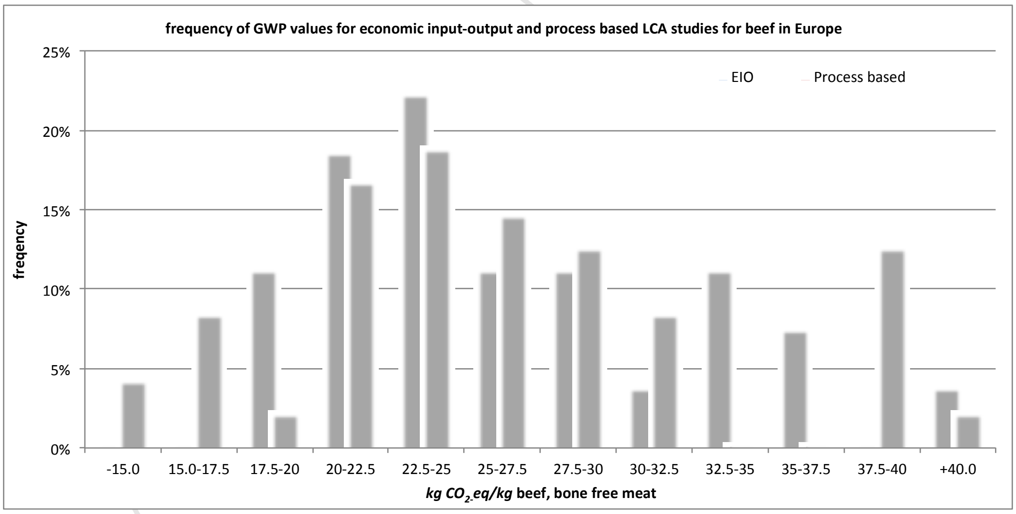

Figure 10 Comparisons of GWP frequencies for economic input-output and process based LCA studies for Beef in Europe

[4] The studies identified arable crops and vegetables to have lower greenhouse gas profiles than dairy, which is lower than poultry and pork, which is lower than beef.

Table 10 Comparisons of GWP values (*kg CO_2-eq/kg*) for economic input-output and process based LCA studies for Beef in Europe

LCA process used	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Beef EU process based LCA studies	24.98	25.76	7.15	28%	10.74	40.00	21.39	28.17	24	48
Beef EU EIO LCA studies	24.30	26.58	6.18	23%	18.30	42.30	21.91	30.45	3	27
Beef EU average combined	24.96	26.05	6.29	24%	10.74	42.30	21.69	29.07	25	75

Several authors have also published papers that compare methodologies between process based, EIO, and hybrid methodologies (e.g. Wiedemann and Yan, 2014), with results generally remaining within a similar quantum.

With respect to publication types, the milk category was the only category where a substantial number of EPDs have been completed to enable comparison between publication types. LCA GWP values were therefore analysed between EPDs (n = 15), conference papers (n = 26), journal papers (n = 174) and grey literature in government and industry reports (n = 22). Minor variation between publication types and GWP values were evident (See Table 11) as results remained within a similar quantum of GWP values.

Table 11 Comparisons of GWP values by publication type with respect to dairy milk (*kg CO_2-eq/L*) for EU, UK, AU, NZ and Nth America

Dairy milk: report type	Median	Mean	Stdev	Deviation from mean	Min	Max	Q1	Q3	No. of LCA studies	No. of GWP values
Report	1.12	1.13	0.16	14%	0.87	1.47	1.05	1.20	8	22
Conference papers	1.21	1.30	0.23	18%	0.94	1.77	1.14	1.60	14	26
Milk average; EU, UK, AU, NZ and Nth America	1.26	1.30	0.28	21%	0.54	2.39	1.14	1.44	74	237
Journal papers	1.28	1.31	0.30	23%	0.54	2.39	1.14	1.47	44	174
Environmental product declarations	1.38	1.35	0.13	10%	1.10	1.61	1.26	1.41	7	15
GWP values for Africa, Asia, Central and South America excluded from the above analysis as the high values skew the results for the conference category. If included the median for conference papers is 1.40 *kg CO_2-eq/L*, and journal articles 1.30 *kg CO_2-eq/L*										

The variations in GWP values could be attributed on a limited number of occasions to different methodology choices, or publication types. For example Ledgard et al. (2010) present a range of methodological choices and impact on GWP values (see Table 12). This could be open to exploitation if authors wish to select methodologies that could present their work with low GWP values that appear favourable.

Table 12 Effect of modelling assumptions and LCA results, as reported by Ledgard et al. (2010) for New Zealand lamb

Variable	Baseline assumption	Alternate assumption	Variation from baseline result (19 *kg CO_2-eq/kg* BFM)
Oceanic shipping emissions	0.05 *kg CO_2-eq /t*	0.015 *kg CO_2-eq /t*	-4%
Allocation method	Biophysical and economic	Nil	+46%
		Mass based	-34%
Animal methane emissions	Product of energy intake	Constant per animal	-50%
GWP methane	GWP_{100}25	GWP_{100}21	-9%
		GWP_{500}7.6	-39%
		GWP_{20}72	+84%
Carbon uptake and release	As per NZ's inventory for IPCC	Sequestration from soils and trees	Unknown

Despite this, more often the regional differences and variations in processes at each stage of the lifecycle assist in explaining the differences in results. In fact, many comparative studies show a diversity of GWP values from differing production processes, geographic locations or yearly yields. For example, there is Desjardins et al.'s study of beef production (2012), Leinonen et al.'s study for chicken (2012), Winther et al.'s study for fish (2009) and Maraseni et al.'s (2010) and Milà i Canals et al.'s (2008) study of vegetable production. Presenting multiple GWP values is consistent with Peters et al.'s (2010) position that a range of impacts should be reported from LCAs, as opposed to a singular figure. The authors' position when reading the meta-analysis is that the variation in farming methods and conditions has a more significant impact on the presented GWP values than methodological choices or publication type.

4.3 Using the meta-analysis for streamline accounting to inform sustainable diets. The meta-analysis and accompanying database provides GWP values for a variety of food types that could be used to calculate the GWP of differing diets in a streamlined manner. For example, median figures from an alpha version of the database in this paper were utilised by Verghese et al. (2014) to estimate and compare the GWP values for a variety of weekly shops illustrated in Menzel and D'Alusio's (2005) photographic text Hungry Planet. The study identified 'hotspots' for potential improvements in weekly diets. For example Fig. 11 shows that 54% of an Australian family's food related GWP was due to meat, fish and egg purchases (Verghese et al., 2014).

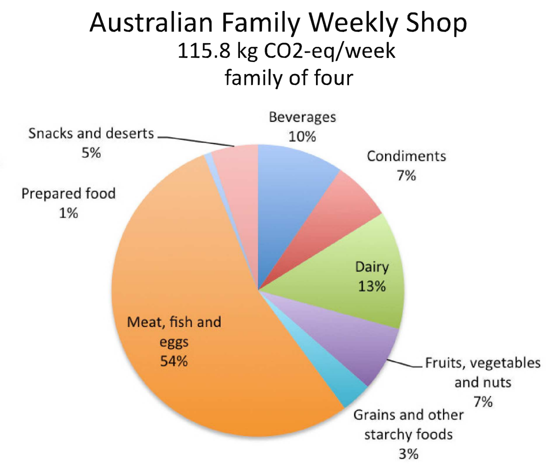

Figure 11 Summary of the GWP for the weekly diet of an Australian family (Verghese et al., 2014).

The meta-analysis and accompanying database from this paper enable numerous alternate scenarios to be created that could reduce the identified 'hotspot' in the 'weekly shop'. Three scenarios were remodelled to illustrate this point, in: a) the original diet[5], b) substituting meats with alternative meats in a 'like for like' manner, and c) creating an alternative plant and fish based diet. Diet c) calculated the protein from food purchased in other sections of Figure 11, and balanced the remaining protein from legumes, nuts and fish to meet the recommended daily intake (RDI) for protein from the National Health and Medical Research Council (2015), replacing all ingredients in Table 13A.

[5] The meat, fish and dairy section only of the original diet were remodelled using median figures from Table 5 and Table 8. There was limited variation in results for the meat, fish and dairy between the alpha version tested by Verghese (2014) and final figures utilised and presented in Table 5.

Table 13 Streamlined accounting of the GWP of the weekly shop for meat, fish and eggs

A. Meat, fish and eggs: original weekly shop	**Quantity kg**	**Protein/ 100 g**	**Protein g/ week**	**Q1** ***kg CO_2-eq/kg***	**Q1** ***kg CO_2-eq*/week**	**Median** ***kg CO_2-eq/kg***	**Median** ***kg CO_2-eq*/week**	**Q3** ***kg CO_2-eq*/ week**	**Q3** ***kg CO_2-eq*/ week**
Beef (AU & NZ)	1.00	20.89	208.90	21.64	21.64	22.88	**22.88**	25.41	25.41
Lamb (AU & NZ)	1.00	18.59	185.85	16.30	16.30	17.63	**17.63**	21.06	21.06
Chicken, whole[a]	1.00	18.56	185.55	2.12	2.12	2.80	**2.80**	4.07	4.07
Chicken breast	1.00	18.56	185.55	2.77	2.77	3.65	**3.65**	5.31	5.31
Eggs	0.38	12.56	47.73	2.45	0.93	3.39	**1.29**	4.05	1.54
Tuna	2.00	23.33	466.60	1.75	3.50	2.95	**5.90**	2.68	5.36
Fish	1.00	15.82	158.15	1.99	1.99	3.49	**3.49**	5.16	5.16
Pork (world average)	0.50	20.60	102.98	4.50	2.25	5.77	**2.89**	6.59	3.30
Ham	0.30	20.60	61.79	4.50	1.35	5.77	**1.73**	6.59	1.98
Salami	0.10	13.50	13.50	2.26	0.23	2.88	**0.29**	3.31	0.33
Total	**8.28**		**1,616.59**		53.08		**62.53**		73.52
a. Whole chicken is calculated using the carcus weight to live weight ration of 1:0.77 provided in Table 1.									
B. Meat, fish and eggs substitute weekly shop 'like for like'[b]	**Quantity kg**	**Protein/ 100 g**	**Protein g/ week**	**Q1** ***kg CO_2-eq/kg***	**Q1** ***kg CO_2-eq*/week**	**Median** ***kg CO_2-eq/kg***	**Median** ***kg CO_2-eq*/week**	**Q3** ***kg CO_2-eq*/ week**	**Q3** ***kg CO_2-eq*/ week**
Kangaroo (beef substitute)	1.00	20.85	208.50	4.10	4.10	4.10	**4.10**	4.10	4.10
Rabbit (lamb substitute 50%)	0.50	20.92	104.60	4.26	2.13	4.70	**2.35**	5.14	2.57
Duck (lamb substitute 50%)	0.50	18.28	91.40	2.58	1.29	3.09	**1.55**	3.59	1.80
Chicken, whole	1.00	18.56	185.55	2.12	2.12	2.81	**2.81**	4.07	4.07
Chicken breast	1.00	18.56	185.55	2.77	2.77	3.65	**3.65**	5.31	5.31
Eggs	0.38	12.56	47.73	2.45	0.93	3.39	**1.29**	4.05	1.54
Tuna	2.00	23.33	466.60	1.75	3.50	2.95	**5.90**	2.68	5.36
Pollock (fish substitute)	1.00	15.82	158.15	1.40	1.40	1.60	**1.60**	1.84	1.84
Pork	0.50	20.60	102.98	4.50	2.25	5.77	**2.89**	6.59	3.30
Ham	0.30	20.60	61.79	4.50	1.35	5.77	**1.73**	6.59	1.98
Salami	0.10	13.50	13.50	2.26	0.23	2.89	**0.29**	3.31	0.33
Total	**8.28**		**1,626.34**		**22.07**		**28.14**		**32.19**
b. 'like for like' attempts to substitute meat protein with another meat, e.g. kangaroo is a red meat substitute for beef, rabbit and duck are a meat substitute for lamb.									
C. Alternative weekly shop to meet RDI guidelines for protein	**Quantity kg**	**Protein/ 100 g**	**Protein g/ week**	**Q1** ***kg CO_2-eq/kg***	**Q1** ***kg CO_2-eq*/week**	**Median** ***kg CO_2-eq/kg***	**Median** ***kg CO_2-eq*/week**	**Q3** ***kg CO_2-eq*/ week**	**Q3** ***kg CO_2-eq*/ week**
Peanuts	0.50	25.50	127.50	0.81	0.81	0.83	**0.42**	0.87	0.87
Almonds	0.50	21.28	106.40	0.76	0.76	1.54	**0.77**	2.33	2.33
Pinto beans	0.40	21.42	85.68	0.73	0.73	0.73	**0.29**	0.73	0.73
Lentils	0.30	25.38	76.14	1.02	1.02	1.03	**0.31**	1.05	1.05
Pilchards	0.80	24.62	196.96	0.94	0.94	1.10	**0.88**	1.26	1.26
Muesli bars	0.25	4.10	10.23	*	*	*	*	*	*
Peanut butter	0.25	25.50	63.62	*	*	*	*	*	*
Baked beans	1.04	4.70	49.03	*	*	*	*	*	*
Milk	3.89	3.37	131.09	*	*	*	*	*	*
Cheese	0.50	23.65	118.00	*	*	*	*	*	*
Yoghurt	0.50	5.25	26.19	*	*	*	*	*	*
Bread	2.89	9.00	260.10	*	*	*	*	*	*
Breakfast cereal	0.50	8.10	40.42	*	*	*	*	*	*
Pasta	1.00	6.00	60.00	*	*	*	*	*	*
White rice	0.50	6.50	32.43	*	*	*	*	*	*
Total	**13.82**		**1,383.79**		2.14		**2.67**		3.22
* Not applicable, as an overconsumption of proteins exists in the diet of scenarios in Tables 13A and 13B. The necessary proteins could come from other type of food sources already computed in the elements of the baseline scenario (highlighted in grey above) and are different from meat, fish and eggs category in Fig.11. The recommended dietary intake for protein for the family of four was calculated to be 1365 grams per week. 40 g/day for a 9-13 year old boy, 45 g/day for a 14-18 year old women, 46 g/day for a 30-50 year old women and 64 grams per day for a 30-50 year old man (NHMRC, 2015). Protein figures are median values from the USDA National Nutrient Database (2015).									

The results from the three scenarios show a large variation in the median GWP per week. Substituting ruminant meat (beef and lamb) for non-ruminant meat (kangaroo, duck and rabbit), and selecting an alternate fish species in pollock (Table 13B) produces an estimate 30% reduction in GWP in relation to the median weekly shop in Fig 11. An alternate diet that attempts to match the recommended weekly protein intake via a plant and fish based diet (Table 13C) produces an estimate 52% reduction in GWP related to the median weekly shop shown in Fig 11[6]. Calculating the diets utilising the lower (Q1) and upper (Q3) quartile values is view by the authors as a proxy measure to calculate data uncertainty, the results provided indicate that there is a significant differences between the three diets (A, B and C) that is far from overlapping, and reliably differentiates between the GWP of the three diets (as desired by Pulkkinen et al., 2015).

The above streamlined results may be less valid than a detailed process based LCA, however this approach can be used to calculate different scenarios and what ifs, helping to better inform consumers of the choices that are available. The compiled database is the foundation for the development of streamlined tools to rapidly calculate the GWP of differing diets. The approach of compiling material $CO_{2\text{-}eq}$ inventories based on LCA data has been utilised to rapidly estimate GWP impacts for packaging (e.g. PIQET design tool), products (e.g. greenfly), and buildings (e.g. Bath Universities ICE database) (Hammond and Jones, 2008; Horne et al., 2009, p.155). As Verghese et al, argue 'While streamlined LCA tools are compromises, they can be potentially useful and have their own unique role in furthering the use of LCA data in decision making' (2010, p.108).

5 Recommendations for future LCA practice

5.1 Study under represented food groups

The meta-analysis indicates that the representation of food categories by LCA studies is unequal with respect to particular foods. The literature review identified that limited studies were available for tree nuts in almonds and cashews, and for quinoa, duck, rabbit, turkey, and kangaroo. Better representation of such foods is important as they are positioned in grey literature and popular texts as alternate low GWP protein sources. The lack of published LCA data makes the GWP values on these foods harder to validate, and is critical if attempts are made to inform dietary choice for environmental purposes.

5.2 Methodological choices to assist comparison

The use of common functional units in food LCAs would make it easier to compare reports, avoid misrepresentation and strengthen the validity of comparisons. As Schau and Fet (2008) argue, standardisation of system boundary descriptions and functional units is required. However, as illustrated in our review, different system boundaries and functional units are commonly used. The consistency of reporting in environmental product declarations EPDs that follow PAS2050, GHG protocol or ISO 14067 standards, and the development of product category rules that attempt to make food LCA's more consistent and therefore comparable is

[6] It is acknowledged that the streamline calculations are for two indicators in protein and GWP only. Changes to diet should be made following nutritional guidelines that include a broader range of metrics. However, the brief calculations above indicate that the modelled diet of the Australian family has a protein intake higher than the recommended daily intake.

welcome[7]. For example the reports available on the 'envirodec' website following the International EPD system based on ISO 14025 and EN 15804 clearly disclose impacts at each stage of the lifecycle to enable comparison (e.g. EPD international, 2015; Stefano, 2013; Villman, 2012).

These two limitations highlight ways that future food GWP comparisons could be strengthened. However, despite the concerns over methodological choices and the limitations of the meta-analysis, the hierarchy identified and median figures collated from a large body of LCA work are valid for use in streamline accounting to enable directional decisions to be made. The collation of data with percentile bands and disclosed standard deviation enables the inclusion of data uncertainty when assessing the greenhouse profiles for food-related diets, as requested by Hallström et al. (2015). The authors agree with Röös et al.'s position that 'when the ranges [of GWP values] are far from overlapping, the exact numbers are less important' (2011, p.329). The meta-analysis of LCAs communicates a clear message and presents generalizable findings that should not be dismissed because of methodological limitations.

6 Conclusion

This paper completed a meta-analysis of data relating to the greenhouse gas emissions for different food categories. While we agree that individual results from LCA studies should not be directly compared with other individual results, the meta-analysis of a large body of LCA work that draws on different methodologies, geographies and farming provides a strong greenhouse gas hierarchy across the food categories. Grains, fruit and vegetables had the lowest impact, with meat from ruminants having the highest impact. This hierarchy is well supported by other comparative literature. The median results could be used with confidence to provide a streamlined estimate of the impact of ingredients for dietary choice or menu planning for individuals and catering companies with a desire to reduce their carbon footprint, primarily by selecting food from differing categories. This is illustrated by a short case study in section 4.3 of an Australian family's weekly shop. The meta-analysis addresses the limitation of previous studies by covering a broader range of food types and GWP values.

Variations in data within each category may be attributable to different LCA approaches, including functional units, methods, geographic location and processes included. The collation of data with percentile bands enables the inclusion of uncertainty when assessing the greenhouse profiles for food-related activities. A key recommendation from the meta-analysis for future LCA practice is to study the underrepresented food types identified in the results and appendix, ideally following protocols (e.g. PAS2050, GHG protocol or ISO 14067) that assist future comparison.

7 Appendix

Please download Appendix.pdf from Data file on page 31

8 References

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[7] Liu et al (2016) paper illustrates in detail the nuanced differences between GHG reporting protocols, and calls for an international standard for carbon labelling. The authors of this paper do not have a position within this debate on which standard is preferable.

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Highlights

- Collates and analyses 369 LCA studies including 168 food types and 1718 GWP values
- Provides generalizable data for the optimisation of low GWP human diets
- Identifies underrepresented food types in need of further study
- Identifies a GWP hierarchy across food categories from low (staples) to high (ruminant livestock)
- Identifies a high variation in fish GWP dependent on species and fishing method