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Mitigating the greenhouse gas emissions embodied in food through realistic consumer choices

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HIGHLIGHTS

- UK-average diet embodies 8.8 kg CO_2e person^{-1} day^{-1} (including avoidable waste).
- Eliminating meat from the diet reduces food-related GHG emissions by 35%.
- Changing from GHG-intensive meats to less intensive meats reduces emissions by 18%.
- Cutting out all avoidable food waste reduces emissions by 12%.
- Avoiding hot-housed food or food air-freighted to the UK reduces emissions by 5%.

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ABSTRACT

The greenhouse gas (GHG) emissions embodied in 66 different food categories together with self-reported dietary information are used to show how consumer choices surrounding food might lead to reductions in food-related GHG emissions. The current UK-average diet is found to embody 8.8 kg CO_2e person^{-1} day^{-1}. This figure includes both food eaten and food wasted (post-purchase). By far the largest potential reduction in GHG emissions is achieved by eliminating meat from the diet (35% reduction), followed by changing from carbon-intensive lamb and beef to less carbon-intensive pork and chicken (18% reduction). Cutting out all avoidable waste delivers an emissions saving of 12%. Not eating foods grown in hot-houses or air-freighted to the UK offers a 5% reduction in emissions. We show how combinations of consumer actions can easily lead to reductions of 25% in food related GHG emissions. If such changes were adopted by the entire UK population this would be equivalent to a 71% reduction in the exhaust pipe emissions of CO_2 from the entire UK passenger car fleet (which totalled 71 Mt CO_2e year^{-1} in 2009).

1. Introduction

Since 1992 international agreements have been in place with the aim of stabilising and eventually reducing the emission rates of radiatively active or “greenhouse” gases (GHGs) into the atmosphere, in order to minimise the likelihood of “dangerous climate change” occurring during the 21st century (Jarvis et al., 2012). This has lead individual states to develop stringent emission targets, such as the UK Government's commitment made in its 2008 Climate Change Act to reduce the emissions of a "basket" of GHGs by 80% by 2050 against a 1990 emission baseline.

To meet such ambitious targets, downward pressure on GHG emissions is required in all sectors of economic activity, as it is clear that GHG reductions in one or several sectors will never be sufficient to meet an 80% reduction target. Where activities lead to the direct combustion of fossil fuels (e.g. transport, space heating, electricity generation and manufacturing) methods to reduce GHG emissions are obvious, if not easy. However, in some sectors of the economy, particularly in those such as agriculture in which there are very significant indirect sources of GHGs, for example, due to land use change, available methods of quantifying and reducing GHG emissions are much less transparent.

The production of food is a major source of GHG emissions to the atmosphere. While difficult to trace, emissions emanating from the global production of meat alone are estimated to be responsible for 15–24% of global GHG emissions, or approximately $(5–7) \times 10^9$ t year^{-1} of GHGs as CO_2-equivalents or CO_2e (Steinfeld et al., 2006; CO_2e being the mass of CO_2 that would have the same global warming potential, when measured over 100 years, as a given mixture of GHG emissions). These emissions occur directly,

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through the combustion of fossil fuels on farms, methane emissions from ruminants and nitrous oxide emissions from fertiliser application, and indirectly, associated with land use change. Furthermore, processes associated with the production and delivery of food to consumers, including processing, manufacturing, transportation, packaging and retail operations all contribute to the direct and indirect emissions of GHG.

Recent research has emphasised the importance of taking a systemic approach to mitigation activity in the food sector, highlighting a range of actions that might be taken to curb emissions (Bows et al., 2012; Audsley et al., 2009). These include production measures such as altering agricultural practices (for example: Audsley et al., 2009; Steinfeld et al., 2006; Williams and Audsley, 2008), supply measures such as localising production and decreasing food miles (for example: Garnett, 2006) and consumption measures relating to purchasing and lifestyle decisions made by consumers (for examples on dietary choices: see Berners-Lee et al., 2012; Coley et al., 1998; Phetterplace et al., 2001; Carlsson-Kanyama, 1998a,b, 2003, 2005; Carlsson-Kanyama and Gonzalez, 2009).

In this paper we focus on the measures that might be taken in relation to food purchasing and consumption habits by UK consumers with the aim of significantly reducing food-related GHG emissions. In order to do this we model a range of scenarios to consider what order of change would be required to reduce GHG emissions for the average diet by ~25%. Savings of this nature, across the entire UK population, are equivalent to a 71% reduction in current exhaust pipe emissions of CO_2 from the entire UK passenger car fleet, therefore offering a potentially significant reduction in GHG emissions at the national scale. The study relies on data on (a) the typical per capita diet in the UK, disaggregated by food type and amount together with loss and wastage; and (b) the GHG emissions embodied in different foods. It is based on dietary data in a UK specific context and GHG estimates based on the products and supply chains of a mid-sized UK food retailer (Small World Consulting, 2010). As such it is a UK-specific case study, but the results and conclusions are sufficiently generalisable to promote useful discussions and inform decision making in other markets.

It should be noted that this is a static assessment of emissions reductions achievable through realistic consumer choices concerning food and diet at the time of writing. As the UK (and other economies) decarbonises in response to the Climate Change Act (and similar policy interventions elsewhere) the dynamics of energy supply and use will result in on-going changes to the relative importance of different economic sectors to overall GHG emissions. In the context of food, it might be, for example, that heating for hot houses is fully decarbonised many years before transportation is decarbonised. Although the relative significance of consumer choices may therefore change in the future, this does not negate the utility of conducting this analysis, and of providing this information to consumers and policy makers, now. Furthermore, given the long lifetime of the major GHGs in the atmosphere and their cumulative nature with respect to effects on climate, it is important that emissions reductions are undertaken as rapidly as possible in sectors of the economy where immediate action will in fact lead to immediate reductions in emissions (Anderson et al., 2008). The food sector is one in which immediate effective action is possible, in contrast to, for example, electricity generation where infrastructure has a turnover timescale of decades.

2. Methods and data used

2.1. Food intake

In line with the method described in Berners-Lee et al. (2012) we obtain data from the National Diet and Nutrition Survey (Food Standards Agency, 2010a,b), a self-reported survey of UK food consumption. Based on this we have calculated an age and gender-weighted average diet with mean energy consumption across the entire population of 1807 kcal person^{-1} day^{-1}. This consumption is disaggregated into 61 food categories, some specific and some rather broad. This provides a bottom-up representation of per capita daily food intake in the UK which we assume to be representative of typical or population-average consumption.

Recent research suggests that 30–50% of food produced globally is wasted before it can be eaten (Institution of Mechanical Engineers, 2012); hence relying solely on the NDNS self-reported calorific intake will significantly underestimate the scale of GHG emissions attributed to food. Therefore we use a top-down estimate of food available for consumption in the UK to reconcile these concerns and ensure a more inclusive coverage of the amount of food currently used to sustain the UK's population. Using data obtained from the UN Food and Agriculture Organisation 'food balance sheets' (FAOSTAT, 2011) we scale the initial estimate of 1807 kcal person^{-1} day^{-1} to provide an estimate of the average food consumption, inclusive of food lost and wasted through the supply chain and in consumer homes (Quested and Parry, 2011).

In addition we factor an underreporting factor of 20% as discussed in Berners-Lee et al. (2012) to account for the known underreporting of food intake in self-reporting surveys (Poppitt et al., 1998; Goris et al., 2000; Johansson et al., 2001; Pryer et al., 1997; Bothwell et al., 2009). Accordingly the approximate per capita energy available in the country is 3458 kcal day^{-1}. The assumption that remains is that all food is wasted, lost or under reported evenly across all of the 61 product categories. We are not aware of any evidence to the contrary although recognise that there may be more waste of some foods (e.g. fruit or vegetables), compared with others (e.g. meat).

The following terms are used to describe the food and energy content dealt with throughout this paper: food *supply*, food *purchased* and food *eaten*. Table 1 defines these terms with the calories associated with each. The specificity of the terms is intentional to maintain precision and accuracy when disaggregating diet and associated emissions.

2.2. Embodied GHG emissions in food

The emissions factors for 66 product categories, from cradle to point of sale, are calculated and reported in kg CO_2e kg^{-1}, based

Table 1
Definitions of the UK *per capita* daily food energy terminologies used in this paper.

Food	kcal day^{-1}	Description
Supply	3458	This is the top-down total availability of calories in the whole food system, including food lost and wasted. Obtained from FAOSTAT, 2010.
Purchased	2789	This is food purchased by the average consumer, including post-purchase waste.
Eaten	2259	This is food actually consumed and thus does not include any waste. This is the NDNS self-reported daily intake, adjusted to account for under-reporting.

on a recent evaluation of a mid-sized UK supermarket's product supply chains. The emissions factor for each product includes emissions from production to the farm gate, transport from farm to processing and/or distribution centres, processing, packaging, storage and supermarket operations (including transport to store). The calculation of embodied GHG emissions follows the principles of the GHG Protocol (Bhatia and Ranganathan, 2004) and draws upon a range of secondary sources. The methods used to derive the emissions factors for each product type are consistent with those in Berners-Lee et al. (2012) but provide a more detailed review of the secondary data sources available to bring the emission factors in-line with the highest quality and most representative data available. For transparency, a description of the process used to derive the emissions factor for each life cycle stage is described in the following paragraphs. The emission factors, along with the secondary sources used to estimate emissions to the farm gate are presented in Table 2.

2.2.1. Farming and processing (cradle – regional distribution centre)

Emissions up to the farm gate are estimated by taking a selection of representative products within each of the food categories and applying emission factors from previously published life cycle assessments (LCA). These sources are listed in Table 2.

Similar reviews of this nature have been conducted previously, the most commonly cited being a Swedish study by Wallen et al. (2004). However, here we update and improve upon predecessors by accounting for the variations in system boundaries and reporting principles of different LCAs. We also include emissions from supermarket operations and non-product supply chains based on a detailed analysis of energy use, refrigerants, transport and procurement. Wherever possible secondary data has been used to calculate the GHG emissions per unit weight of product from cradle to the regional distribution centre (RDC), excluding transport and packaging for which we have bespoke data from the case study supermarket. In a few cases where it was not possible to separate out the transport to the RDC and/or packaging we have deducted our bespoke transport and/or packaging emissions in order to eliminate double counting whilst making full use of the most accurate and appropriate data available for each life cycle stage.

In most cases, primary food processing emissions (for example, grain milling) are included in the secondary data obtained for emissions factors. Where this is not the case or where there is substantial secondary processing (for example, in the production of ready meals) we include an estimate of the emissions based on bespoke data from the supermarket on the processes occurring and emissions factors from Foster et al. (2006).

2.2.2. Packaging (transit and consumer)

As described in Berners-Lee et al. (2012), the emissions embodied in packaging materials are based on data supplied by the retailer on the mass of packaging associated with each food category, disaggregated by material. An emissions factor (kg CO_2e kg^{-1}) associated with each material type was obtained (Hammond and Jones, 2008; Utrecht Centre for Energy Research, 2001). The emissions from transit packaging and plastic bags were estimated similarly.

2.2.3. Transport

The GHG emissions for transport of food from the point of production to the RDC are estimates obtained by modelling specific journey options for a range of representative products within each category. Emission factors from Defra (2011) are used for each transport mode, supplemented with environmental input–output (EIO) methods (Hendrickson et al., 1998; Miller and Blair, 1986) to accommodate indirect emissions from transport, for example, the emissions resulting from fuel supply chains and embodied emissions and upkeep of vehicles (see Berners-Lee et al., 2011, for a full description of this method).

Despite these measures there remain two sources of uncertainty. Firstly, due to the inadequacy of available data at the time of publication, our calculations do not accommodate differences in the carbon intensity of transport within different countries. Consequently the emissions of transporting a tonne of products per kilometre in China are treated equally to that of transporting the same product per kilometre in the UK, for example. Secondly, due to the complexity of the food distribution network, there are insufficient data available to allocate specific vehicles for every journey leg. We base our calculations on representative transport categories from Defra (2011). Transport by sea is allocated to the bulk carrier 100,000–199,999 dwt category (average 50% load; 0.008 kg CO_2e tonne^{-1} mile^{-1}); transport by land is based on a UK average for all HGVs (0.380 kg CO_2e tonne^{-1} mile^{-1}) and air freight separated into long haul and short haul journeys (5.35 and 2.44 kg CO_2e tonne^{-1} mile^{-1} respectively, including uplift and great circle distance adjustments as detailed in Defra, 2011).

2.2.4. Warehouse and distribution, refrigeration and overheads

GHG emissions from warehouse energy use, transport from the RDC to stores and in-store refrigeration are calculated and allocated to product categories by weight sold (emissions from refrigeration are allocated to chilled product categories only). Overheads refer to the other retailer activities, including energy consumption, staff business travel, postage and courier services, waste disposal, paper, printing and other office and marketing consumables. The direct and indirect emissions from these activities were calculated using a hybrid process based LCA and environmentally extended input–output analysis and attributed to food product categories by value.

2.3. Calculating dietary GHG emissions data

Using the 66 product categories from the supermarket evaluation we are able to map the emissions to 61 closely-corresponding food groups in the NDNS survey, thus establishing an average emissions factor for each category based on representative products. Having established the emissions factor for each category and with the associated nutritional data for each we calculate the "carbon footprint" of a typical, age and gender weighted, UK diet by combining the emissions data (kg CO_2e kg^{-1}) with the daily mass of each food type consumed.

We calculate that the baseline figure for the GHG emissions from the UK average diet is 8.81 kg CO_2e person^{-1} day^{-1}. For clarification this figure includes both food eaten and food wasted (post-purchase). This is 19% higher than the Berners-Lee et al.'s (2012) estimate of 7.4 kg CO_2e per person^{-1} day^{-1}, following our more fine-grained analysis of secondary data on the embodied emissions in food products and a re-evaluation of the supply chain practices of our case-study supermarket. Consequently, in some cases the emissions factors have changed, the most notable example being the inclusion of emissions from deforestation resulting from some cattle supply chains. The emissions factors for production of beef and dairy include an allocation for deforestation based on attribution of deforestation emissions to the output from deforested land according to value. The detail of this process is contained within the methodologies of the LCAs used (Williams et al., 2006; Williams and Audsley, 2008). In other cases, our product categories have altered, to refine those used in the previous study. For example 'cabinets raw' as a category in the

Table 2
kg CO_2e kg^{-1} by life cycle stage (to point of sale) for 66 product categories.

	Farming & processing	Transit packaging	Consumer packaging	Transport	Warehouse & distribution	Refrigeration	Overheads	Total	Secondary sources (for farming & processing LCA)
	kg CO_2e kg^{-1}								
Wines	0.55	0.07	0.51	0.52	0.04	0.03	0.70	2.41	Garnett (2007)
Spirits and liqueurs	0.65	0.07	0.49	0.25	0.04	–	1.67	3.16	Garnett (2007)
Beer and cider	0.28	0.07	0.56	0.17	0.03	–	0.24	1.35	Garnett (2007)
Soft drinks	0.19	0.08	0.23	0.27	0.02	–	0.11	0.90	Bespoke calculation based on water and sugar in ratio 13:87
Juice	0.71	0.08	0.11	0.54	0.02	–	0.15	1.61	Beccali et al. (2010)
Water	0.03	0.08	0.29	0.11	0.02	–	0.04	0.58	Bespoke calculation based on Foster et al. (2006)
Apples and pears	0.20	–	0.01	0.21	–	0.03	0.22	0.66	Williams and Audsley (2008) (64% British, 36% New Zealand)
Citrus	0.33	–	0.01	0.24	–	–	0.31	0.90	Ribal et al. (2009)
Bananas	0.33	–	0.00	0.14	–	–	0.12	0.60	Assumed similar as citrus to farm-gate
Berries	0.66	–	0.05	1.77	–	0.10	0.84	3.42	Williams and Audsley (2008) (38% British, 62% Spanish)
Stone fruit & grapes	0.53	–	0.09	0.55	–	0.10	0.53	1.80	Assumed similar as berries to farm-gate
Melons	0.33	–	0.01	0.24	–	–	0.63	1.21	Assumed similar as citrus to farm-gate
Exotic fruit	0.33	–	0.03	1.64	–	0.26	0.63	2.90	Assumed similar as citrus to farm-gate
Dried fruit and vegetables, nuts & seeds	2.66	0.07	0.08	0.61	0.02	–	0.82	4.26	50% Nuts, treated as fruit, 50% berries in ratio 5:1 wet weight to dry weight
Frozen Fruit	0.71	–	0.22	0.13	0.67	0.52	0.51	2.77	Weighted average for fruit. Assume 10% offcuts.
Prepared fruit	0.47	0.03	0.05	0.53	0.01	0.52	0.85	2.46	Weighted average for fruit. Assume 10% offcuts.
Tinned fruit	0.60	0.07	0.22	0.38	0.02	–	0.29	1.58	Weighted average for fruit. Assume 10% offcuts.
Potatoes	0.23	–	0.01	0.16	–	–	0.12	0.52	Williams and Audsley (2008) (15% earlies, 5% Mediterranean, 83% British main crop)
Other roots	0.23	–	0.01	0.15	–	0.08	0.13	0.60	Assumed similar as potatoes to farm-gate
Salad	0.39	0.08	0.78	0.55	0.02	0.52	1.32	3.66	Hospido et al. (2009)
Tomatoes	3.40	–	0.18	0.18	–	–	0.44	4.20	Williams and Audsley (2008)
Other vegetables	1.15	–	0.12	0.24	–	0.26	0.37	2.13	Weighted average of all vegetable categories
Mushrooms	3.40	–	0.40	0.15	–	–	0.45	4.40	Treated as tomatoes
Exotic vegetables	3.40	0.00	0.09	3.75	0.00	0.26	0.61	8.10	Treated as tomatoes
Frozen vegetables	1.51	–	0.04	0.12	0.63	0.52	0.23	3.06	Weighted average of all vegetable categories
Prepared vegetables	1.26	0.03	0.07	0.20	0.01	0.52	0.64	2.73	Weighted average of all vegetable categories
Tinned vegetables	1.39	0.07	0.27	0.38	0.03	–	0.21	2.34	Weighted average of all vegetable categories
Milk	0.97	–	0.05	0.01	–	0.52	0.08	1.64	Based on mass balance in FAO (2010)
Cheese	12.12	0.08	0.08	0.17	0.02	0.52	0.66	13.65	Based on mass balance in FAO (2010)
Cream	4.56	0.08	0.16	0.06	0.02	0.52	0.39	5.77	Based on mass balance in FAO (2010)
Yoghurt & fromage frais	2.69	0.08	0.10	0.13	0.02	0.52	0.33	3.87	80% Fermented milk, (FAO, 2010); 20% average fruit
Butter	9.66	0.08	0.02	0.19	0.02	0.52	0.59	11.08	Nilsson et al. (2010)
Margarine	1.16	0.08	0.08	0.19	0.02	0.52	0.37	2.43	Nilsson et al. (2010)
Soya	0.19	0.08	0.07	0.19	0.02	0.52	0.18	1.26	10% Soyabean (Williams et al., 2006) 90% water
Ice cream	1.10	0.08	0.15	0.20	0.02	0.52	0.30	2.36	Based on mass balance in FAO (2010)
Powdered milk	10.56	0.07	0.26	0.11	0.02	–	0.63	11.65	Based on mass balance in FAO (2010)
Eggs	4.25	0.08	0.10	0.06	0.02	–	0.40	4.90	Williams et al., 2006
Beef	23.97	0.01	0.01	0.06	0.02	0.52	0.54	25.13	Williams and Audsley (2008)
Lamb	14.14	0.01	0.00	0.06	0.02	0.52	0.77	15.53	Williams and Audsley (2008)
Poultry	2.82	0.01	0.02	0.07	0.02	0.52	0.59	4.05	Williams and Audsley (2008)
Pork, bacon & sausages	9.07	0.01	0.01	0.09	0.02	0.52	0.57	10.29	Williams et al. (2006)
Processed & cooked meat	10.46	0.08	0.12	0.17	0.95	0.52	1.31	13.61	Weighted average for meat
Tinned meat	10.59	0.07	0.39	0.75	0.03	–	0.67	12.50	Weighted average for meat
Fresh fish	1.12	0.01	0.06	0.17	0.02	0.52	0.78	2.68	Nielsen et al. (2003)
Tinned fish	1.34	0.07	0.68	0.47	0.03	–	0.91	3.50	Nielsen et al. (2003)
Vegetarian (meat alternatives)	3.09	0.07	0.27	0.11	0.02	0.52	0.73	4.81	Mixture of soya, weighted average of all vegetable categories, wheat flour (Williams et al., 2006) and cheese in ratio 40:30:15:15
Frozen meat and fish	9.91	–	0.17	0.13	0.67	0.52	0.80	12.20	Weighted average for meat and fish (exc. frozen, tinned) multiplied by ratio of frozen cod: fresh cod (Nielsen et al., 2003)
Other meat and fish	8.49	–	0.01	0.17	–	0.52	0.44	9.62	Weighted average for meat and fish (exc. frozen, tinned)

Sandwiches	6.28	–	0.11	0.06	0.02	0.52	0.98	7.97	From ingredients
Pies	2.76	0.07	0.06	0.05	0.02	0.52	0.61	4.08	From ingredients
Ready meals, pizza, fresh pasta	4.58	0.07	0.19	0.16	0.02	0.52	0.66	6.20	From ingredients
Desserts	1.80	0.07	0.25	0.10	–	0.52	0.59	3.33	From ingredients
Bread	0.84	–	0.03	0.24	0.02	–	0.27	1.40	Nielsen et al. (2003)
Rice	2.93	0.07	0.16	0.23	0.02	–	0.41	3.82	Kasmaprapruet et al. (2009)
Pasta	1.01	0.07	0.09	0.18	0.02	–	0.26	1.63	As for flour Williams et al. (2006)
Cake	3.24	0.07	0.20	0.17	0.02	–	0.71	4.41	From ingredients
Biscuits	3.35	0.07	0.24	0.19	0.02	–	0.61	4.47	From ingredients
Cereals	0.89	0.07	0.20	0.13	0.02	–	0.43	1.73	From ingredients
Crisps & snacks	2.61	0.07	0.25	0.30	0.02	–	0.84	4.09	Nilsson et al. (2011)
Home baking (exc. eggs)	0.82	0.07	0.03	0.40	0.02	–	0.08	1.43	Flour 45% (Williams et al., 2006) sugar 55%
Jam, honey, marmalade	1.15	0.07	0.61	0.86	0.04	–	0.54	3.27	Sugar 50%, berries 30%, citrus 20%
Soup	2.11	0.07	0.46	0.14	0.03	–	0.30	3.11	From ingredients
Condiments	1.19	0.07	0.51	0.26	0.03	–	0.54	2.60	From ingredients
Confectionary	2.71	0.07	0.39	0.29	0.03	–	0.98	4.46	Busser and Junglbuth (2009), Nilsson et al. (2011)
Beverages	10.08	0.07	0.42	0.47	0.10	–	1.33	12.46	Busser et al. (2008), Doublet et al. (2010), Ntiamoah et al. (2008)
Miscellaneous food	0.71	0.08	0.57	0.30	–	0.26	0.55	2.47	Average all food

previous assessment has been disaggregated into ‘chicken’, ‘pork’, ‘beef’, ‘lamb’ and ‘processed meats’ to enable greater accuracy, flexibility and a more intuitive assessment of the GHG emissions in different product lines. A further area of disparity occurs as the supply chains of the case study supermarket have altered in response to GHG mitigation efforts since the previous study. We assume these to be representative of the industry as a whole. If however, these changes are industry leading, the GHG emissions modelled here will be conservative estimates of the national average.

2.4. *Nutrition and cost data*

By multiplying data on the nutritional content of each food type, obtained from the NDNS dataset (protein, carbohydrate, added sugar, fat, and sodium), by the food mass in each diet, a comparison can be made between the embodied CO_2e emissions and the nutrients in a diet to establish which foods provided the most nutrients for the amount of GHGs released and to understand some of the health implications of different dietary choices. In order to compare the costs of each scenario we use food price data from the case-study retailer. Although these costs are likely to be slightly higher than the national average for each item, they allow the relative monetary costs of different dietary choices to be compared.

2.5. *Scenarios*

Here we use the quantitative estimate of the GHG emissions associated with different components of the average UK diet to consider the relative significance of realistic actions that might be taken by consumers. These are combined to consider a range of scenarios that would enable consumers to substantively reduce their GHG emissions from food (by 25%), targeting actions in different stages of the life cycle that might realistically provide a significant point of intervention for the average consumer. These are (i) actions that can be taken without changing diet; (ii) actions that can be taken without changing existing practices around food waste; (iii) actions that can be taken without special attention paid to the origin of food; and (iv) a mixture of all actions.

2.5.1. *Variables*

We use the following variables as a means to explore the above scenarios: waste; overall meat consumption; a shift to pork and poultry; air-freighting and hot-housing; and packaging. These are modelled so as to eliminate double counting. For example, the benefits of a shift of meat consumption from ruminants to other animals (see below) will offer no further advantage if a 100% meat reduction is achieved.

2.5.2. *Waste*

At the global scale, 30–50% of all food produced is wasted before it can be consumed (Institute of Mechanical Engineers, 2012). In order to quantify the impact consumer choices around waste it is necessary to distinguish between post-purchase waste and waste resulting elsewhere in the supply chain. Post-purchase waste in the UK is estimated to be approximately 19% of all food, over 7.2 million tonnes, of which 4.4 million tonnes (12% of all food) is avoidable (Quested and Parry, 2011). Based on this, the variable modelled here quantifies the effects of reducing the amount of food wasted in 5% increments, with a 100% reduction equivalent to the elimination of all avoidable post-purchase food waste.

Although it is unlikely that waste is avoided equally across all categories there are insufficient data available to allow defendable alternative assumptions to be made. The foods most likely to be wasted are a mix of short shelf-life products and foods that are bought or cooked in more bulk than can be eaten at one meal. Short shelf-life foods include fresh meat, dairy fruit, vegetables and bread. Some but not all of these are associated with higher emissions. Overall we see no obvious strong basis for assuming that wasted food is either more or less emissions-intensive than average.

2.5.3. Reductions in meat consumption

Berners-Lee et al. (2012) considered the relative benefits of different vegetarian and vegan diets in detail. In this model we estimate the relative impacts of decreasing meat consumption (again using 5% increments). This is consistent with Scenario 3, the "healthy" vegetarian diet, modelled in Berners-Lee et al. (2012). This redistributes calories from meat consumption across realistic plant-based alternatives, whilst dairy consumption remains unchanged. In this action we assume that the consumption of all meats is reduced by the same proportion.

2.5.4. Shift from ruminants (beef and lamb) to pork and poultry

This variable models the impact of replacing the calorific value of meat from highly carbon-intensive ruminant animals with the lower carbon-intensive meat alternatives, pork and poultry. We modelled this as a binary 'all or nothing' action in which there is either a 100% shift or no change. The difference in the emissions intensities of different meats shown in Table 3 which illustrates the possibility for cutting emissions without cutting meat consumption.

2.5.5. Packaging

In this variable we model the impact of reducing food packaging in 5% increments by reducing the overall mass of packaging across different products, with 100% assuming all packaging is avoided. However it is unlikely that a 100% reduction could be achieved, or would even be desirable, as some packaging serves to extend the life, integrity and hygiene of food products (WRAP, 2013).

2.5.6. Air-freight and hot-housing

In this scenario we model the impact of switching transport from air-freighting to shipping and eliminating hot-housing. To remove the air-freighted component we shift the calories to products that have a longer shelf life but similar nutritional and farm emission intensity, such as from cherries to apples. In a similar fashion we shift the calories from hot-housed produce to similar seasonal alternatives. This is a binary choice, where air freight and hot-housing is either 100% changed or not at all.

These two variables are modelled in combination as to separate them risks oversimplifying the issue of local produce or air-miles. While consumers can achieve GHG reductions by choosing locally produced products this needs to be carefully balanced against seasonality. For example, purchasing British grown tomatoes out-of-season is currently more carbon intensive than shipping them from Spain, but may offer saving compared to those transported by air from further afield. While there is more to this debate than simply GHG emissions it is worthy of note that from a GHG perspective the issue of localising production is problematic.

Table 3
Comparison of emissions factors (field to checkout) for different meats.

Meat	kg CO_2e kg^{-1}
Beef	25.13
Lamb	15.53
Poultry	4.05
Pork, bacon and sausages	10.29

3. Results

Table 4 shows the average daily and annual values per capita and the potential reductions in GHG emissions as a proportion of the baseline for each of the actions taken at 100%. We also show the total saving if actions were taken across the whole UK population.

Using the actions described above, the maximum calculated food-related GHG emissions reduction that is possible to achieve by cutting out all waste, meat, packaging, air-freighting and hot-housing delivers a 53% reduction in GHG emissions. This gives a food 'carbon footprint' of 4.16 kg CO_2e per capita per day, compared to the current UK average of 8.81 kg CO_2e per capita per day. This is equivalent to 107 Mt CO_2e saved per year if the whole population of the UK were to make these changes. This is a theoretical limit rather than a realistic possibility.

Cutting out all meat consumption results in a 35% GHG emissions saving. This is a realistic option already adopted by millions of vegetarians, yet one to which many other people are strongly adverse. Clearly this option can be partially adopted with partial emissions benefits achieved. To complement these emission savings, there are small cost savings (3%) achieved whilst retaining a balanced diet.

Shifting consumption from higher carbon-intensive meats, i.e. beef and lamb, to less carbon-intensive meats, i.e. pork and poultry, delivers an 18% reduction in total emissions. This is a realistic option which may be acceptable to those who would not consider reducing their meat consumption. It also offers a small complementary cost savings (2%).

Cutting out all avoidable waste delivers a smaller emissions saving of just 12%, with greater cost savings (10%). At face value this action looks straightforward and has clear co-benefits that will interest almost all consumers. Total waste elimination is considered unrealistic (calculations are based on Quested and Parry's (2011) estimate that avoidable post-purchase food waste makes up 12% of all food) but partial implementation is also beneficial and can be done without diet change and in addition to other actions.

Eliminating hot-housing and air-freighting offers a 5% reduction in emissions with little impact on cost or diet. This may be a relatively difficult action for individual consumers to implement at present due to the paucity of available information on the details of transport and growing practices. However if that barrier were removed by provision of information, the action could be relatively easy to implement and may be combined with any or all other actions.

The total elimination of packaging is neither possible nor desirable and delivers just 3% emissions savings and no cost savings. Nevertheless partial implementation of this action, avoiding obvious excesses, could be relatively easy for many and can be done in conjunction with any or all other actions.

3.1. Thinly spread

Table 5 shows the results for a range of scenarios which can broadly be termed as "thinly spread" actions. It shows that substantial reductions in GHG emissions can be made without compromising the health or the financial wellbeing of the individual, with some flexibility as to how this might be achieved.

Firstly, by reducing meat consumption, waste and packaging by 50% with no action taken to remove air-freighting or hot-housing

Table 4
Average food impacts of the different scenarios.

	Daily average food supply ($person^{-1}$)				Nutrients eaten (g^{-1} $person^{-1}$ day^{-1})					Annual average food supply ($person^{-1}$)			Annual total for UK population	
	Energy	Mass	GHG emissions	Cost	Protein	Carbs.	Added sugar	Fat	Sodium	Mass	GHG emissions	Change	Mass	GHG emissions
Units	kcal	g	kg CO_2e	£	g	g	g	g	g	kg	kg CO_2e	%	Mt	Mt CO_2e
Baseline	3458	2325	8.81	7.48	87	283	72	82	2.61	849	3214	0	53.6	203.07
Maximum action taken	3056	2218	4.16	6.53	57	306	64	60	2.16	810	1517	−53	51.2	95.87
Eliminate waste	3056	2055	7.79	6.74	77	250	63	72	2.31	750	2843	−12	47.4	179.62
Eliminate meat	3458	2509	5.76	7.25	64	346	73	67	2.44	916	2103	−35	57.9	132.84
Eliminate ruminants	3458	2324	7.26	7.31	91	282	72	82	2.85	848	2649	−18	53.6	167.37
Eliminate air-freight & hot-housing	3458	2325	8.36	7.48	87	283	72	82	2.61	849	3053	−5	53.6	192.87
Eliminate packaging	3458	2325	8.52	7.48	87	283	72	82	2.61	849	3111	−3	53.6	196.54
Eliminate meat and packaging	3257	2277	6.73	7.00	71	296	68	70	2.38	831	2456	−24	52.5	155.15
All actions taken that do not require dietary change	3056	2055	7.15	6.74	77	250	63	72	2.31	750	2609	−19	47.4	164.83
All actions taken that do not require sourcing change	3056	2218	4.84	6.53	57	306	64	60	2.16	810	1767	−45	51.2	111.61
All actions taken that do not require waste reduction	3458	2509	4.70	7.25	64	346	73	67	2.44	916	1715	−47	57.9	108.33

Table 5
Average calorific intake, GHG emissions (kg CO_2e $person^{-1}$ day^{-1}), cost ($person^{-1}$ day^{-1}) and reduction from baseline scenario (%).

	Energy (kcal)		GHG (kg CO_2e)		Cost (£)	
	Supply required	Saving (%)	Resulting from diet	Saving (%)	Resulting from diet	Saving (%)
50% Less meat consumption, 50% less waste and 50% less packaging	3257	5.8	6.73	23.6	7.00	6.5
25% Less meat consumption, shift to pork and poultry, 25% less waste and 25% less packaging	3357	2.9	6.62	24.8	7.12	4.9
15% Less meat and packaging, shift to pork and poultry and 50% less waste	3257	5.8	6.59	25.2	6.94	7.3

or to switch from beef and lamb to pork and poultry achieves a 24% saving in GHG emissions, resulting in embodied GHG emissions in the diet of 6.73 kg CO_2e day^{-1}. Secondly, a switch from lamb and beef to pork and poultry combined with 25% levels of action in all other areas (excluding air-freighting and hot-housing) obtains similar savings of 25% (6.62 kg CO_2e day^{-1}). The third variation modelled considers a 15% reduction in meat consumption, broadly consistent with the 'Meat-free Monday' ethos of avoiding meat entirely for one day a week. To obtain savings in the region of 25% this must be combined with a complete switch from lamb and beef to pork and poultry and some combination of the other variables, with reducing waste offering the most fruitful savings. In the scenario modelled here a 15% reduction in meat combined with a shift to pork and poultry, 50% less waste and 15% less packaging, but no change to air-freighted and hot-housed produce obtains savings of approximately 25% resulting in a diet of 6.59 kg CO_2e day^{-1}.

In addition to GHG mitigation, each of these diets offer financial savings (5–7% saving from baseline) and a reduced calorific intake (3–6%) while maintaining a healthy balance of protein, carbohydrates, fats, sugars and sodium.

3.2. No change to product sourcing

Table 6 shows the results for a selection of action scenarios that do not involve the individual concerning themselves with the origin or mode of transport of the food products they consume. Again, substantial reductions in GHG emissions are obtainable and there remains flexibility as to how this might be achieved.

Removing air-freighting and hot-housing places greater dependence on other variables. However as one of variables with least impact (see Table 4) the scenarios remain realistic, without necessarily requiring the individual to take up a vegetarian diet or a militant approach to waste.

By combining a meat free day with a switch from lamb and beef to pork and poultry requires a 50% reduction in waste and 25% reduction in packaging to obtain overall GHG savings of 26% with a diet of 6.56 kg CO_2e day^{-1}. Alternatively two meat free days combined with a shift to pork and poultry, 20% less waste and 25% less packaging achieves a slightly reduced saving of 25%, both resulting in a diet of 6.58 kg CO_2e day^{-1}.

Conversely, without a shift to pork and poultry a concerted effort to reduce all other areas is required to compensate. The scenario modelled, 50% less meat and 65% less waste and packaging, achieves a 25% reduction in GHG emissions, giving a diet resulting in 6.56 kg CO_2e day^{-1}.

Finally, for comparison, similar savings can be obtained by reducing meat alone by 75%, giving a diet resulting in 6.52 kg CO_2e day^{-1}.

Scenarios under this banner offer financial savings (2–8%) and reduced calorific intake ($\leq 7.5\%$) while maintaining a healthy balanced diet.

3.3. No attention to waste or packaging

Table 7 shows the results for a selection of scenarios that fit within this category. By varying changes to meat consumption and composition combined with reducing air-freighted produce,

Table 6
Average calorific intake, GHG emissions (kg CO_2e person^{-1} day^{-1}), cost (person^{-1} day^{-1}) and reduction from baseline scenario (%).

	Energy (kcal)		GHG (kg CO2e)		Cost (£)	
	Supply required	Saving (%)	Resulting from diet	Saving (%)	Resulting from diet	Saving (%)
15% Less meat, shift to pork and poultry, 50% Less waste, 25% less packaging	3257	5.8	6.56	25.5	6.94	7.3
30% Less meat, shift to pork and poultry, 20% Less waste, 25% less packaging	3378	2.3	6.58	25.2	7.15	4.5
50% Less meat, 65% less waste and packaging	3197	7.5	6.56	25.5	6.89	7.9
75% Less meat	3458	0	6.52	25.9	7.31	2.3

Table 7
Average calorific intake, GHG emissions (kg CO_2e person^{-1} day^{-1}), cost (person^{-1} day^{-1}) and reduction from baseline scenario (%).

	Energy (kcal)		GHG (kg CO_2e)		Cost (£)	
	Supply required	Saving (%)	Resulting from diet	Saving (%)	Resulting from diet	Saving (%)
Shift to pork and poultry, 20% less meat, eliminating air-freighting and hot-housing	3458	0	6.45	26.7	7.30	2.4
Shift to pork and poultry, 40% less meat	3458	0	6.66	24.4	7.29	2.6
No shift to pork and poultry, 55% less meat, no AF&HH	3458	0	6.51	26.1	7.36	1.7

Table 8
Average calorific intake, GHG emissions (kg CO_2e person^{-1} day^{-1}), cost (person^{-1} day^{-1}) and reduction from baseline scenario (%).

	Energy (kcal)		**GHG (kg CO_2e)**		**Cost** (£)	
	Supply required	Saving (%)	Resulting from diet	Saving (%)	Resulting from diet	Saving (%)
100% Less waste and packaging, elimination of air-freighting and hot-housing	3056	11.6	7.15	18.8	6.74	10.0
25% Less waste and packaging, elimination of air-freighting and hot-housing	3357	2.9	8.05	8.5	7.30	2.5

reductions in GHG of approximately 24–27% are achieved, resulting in emissions of ~6.5 kg CO_2e day^{-1}.

While substantial savings are achievable, it requires a concerted effort to reduce meat consumption and/or a switch from lamb and beef to pork and poultry as avoiding air-freighting offers a relatively small proportion of the savings.

No reductions in calorific intake are achieved, unlike the previous scenarios, as the changes observed here result from where the calories are obtained (i.e. less meat), not changing the amount purchased. This, again, maintains a healthy, balanced diet. However the financial savings are less, in the region of 2–3%.

3.4. No change in diet

Table 8 demonstrates that even with the maximum possible reductions in waste, packaging and air-freighting a scenario in which diet itself is not changed makes achieving a 25% reduction in emissions impossible. In the most extreme scenario (which is equivalent to 'Zero Diet Change' in Table 4) GHG emissions savings are only in the region of 19%, obtaining a diet resulting 7.15 kg CO_2e day^{-1}. In a more conservative version, with 25% reduction in waste and packaging in addition to eliminating hot-housing and air-freighting, savings only equate to an 8.5% reduction from the baseline, a diet of 8.05 kg CO_2e day^{-1}.

The relatively large financial savings (10%) offered in the extreme scenario are the result of households consuming all food purchased and avoiding as much waste as possible, thereby reducing the amount of food purchased overall.

4. Discussion

Our estimates are subject to a number of uncertainties. Firstly, each of the data sources for the average diet contain methodological uncertainties somewhat reconciled by combining top-down estimates of total food available and bottom-up estimates of food eaten, as discussed in the methodology. Secondly, while the reassessment of the supermarket analysis conducted here enabled a much closer match between the food categories reported in the NDNS data and the food categories in our LCA/EIO analysis, some disparity remains. Thirdly, while care has been taken to identify the most accurate, up-to-date and consistent emissions factors available, each is based on LCA that are subject to considerable uncertainty. Finally, there are always difficulties in applying secondary data for emissions factors to products due to their highly case-specific nature. However, we have identified no basis to suggest uncertainties in emission factors should vary across food categories. Therefore comparisons can be made across diets, even if the absolute values are not necessarily accurate.

Using predominantly process-based LCA supported by EIO analysis to improve system completeness, we estimate the current average diet in the UK, weighted by age and gender, to generate GHG emissions in the order of 8.8 kg CO_2e person^{-1} day^{-1}. This equates to approximately 3.2 t CO_2e person^{-1} year^{-1} or 203 Mt CO_2e year^{-1} for the UK population. This represents approximately 20% of UK GHG emissions (including those embodied in goods produced abroad).

We have demonstrated that it is feasible for consumers to make changes to their consumption of food that result in substantial

Table 9
Resultant GHG intensity of diet following actions taken (kg CO_2e person^{-1} day^{-1}).

	Saving as single action	Compound impact of actions (maximum action taken)				
		Eliminate waste	Eliminate meat	Eliminate ruminants	Eliminate air freight & hot-housing	Eliminate packaging
Baseline	8.81					
Eliminate waste	7.79	7.79				
Eliminate meat	5.76	5.10	5.76			
Eliminate ruminants	7.26	5.10	5.76	7.26		
Eliminate air freight & hot-housing	8.36	4.41	4.99	6.82	8.36	
Eliminate packaging	8.52	4.16	4.70	6.54	8.08	8.52

GHG emissions savings (~25%). In all cases the resulting consumption offers a diet that is cheaper, less GHG intensive and potentially healthier. All diets contain adequate protein, most have less fat and sugars and none lead to an increase in salt consumption (with the exception of those which rely on a shift to pork and poultry). A reduction of 25% in food-related GHG emissions across the whole UK population equates to ~50 Mt CO_2e year^{-1}. This is equivalent to a 71% reduction in the exhaust pipe emissions of CO_2 from the entire UK passenger car fleet (2009). Additionally, while the scenarios modelled here pose a means of achieving 25% reductions, the maximum combined impact is 53%, amounting to ~107 Mt CO_2e year^{-1}. With action taken across the supply chain this reduction could be greater still.

Of the scenarios modelled it is clear that those with efforts to reduce meat consumption and/or switch from GHG-intensive meats, i.e. beef and lamb, towards less emissions-intensive meats, i.e. pork and poultry, are the most influential for GHG mitigation. Eliminating meat consumption entirely offers a GHG saving of 35% compared to the UK average diet and a shift to pork and poultry approximately 18%. Next most fruitful is waste reduction with eliminating post-purchase waste offering approximately 12% reduction in emissions. This could be greatly enhanced by reducing waste throughout the supply chain. It is worth noting, however, that the potential for emissions savings through waste reduction becomes less efficient as meat consumption decreases. This is due to the carbon intensity (i.e. kg CO_2e kg^{-1}) of the foods being wasted decreasing. This means that about only an 8% overall reduction in emissions from the baseline can be achieved through waste mitigation after meat is eliminated from the diet. Thus the cumulative action of eliminating meat and waste instead totals approximately a 42% reduction, rather than a sum-of-the-parts total of 47%.

Finally eliminating air-freighting and hot-housing, and eliminating packaging can also offer small savings of approximately 5% and 3% respectively. These actions can be taken in addition to any of the others offering a small but complimentary GHG emission reduction. However, without some changes to diet, away from meat consumption savings of this magnitude are impossible. This is in support of our previous findings (Berners-Lee et al., 2012) yet highlights the benefits of a basket of mitigation actions that might be taken to manage emissions from food.

5. Conclusion

We have demonstrated that there is scope for meaningful reductions (~25%) resulting from changes in consumer habits around food, offering fruitful contributions towards GHG mitigation targets. Furthermore, these reductions can be gained by following a small number of simple rules rather than requiring detailed technical understanding or engagement with numerical carbon labelling. The three principal actions are: (i) to reduce meat consumption, (ii) to switch the balance of meat consumption away from high impact meats (beef and lamb) to low impact meats (pork and poultry) and (iii) to reduce waste.

Other smaller savings can be gained by avoiding hot-housed or air freighted produce (which together total ~5%). The simple consumer guideline for these two actions combined may be to stick to fruit and vegetables that are either in season or have sufficient shelf life to allow travel by ship rather than aircraft. Finally, smaller savings can be gained by avoiding unnecessary packaging. However the elimination of all packaging (resulting in 3% savings of GHGs) is neither practical nor desirable since packaging also performs a variety of important functions such as improving shelf life, protecting and identifying foods (Quested and Parry, 2011). Table 9 summarises these findings.

We have also demonstrated the level of flexibility available to reach a target reduction of 25%, enabling consumers to make decisions which suit their personal preferences. It is possible to achieve this target by either removing meat from the diet, switching to non-ruminant sources or through a combination of actions. However we have further shown that action on waste, packaging or locality alone will not suffice.

There is clearly much that food retailers can do to enable and support the mitigation actions we have modelled and others: ensuring information on these simple guidelines is readily available and easily understood; ensuring that the less carbon-intensive options are available for purchase, are made to look appetising and are promoted; and encouraging consumers to buy only what they will eat. None of these actions necessitate carbon labelling on individual product. Indeed it may be that provision of too much information on GHG emissions associated with individual products may be counterproductive and that promotion of the simple guidelines established here may be more effective in guiding consumer choices.

Finally we note there are further emissions reductions achievable than those covered here, through reducing purchase, consumption and waste of dairy products and also if consumers are prepared to build up more detailed knowledge of the emissions behind different food products. Importantly, however, our analysis provides consumers with information on how to make rapid changes to their greenhouse gas emissions, recognising the urgency of such actions if dangerous climate change is to be avoided.

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References

Anderson, K., et al., 2008. From long-term targets to cumulative emission pathways: reframing UK climate policy. Energy Policy 36, 3714–3722.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bokern, D., Webster, C., Williams, A., 2009. How low can we go? An assessment of GHG emissions from the UK food system and the scope to reduce them by 2050. FCRN-WWF-UK. ⟨http://assets.wwf.org.uk/downloads/how_low_report_1.pdf⟩ (Retrieved February 2013).

Bhatia, P., Ranganathan, J., 2004. Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard – Revised Edition. World Business Council for Sustainable Development, Geneva and World Resources Institute, Washington.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2010. Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. Journal of Environmental Management 91, 1415–1428.

Berners-Lee, M., Hoolohan, C., Cammack, H., Hewitt, C.N., 2012. The relative greenhouse gas impacts of realistic dietary choices. Energy Policy 43, 184–190.

Berners-Lee, M., Howard, D.C., Moss, J., Kaivanto, K., Scott, W.A., 2011. Greenhouse gas footprinting for small businesses – the use of input–output data. Science of Total Environment 409, 883–891.

Bothwell, E.K., Ayala, G.X., Conway, T.L., Rock, C.L., Gallo, L.C., Elder, J.P., 2009. Underreporting of food intake among Mexican/Mexican-American Women: rates and correlates. Journal of American Dietetic Association 109, 624–632.

Bows, A., Dawkins, E., Gough, C., Mander, S., McLachlan, C., Röder, M., Thom, L., Thornley, P., Wood, R., 2012. What's Cooking? Adaptation & mitigation in the UK food system. A report prepared by the Sustainable Consumption Institute at the University of Manchester, UK.

Carlsson-Kanyama, A., 1998a. Climate change and dietary choices – how can emissions of GHG emissions from food consumption be reduced? Food Policy 23, 277–293.

Carlsson-Kanyama, A., 1998b. Food consumption patterns and their influence on climate change. AMBIO 27, 528.

Carlsson-Kanyama, A., Engstrom, R., Kok, R., 2005. Indirect and direct energy requirements of city households in Sweden. Journal of Industrial Ecology 9, 221.

Carlsson-Kanyama, A., Ekstrom, M.P., Shanahan, H., 2003. Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecological Economics 44, 293–307.

Carlsson-Kanyama, A., Gonzalez, A.D., 2009. Potential contributions of food consumption patterns to climate change. American Journal of Clinical Nutrition 89, 1704S–1709S.

Coley, D.A., Goodliffe, E., Macdiarmid, J., 1998. The embodied energy of food: the role of diet. Energy Policy 26, 455–459.

Defra, 2011. 2011 Guidelines to Defra/DECC's GHG conversion factors for company reporting. ⟨http://www.Defra.gov.uk/environment/⟩ (Retrieved February 2013).

FAOSTAT, 2011. Food balance sheet for the UK for 2007. ⟨http://faostat.fao.org/site/368/DesktopDefault.aspx?PageID=368#ancor⟩ (Retrieved February 2013).

FAO, 2010. Greenhouse gas emissions from the dairy sector: a life-cycle assessment. ⟨http://www.fao.org/docrep/012/k7930e/k7930e00.pdf⟩ (Retrieved February 2013).

Food Standards Agency, 2010a. National Diet Nutrition Survey: Headline Results from Year 1 (2008/2009): Report. ⟨http://www.food.gov.uk/multimedia/pdfs/publication/ndnsreport0809year1results.pdf⟩ (Retrieved February 2013).

Food Standards Agency, 2010b. National Diet Nutrition Survey: headline results from year 1 (2008/2009): Tables. ⟨http://www.food.gov.uk/multimedia/pdfs/publication/ndnstables0809year1results.pdf⟩ (Retrieved February 2013).

Foster, C., et al., 2006. Environmental Impacts of Food Production and Consumption. A Report to Defra. ⟨http://randd.defra.gov.uk/Document.aspx?Document=EV02007_4601_FRP.pdf⟩ (Retrieved February 2013).

Garnett, T., 2006. Fruit and Vegetables & UK Greenhouse Gas Emissions: Exploring the Relationship. Working Paper Produced as Part of the Work of the Food Climate Research Network. ⟨http://www.fcrn.org.uk/sites/default/files/fruitveg_paper_final.pdf⟩ (Retrieved February 2013).

Garnett, T., 2007. The Alcohol We Drink and its Contribution to UK GHG Emissions. Working Paper Produced as Part of the Work of the Food Climate Research Network. ⟨http://www.fcrn.org.uk/fcrn/publications/alcohol-we-drink-and-its-contribution-uks-greenhouse-gas-emissions-discussion-paper⟩ (Retrieved February 2013).

Goris, A.H.C., Westerterp-Plantenga, M.S., Westerterp, K.R., 2000. Undereating and underrecording of habitual food intake in obese men: selective underreporting of fat intake. American Journal of Clinical Nutrition 71, 130–134.

Hammond, G., Jones, C., 2008. Inventory of Carbon and Energy (ICE) version 1.6, Bath University.

Hendrickson, C., Horvath, A., Joshi, S., Lave, L., 1998. Economic input–output models for environmental life cycle analysis. Environmental Science & Technology 32, 184A–191A.

Hospido, A., Milà i Canals, L., McLaren, S., Truninger, M., Edwards-Jones, G., Clift, R., 2009. The role of seasonality in lettuce consumption: a case study of environmental and social aspects. International Journal of Life Cycle Assessment 14, 381–391.

Institution of Mechanical Engineers, 2012. Global Food: Waste not. Want not. URL: ⟨http://www.imeche.org/docs/default-source/reports/Global_Food_Report.pdf?sfvrsn=0⟩ (Retrieved February 2013).

Jarvis, A.J., Leedal, D.T., Hewitt, C.N., 2012. Climate-society feedbacks and the avoidance of dangerous climate change. Nature Climate Change 2, 668–671.

Johansson, G., Wikman, Å., Åhrén, A.-M., Hallmans, G., Johansson, I., 2001. Underreporting of energy intake in repeated 24-hour recalls related to gender, age, weight status, day of interview, educational level, reported food intake, smoking habits and area of living. Public Health Nutrition 4, 919–992.

Kasmaprapruet, S., Paengjuntuek, W., Saikhwan, P., Phungrassami, H., 2009. Life-cycle assessment of milled rice production: case study in Thailand. European Journal of Scientific Research 30, 195–203.

Nielsen, P.H., Nielsen, A.M., Weidman, B.P., Dalgaard, R., Halberg, N., 2003. LCA Food Data Base. "Lifecycle Assessment of Basic Food" (2000 to 2003). Aarhus University, Denmark.

Nilsson, K., Sund, V., Florén, B., 2011. The Environmental Impact of the Consumption of Sweets, Crisps and Soft Drinks. A Report for Nordic Council of Ministers. Copenhagen 2011.

Miller, R., Blair, D., 1986. Input–output Analysis, Foundations and Extensions. Prentice Hall, New Jersey.

Phetterplace, H.W., Johnson, D.E., Seidl, A.F., 2001. GHG emissions from simulated beef and dairy livestock systems in the United States. Nutrient Cycling in Agroecosystems 60, 99–102.

Poppitt, S.D., Swann, D., Black, A.E., Prentice, A.M., 1998. Assessment of selective under-reporting of food intake by both obese and non-obese women in a metabolic facility. International Journal of Obesity and Related Metabolic Disorders 22, 303–311.

Pryer, J.A., Vrijheid, M., Nichols, R., Kiggins, M., Elliott., P., 1997. Who are the 'low energy reporters' in the dietary and nutritional survey of British adults? International Journal of Epidemiology 26, 146–154.

Quested, T., Parry, A., 2011. New Estimates for Household Food and Drink Waste in the UK. A Report for WRAP. ⟨http://bit.ly/YiFr3r⟩ (Retrieved February 2013).

Ribal, J., Sanjuán, N., Clemente, G., Fenollosa, L., 2009. Medición de la eco-eficiencia en procesos productivos en el sector agrario. Caso de estudio sobe producción de cítricos. Economía Agraria y Recursos Naturales 9, 125–148.

Small World Consulting, 2010. The Greenhouse Gas Footprint of Booths. A Report by Small World Consulting Ltd. ⟨http://www.booths.co.uk/Documents/Booths_Full_Report_100720.pdf⟩ (Retrieved February 2013).

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Roseles, M., de Haan, C., 2006. Livestock's Long Shadow: Environmental Issues and Options. Rome, Food and Agriculture Organization of the United Nations. ISBN: 978-92-5-105571-7.

Wallen, A., Brandt, N., Wennersten, R., 2004. Does the Swedish consumer's choice of food influence greenhouse gas emissions? Environmental Science & Policy 7, 525–535.

Williams, A.G., Audsley, E., Sandars, D.L., 2006. Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. Main Report. Defra Research Project IS0205. Cranfield University and Defra, Bedford. ⟨http://bit.ly/12YBv9A⟩ (Retrieved February 2013).

Williams, A.G. Audsley, E., 2008. Comparative Life-Cycle Assessment of Food Commodities Procured for UK Consumption Through a Diversity of Supply Chains. Defra Project Report FO0103: ⟨http://bit.ly/YBssEF⟩.

WRAP (Waste Resource Action Plan), 2013. Reducing food waste – how packaging can help. ⟨http://www.wrap.org.uk/fresherforlonger⟩ (Retrieved February 2013).

Utrecht Centre for Energy Research, 2001. ICARUS – 4 sector study for the paper and board industry and the graphics industry. ⟨http://copernicus.geog.uu.nl/uce-uu/downloads/Icarus/Paper.pdf⟩ (Retrieved February 2013).