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The relative greenhouse gas impacts of realistic dietary choices

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ABSTRACT

The greenhouse gas (GHG) emissions embodied in 61 different categories of food are used, with information on the diet of different groups of the population (omnivorous, vegetarian and vegan), to calculate the embodied GHG emissions in different dietary scenarios. We calculate that the embodied GHG content of the current UK food supply is 7.4 kg CO_2e person^{-1} day^{-1}, or 2.7 t CO_2e person^{-1} y^{-1}. This gives total food-related GHG emissions of 167 Mt CO_2e (1 Mt$=10^6$ metric tonnes; 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 greenhouse gases) for the entire UK population in 2009. This is 27% of total direct GHG emissions in the UK, or 19% of total GHG emissions from the UK, including those embodied in goods produced abroad. We calculate that potential GHG savings of 22% and 26% can be made by changing from the current UK-average diet to a vegetarian or vegan diet, respectively. Taking the average GHG saving from six vegetarian or vegan dietary scenarios compared with the current UK-average diet gives a potential national GHG saving of 40 Mt CO_2e y^{-1}. This is equivalent to a 50% reduction in current exhaust pipe emissions from the entire UK passenger car fleet. Hence realistic choices about diet can make substantial differences to embodied GHG emissions.

1. Introduction

Emissions of radiatively active “greenhouse” gases (GHGs) into the Earth’s atmosphere resulting from Man’s activities are changing the composition of the atmosphere, with effects on the radiative balance of the atmosphere, and, ultimately, on global climate. The IPCC (2007) estimates, with a very high level of confidence, that there has been an increase in radiative forcing of about $+2.6\,\mathrm{W\,m^{-2}}$ from the mid-1700s to the present day, mainly due to emissions of the three most important anthropogenic GHGs, carbon dioxide, methane and nitrous oxide (1.66, 0.48 and $0.16\,\mathrm{W\,m^{-2}}$, respectively). This is believed to have contributed to, or caused, the increase in global average surface temperature which has been observed over the past 150 years, the best estimate of which is 0.7 ± 0.2 °C since 1860 (Brohan et al., 2006).

In 1992 the United Nations Framework Convention on Climate Change (UNFCCC) called for the “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…” and in 1997 developed nations agreed in Kyoto, for the first time, to reduce their emissions of greenhouse gases by an average of 5% below 1990 levels. Since then, although some countries have not ratified the Kyoto agreement and their emissions have continued to grow, others have put in place extremely ambitious emissions reduction targets. For example, the UK, through the UK Climate Change Act of 2008, has a legally binding target of at least an 80% reduction in the emissions of a “basket” of GHGs by 2050, to be achieved through action in the UK and abroad, with an intermediate target for reductions in emissions of at least 34% by 2020. Both these targets are against a 1990 emissions baseline.

Greenhouse gas emissions result from any activity involving the combustion or other use of fossil fuels, including electricity generation, heating, transport and industrial processes. Forestry and agriculture are also significant sources of GHGs to the atmosphere, both directly and indirectly through land use change. The relative importance of these various sources to total emissions varies significantly from country to country. However, it is clear that in order to meet the ambitious emissions reductions targets agreed in the UK and elsewhere, emissions from every possible source category have to be addressed and driven down. While some sources of GHGs (e.g., the use of fossil fuels for residential lighting and heating) are relatively easy to monitor and reduce, at least temporarily (e.g., by increasing building insulation, improving boiler efficiency, installation of low-energy lighting systems etc), others, especially agriculture, are much less tractable.

The production of food for human consumption, particularly by industrialised agricultural practises, causes significant emissions of GHGs. These may occur directly, for example carbon

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dioxide emissions from fossil fuel use on the farm or in the supply chain, nitrous oxide emissions resulting from fertiliser application, or methane emissions from animals; or indirectly as a result of land use change. As well as the agricultural production process, the transport, processing, packaging, marketing, sales, purchasing and cooking of food also all contribute to GHG emissions.

Various estimates have been made of the relative importance of GHG emissions embodied in food. This has been done for individual food types and for total food consumption. For example, Steinfeld et al. (2006) estimated that the global production of meat contributes $(5–7)\times10^9$ t y^{-1} of GHGs as CO_2-equivalents or CO_2e (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 greenhouse gases), or 15–24% of total GHG emissions. As an example of the total GHGs embodied in diet, Weber and Matthews (2008) estimated that average *per capita* food consumption in the US has embodied emissions of 3.1 t CO_2e y^{-1}.

The notion that personal choice of diet might play a role in environmental sustainability, and specifically in the emissions of greenhouse gases, is relatively new. Goodland (1997) pointed out that “diet matters” and Coley et al. (1998) and others (e.g., Phetteplace et al., 2001) began to calculate the embodied energy and GHG emissions of food in different diets. Since then, using life cycle analysis and input-output models, it has been shown that consumption of different foodstuffs results in differing energy consumptions and GHG emissions. Carlsson-Kanyama and co-workers (1998a,1998b; 2003; 2005; 2009) used life cycle analysis of different foodstuffs in Sweden to discuss the role of dietary choices in GHG emissions. Similar analyses have been conducted for the Netherlands (Kramer et al., 1999), Sweden (Wallen et al., 2004), the UK (Druckman and Jackson, 2009; Audsley et al., 2009), the US (Weber and Matthews, 2008; Eshel and Martin, 2006) and globally (Stehfest et al., 2009). The last two of these studies, in particular, highlight the disproportionately high emissions of GHGs associated with meat and dairy production, compared with plant-based foods. Very recently, in an analysis of “solutions for a sustainable planet” Foley et al. (2011) highlighted the potential role of shifting diets and reducing food waste in improving global food availability.

Here we quantify the emissions of greenhouse gases, expressed as CO_2e, associated with different types of diet, in order to examine what reductions in GHG emissions are plausible as a result of realistic dietary choices. Although this is a case study, based on dietary data from the UK and USA and on GHG emissions embodied in various specific foodstuff categories, as purchased from a mid-size supermarket chain in the UK, it is hoped the results can promote discussion and inform decision-making both in the UK and elsewhere.

2. Methods and data used

This study relies on data on (a) the types and amounts of food that different groups of the population in the UK with different dietary habits consume, together with associated losses and wastage, and (b) the GHGs embodied in different foods.

2.1. Food intake

First, we use total “food supply” (expressed as kcal $person^{-1}$ day^{-1}) for the UK for 2007 obtained from the UN Food and Agriculture Organisation “food balance sheets” (FAOSTAT, 2011). This gives a top–down assessment of the amount of food available for consumption in the country, and hence is the amount of food currently used to sustain the UK's population (i.e., the amount of food consumed plus the amount of food lost and wasted). We then use data from the UK National Diet and Nutrition Survey (NDNS, 2010) to obtain the weighted average typical daily food intake in different food categories in the UK, as recorded in food diaries. To obtain the differences in diet between omnivores, vegetarians and vegans we used data from the US (Haddad et al., 1999; Haddad and Tanzman, 2003) and assumed that these differences also apply to vegetarians and vegans in the UK. We assume that food loss and wastage occur equally over the different dietary groups.

Whilst the NDNS data are assumed to be representative of self-reported food intake in the UK, it differs from total food supply in three important ways. First, self-reported food intake surveys, such as the NDNS, are known to suffer from systematic under-reporting of energy consumed. Second, NDNS self-reported food intake data do not include food that is purchased but not eaten, i.e., food that is wasted by the consumer post-purchase (WRAP, 2009). Third, the NDNS data do not account for food lost or wasted prior to sale, i.e., during processing, transport, storage or sale. We use these factors in discussion below to reconcile the considerable difference that exists between what people say they eat and the total amount of *per capita* food supply available in the country.

2.2. Embodied GHG emissions in foodstuffs

We place every food item consumed into one of 61 different foodstuff categories. To calculate the GHG emissions embodied in each category we used estimates of greenhouse gas emissions up to the point of sale at a mid-sized supermarket chain in the northwest of England. The 61 foodstuff categories are those used by the retailer for operational management and accounting purposes and are listed in Fig. 1. This chain has 26 stores and, although positioned in the market as one of the UK's premium supermarket brands, we assume that the greenhouse gases embodied in its product range are representative of those sold by all other food retailers in the country. The calculation of embodied GHG emissions follows the principles of the Greenhouse Gas Protocol (World Business Council for Sustainable Development, 2004) and draws upon a range of secondary sources of life cycle analysis studies. A detailed description of the methodology is available on-line (Small World Consulting, 2010) and a summary follows.

The embodied GHG emission estimates for each of the 61 food categories include components for production as far as the farm gate, transport from farm to processing and/or distribution centres, packaging, storage and supermarket operations (including transport to store). Emissions up to the farm gate are estimated by taking a selection of representative products within each of the categories and applying emission factors from previously published life cycle analyses (LCAs), including Audesley et al. (2009), Defra (2006), FCRN (2006,2007), Wallen et al. (2004), Nielsen et al. (2003) and Williams, 2006). The specific LCAs used were selected on the basis of credibility, consistency of method and closeness of the supply chains studied to those adopted by the case-study supermarket itself.

GHG emissions within each category associated with transport from the point of production to the supermarket distribution centre are estimated by modelling a range of representative products within each category. Emission factors for each transport mode are from Defra (2009) and environmental input–output methods (Hendrickson et al., 1998; Miller and Blair, 1986) were used to take account of emissions within the supply chains of each transport journey (for example, the embodied emissions in fuel supply chains and vehicles). The methodology used for the input–output analysis is described in detail by Berners-Lee et al. (2011). Neither Defra's emissions factors for

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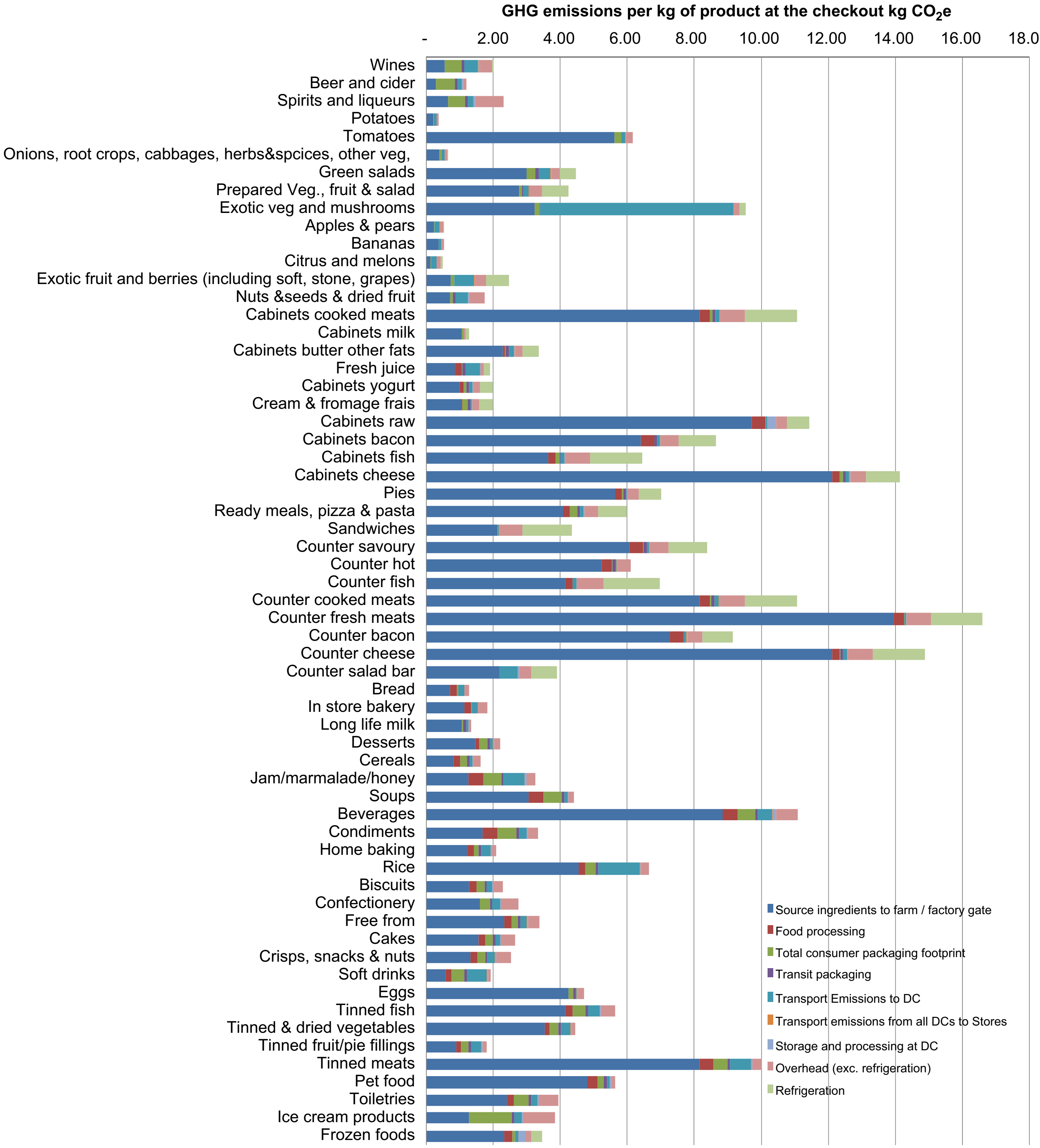

Fig. 1. Greenhouse gas emissions (kg CO_2e kg^{-1}) embodied in 61 food categories, at the point of purchase.

international freight nor the input–output model used take account of the any differences in the carbon intensity of transport modes between countries. For example, the emissions resulting from transporting a tonne of grain for one kilometre in Brazil is assumed to be the same as it would be in the UK. Food processing emissions are calculated in a similar way to farm emissions up to the farm gate.

GHG emissions embodied in food packaging materials were estimated using data on the mass of packaging materials associated with each food category, supplied by the retailer, together with emission factors for different materials (Association of Plastic Manufacturers Europe, 2008; Hammond and Jones, 2008; Utrecht Centre for Energy Research, 2001). Secondary (transit) packaging was taken into account in the same way, although attribution to product groups was less exact since the retailer keeps only aggregated records. GHG emissions due to refrigeration during storage and in-store were distributed among chilled and frozen products by weight sold.

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Direct and indirect GHG emissions resulting from supermarket management and operation, including energy consumption, staff business travel, postage and courier services, waste disposal, paper, printing and other office and marketing consumables were calculated and attributed to food product categories by value.

2.3. *Calculating dietary greenhouse gas emissions data*

Having established the GHG footprint and the nutritional value of each food category we combined these with the amount of food consumed in each diet to find the GHGs embodied in the age and gender-weighted average diet for each of the 61 food category for each diet. This was done by multiplying the calculated CO_2e per kg values by the mass of each food type consumed.

2.4. *Nutrition and cost data*

By multiplying data on the nutritional content of each food type, obtained from suppliers (protein, carbohydrate, added sugar, fat, and sodium), by the food mass in each diet, a comparison can be made between the CO_2e and 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. These costs may be a little higher per kilogram than the national average for each item, but allow the relative costs of different dietary choices to be compared.

2.5. *Alternative dietary scenarios*

In order to calculate the GHGs embodied in the national food supply, we use, as our starting point, the NDNS self-reported UK average diet, which has an age and gender-weighted energy content of 1807 kcal person^{-1} day^{-1} in 61 food categories. This is representative of the self-reported dietary intake of the UK population, weighted for age and gender. We then scale this to the *per capita* amount of food energy available in the country (3458 kcal day^{-1}, obtained from FAOSTAT, 2010). This is the amount of food energy currently used to sustain the population, including food lost and wasted, and provides our baseline for GHG emissions from food in the UK. We then look at six scenarios, three vegetarian and three vegan, with different meat and diary substitutes applied. In all cases, we maintain the *per capita* energy at 3458 kcal day^{-1} to allow the effects of dietary choices on GHG emissions to be examined, and in all cases we assume the amount of food wasted remains the same over the 61 categories.

Scenario 1: Replacing all meat with dairy products (i.e., eliminating meat consumption and scaling up all dairy intake by the proportion required to maintain the available energy at the UK average of 3548 kcal person^{-1} day^{-1}). This scenario might represent the diet of a vegetarian who directly replaces meat with dairy products in their diet and hence may be that of an "undiscriminating" vegetarian.

Scenario 2: Adopting a typical self-reported vegetarian diet in the US, as described by Haddad and Tanzman (2003), scaled to the UK-average available energy of 3548 kcal person^{-1} day^{-1}. This scenario represents the self-reported diet of a "typical" US vegetarian but scaled to the UK-average available energy. This diet is probably close to that of the average UK vegetarian.

Scenario 3: Replacing meat with those categories of plant-based foods that might reasonably be considered to be healthy alternatives to meat, i.e., pastas, rice, pulses, cereals, breads, salads, vegetables, fruit, nuts and seeds, and scaling to the UK average available energy of 3548 kcal person^{-1} day^{-1}. In this scenario dairy consumption is unchanged from the UK average but meat is replaced by realistic plant-based alternatives. This may represent the diet of a "thoughtful" vegetarian.

Scenario 4: Eliminating all meat and dairy products and scaling up all other food categories to maintain the UK-average available energy of 3548 kcal person^{-1} day^{-1}. In this scenario, calories derived from meat and dairy products are replaced by the full range of other foods, so intake of alcohol, sweet drinks, confectionary etc increase by the same proportion as more nutritionally-sensible alternatives. This may represent the diet of an "undiscriminating" vegan.

Scenario 5: Adopting the typical self-reported vegan diet in the USA, as described by Haddad et al. (1999). This scenario is representative of a vegan in the UK who makes the same food choices as does a typical vegan in the USA, but scaled to the UK-average available energy.

Scenario 6: Eliminating all meat and dairy products and making up the available energy to the UK average of 3548 kcal person^{-1} day^{-1} by scaling up with nutritionally-sensible plant-based substitutes only, as for option 3 above. This scenario may be representative of a "thoughtful" vegan in the UK.

3. Results

Fig. 1 shows the GHGs, as CO_2e, embodied in each of the 61 food categories used in this analysis, by segments of the food supply chain. In general terms, meat and dairy-based product categories have the highest carbon intensities, and this is largely accrued before the farm gate, i.e., during production. Methane from rumination, slurry and farmyard manure and nitrous oxide from fertilizer, slurry and manure are the main animal-related on-farm emissions, with fossil fuel combustion, both directly and within the farm supply chains, being of lesser importance. The food category with the largest embodied greenhouse gas emissions is fresh meat, with 17 kg CO_2e kg^{-1} at the checkout. Cheese has 15 kg CO_2e kg^{-1}. Exotic fruit and vegetable categories have high transport components, since many of the products in these categories are air freighted or may be grown in heated glasshouses. They have GHG emissions of ~10 kg CO_2e kg^{-1}. In contrast, fruit and vegetables that are grown without artificial heating and/or are shipped to the UK by sea have low emissions.

3.1. *UK-average overall food consumption*

The population-weighted total daily energy intake for the UK, as determined from the self-reporting food intake diary data of the NDNS, is 1807 kcal person^{-1} day^{-1}. However, this is biologically implausible and is only 52% of the food supply available in the country. Although the NDNS energy intake is not required for the calculation of GHG emissions, it is informative to be able to reconcile this with the FAOSTAT food supply data.

Self-reported food intake diaries are known to suffer from systematic under-reporting of food intake (both of total food intake and of specific food types) especially in the US and Europe (e.g., Poppitt et al., 1998; Goris et al., 2000; Johansson et al., 2001; Pryer et al., 1997; Bothwell et al., 2009). Quantification of under-reporting is difficult but is possible using covert surveillance, mass-energy balance studies (e.g., Scagliusi et al., 2003) and isotope labelling studies (e.g., Ferriolli et al., 2010), with significant fractions of groups studied under-reporting their energy intake by 10–33%. However, these techniques have only been used on small sub-groups of the population and hence major uncertainties remain about population-average under-reporting.

Here, we use a best estimate of 20% for the under-reporting of energy intake, while acknowledging the large uncertainty in this. Applying this factor adjusts the UK population-average self-reported

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energy intake of 1807 kcal day^{-1} to an actual energy intake of 2259 kcal day^{-1} averaged across people of all ages and of both sexes. This is broadly in line with the Recommended Dietary Allowance (RDA) for adults of 2350 kcal day^{-1} (IOM, 2002).

The amount of food that is wasted prior to consumption in the UK is estimated to be ~22% (WRAP, 2009). Applying this factor to the UK-average energy intake estimate of 2259 kcal day^{-1} implies the amount of food purchased for consumption is 2915 kcal person^{-1} day^{-1}.

Since we use emission factors for foods at the checkout, the GHG footprint of each diet relates to this amount of purchased food energy. We then assume that the difference between this and the available food supply (3458–2915 = 544 kcal person^{-1} day^{-1}) is lost during processing, transport and storage prior to purchase. Since detailed information is not available on the preferential wastage of different food types we assume that both under-reported consumption and food wastage are uniform across all food types. If, in fact, the specific types of food that are wasted and under-reported are skewed towards those that are associated with higher GHG emissions per unit of calorific value than the average, then this assumption will result in an under-estimation of the climate change impact of the dietary choices studied, and vice versa.

3.2. GHG emissions in the UK food supply

We calculate that the embodied GHG content of the UK food supply of 3458 kcal person^{-1} day^{-1}, (of which 2915 kcal person^{-1} day^{-1} are purchased at the checkout and 2259 kcal person^{-1} day^{-1} are actually consumed) is 7.4 kg CO_2e person^{-1} day^{-1} or 2.7 t CO_2e person^{-1} y^{-1}. This gives total food-related GHG emissions of 167 Mt CO_2e for the entire UK population (61,792,000 in 2009) (1 Mt = 10^6 t). Direct *per capita* GHG emissions in the UK in 2008 were 10.16 t CO_2e y^{-1}, excluded GHGs embodied in goods and services produced abroad (DECC, 2010), or 14.5 t CO_2e y^{-1} when these are included (Berners-Lee et al., 2011). Hence the GHGs currently embodied in the UK's food supply accounts for 27% of direct UK emissions, or 19% of total UK emissions (including those embodied in goods produced abroad).

Clearly, eliminating food wastage pre- and post-purchase could reduce GHG emissions in the UK significantly, by 2.6 kg CO_2e person^{-1} day^{-1} or 0.94 t CO_2e person^{-1} y^{-1} or 58 Mt CO_2e y^{-1} overall. Hence, the amount of GHGs embodied in the food actually eaten only represents 17% of direct UK GHG emissions or 12% of total UK emissions.

For comparative purposes, we calculate that the cost of purchasing 2915 kcal^{-1} person^{-1} day^{-1}, distributed between the 61 food categories as implied by the NDNS self-reported "typical" diet in the UK, at the case-study food retailers in NW England is £6.59 day^{-1} (at October 2010 prices). We also calculate that this diet, normalised to the average amount of food eaten of 2259 kcal person^{-1} day^{-1}, contains 88 g of protein, 286 g carbohydrate, 72 g added sugar, 83 g fat and 2.6 g sodium. The UK's RDA of protein for adult men is 56 g day^{-1}, and for adult women 46 g day^{-1} (IOM, 2002).

3.3. Scenarios

In order to compare embodied GHG emissions in alternative vegetarian and vegan diets, we normalise all diets to the FAOSTAT (2011) food supply value of 3458 kcal person^{-1} day^{-1} – assuming that the amounts of pre- and post-purchasing waste do not change. However, for comparing total daily cost we normalise all diets to the amount of food purchased – i.e., 2915 kcal person^{-1} day^{-1}. For comparing the amounts of daily protein, added sugar, fat and sodium consumed we normalise all diets to the amount of food eaten – i.e., 2259 kcal person^{-1} day^{-1}.

Scenario 1: Simply replacing all meat consumption in the UK-average (NDNS) diet with the same amount (kcal) of dairy products, reduces *per capita* GHG emissions from 7.4 kg CO_2e day^{-1} to 5.8 kg CO_2e day^{-1}, giving an annual reduction of 0.6 t CO_2e person^{-1} y^{-1} or 22%. As shown in Table 1, this hypothetical vegetarian diet has less protein, less sodium and is significantly cheaper to buy, but contains more carbohydrates, slightly more added sugar and more fat (+7%) than the average omnivorous diet it replaces.

Swapping meat for dairy products is beneficial in terms of embodied GHGs because cheese is so energy-dense. However, it is probably unlikely that most vegetarians simply substitute a UK-average meat-based protein intake of 76 g day^{-1} with 76 g day^{-1} of protein from milk and cheese, and hence this scenario may not be typical of UK vegetarians.

Scenario 2: Using the more realistic self-reported food intake data for US vegetarians (Haddad and Tanzman, 2003) gives a total GHG emission of 6.1 kg CO_2e day^{-1}, or a reduction of 18% compared to the UK-average (NDNS) diet. It also contains less protein, less fat, less sodium, and is cheaper to buy. The main reason it is more GHG-intensive than scenario 1 is that it contains more fruit and vegetables, some of which are air-freighted or grown in heated glasshouses.

Scenario 3: In the "thoughtful" vegetarian diet of scenario 3, in which meat is replaced by realistic plant-based alternatives and dairy consumption remains unchanged from the UK average, the total embodied GHG emissions are 5.5 kg CO_2e day^{-1}, or a reduction of 25% compared to the UK-average (NDNS) diet. This diet is cheaper, has less fat, less protein and less sodium, more carbohydrate and the same amount of added sugar as the UK-average diet.

Scenario 4: In this "undiscriminating vegan" scenario all meat and diary products are replaced by scaling up consumption of all other (plant-based) products, including, for example, alcoholic and soft drinks and confectionary. It is therefore likely to be less healthy. It has an embodied GHG emission of 5.1 kg CO_2e day^{-1}, or 31% lower than the UK-average diet. This scenario has the lowest protein (although only just under the RDA value), is high in carbohydrate and has the most added sugar, at 32% above that of the UK average diet.

Scenario 5: In this US self-reported vegan diet, the embodied GHG emissions are 5.7 kg CO_2e day^{-1}, or 23% lower than the UK-average diet.

Scenario 6: In this "thoughtful" vegan diet, the embodied GHG emissions are 5.6 kg CO_2e day^{-1}, or 25% lower than the UK-average diet. This diet has the highest carbohydrate content, the lowest added sugar and the lowest fat content of all the diets. The sodium content is unchanged from the UK-average diet. The protein content (62 g) is above the recommended value. It is £380 y^{-1} cheaper than the UK-average diet.

4. Discussion

Uncertainties arise in our estimates of GHG emissions in several ways. First, obtaining accurate information on food consumption is not easy. However, the fact that we are able to reconcile the "bottom–up" self-reported estimates of food intake, adjusted for under-reporting and food loss and wastage, with the "top–down" assessment of the amount of food available in the country, gives confidence in our estimates. Second, in the NDNS, food types are grouped into 58 categories. This categorisation is not the same as that used in our LCA/I–O analysis of supermarket products. It was therefore necessary to map the 58 NDNS food categories onto our 61 categories of supermarket products, by merging categories or, with reference to fine-grained sales data, splitting supermarket categories. Third, the GHG emission factors

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Table 1
Greenhouse gas emissions (kg CO_2e person^{-1} day^{-1}) embodied in different diets, cost at point of purchase, mass of carbohydrates, mass of added sugar, mass of fat and mass of sodium consumed per day.

	GHG (kg CO_2e person^{-1} day^{-1}) embodied in diet	Cost at checkout (£ person^{-1} day^{-1})	Protein eaten (g person^{-1} day^{-1})	Carbohydrate eaten (g person^{-1} day^{-1})	Daily added sugar eaten (g person^{-1} day^{-1})	Daily fat eaten (g person^{-1} day^{-1})	Daily sodium eaten (g person^{-1} day^{-1})
Baseline							
Current average *per capita* UK food supply of 3458 kcal day^{-1}	7.40	6.59	88	286	72	83	2.63
Vegetarian scenarios							
1: UK average diet with meat energy replaced by diary energy, normalised to UK food supply *per capita* energy	5.79	5.63	76	296	76	89	2.28
2: US average vegetarian diet, normalised to UK food supply *per capita* energy	6.06	6.01	64	328	84	71	2.35
3: UK average diet with meat energy replaced by "healthy" non-dairy alternatives, normalised to UK food supply *per capita* energy	5.54	5.78	66	349	73	69	2.46
Vegan scenarios							
4: UK average diet with meat and dairy energy replaced by all plant-based alternatives, normalised to UK food supply *per capita* energy	5.14	5.65	50	370	104	62	2.11
5: US vegan diet, normalised to UK food supply *per capita* energy	5.68	6.26	54	352	79	66	2.03
6: UK average diet with meat and diary energy replaced by "healthy" plant-based alternatives, normalised to UK food supply *per capita* energy	5.55	5.99	62	382	67	56	2.63

used for each 61 food categories are themselves subject to uncertainties, which at this point are difficult or impossible to quantify. Not only do the LCAs themselves contain uncertainties but their use as proxies for the specific supply chains of the case-study supermarket introduces a level of uncertainty. The LCAs were chosen to most accurately represent the supply chains in question, but in some cases they related to production in different countries from those actually used by the case-study supermarket itself and consequently may relate to somewhat different climates, production methods, modes of transport and industry structures. However, we see no reason why uncertainties or errors in emission factors should systematically vary across food categories, and our analysis therefore allows for comparisons to be made across diets, even if the absolute values are in error. We also assume uniform degrees of wastage across food types and sectors of the population.

Using a hybrid input–output/life cycle analysis of GHGs embodied in foodstuffs sold in a typical mid-size supermarket chain in the north-west of England, combined with available data on food intake and food wastage, we estimate that the average population-weighted diet in the UK has a GHG "footprint" of 7.4 kg CO_2e person^{-1} day^{-1} or 2.7 t CO_2e y^{-1}. This represents 27% of direct UK GHG emissions, or 19% of total UK emissions (including those embodied in goods produced abroad). We calculate that a GHG saving of 22% is made by changing from an omnivorous diet to a vegetarian diet (average of all three vegetarian scenarios presented above). A saving of 26% is made by changing to a vegan diet (average of all three vegan scenarios presented above). However, our GHG emission factors do not consider the effects of land use change on GHG emissions. If they did, the GHG savings due to a vegan diet might be substantially greater (Audsley et al., 2009).

All the diets in our six scenarios (Table 1) are cheaper to buy than the UK-average diet. All have adequate protein content and none have more sodium than the UK-average diet. Two have more added sugar and one has slightly more fat than the UK-average diet. However, both the "healthy" vegetarian diet (scenario 3) and the "thoughtful" vegan diet (scenario 6) have substantially reduced GHG emissions, are cheaper, have adequate protein, lower fat and the same or less sodium than the UK-average diet. This analysis therefore shows that informed dietary choices can make a significant difference to GHG emissions, reducing food-related emissions by around a quarter, with additional health benefits.

Alongside the basic dietary choices we have outlined there are further important opportunities to reduce GHGs emissions in food consumption. Reducing or eliminating food waste, both pre- and post-purchase, would yield very large GHG savings, given that less than two-thirds of available food is currently consumed. A second area of further reductions is possible by shifting consumption towards in-season fresh produce and/or fresh produce transported by ship and not by air. Our analysis has assumed the fresh fruit, vegetables and salads consumed in all diets consist of a supermarket-typical mix, including produce grown in heated glasshouse conditions and produce grown in warmer regions of the world and transported by air. These out-of-season products contribute significantly to total GHG emissions. The supermarket data also suggests that still further reductions of a few per cent are possible through the reduction of unnecessary packaging. The adoption of all these measures alongside the "thoughtful" vegan diet might lead to reductions in GHG emissions in excess of 50% compared with a current "typical" UK diet. Within an omnivorous diet, and even without reducing meat content, there are some opportunities to reduce GHG emissions by selecting less GHG-intensive meats, such as chicken, in preference to ruminants. Finally, and less simple for the consumer to discern, are the

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possibilities to achieve GHG savings by buying products that have been produced using less GHG-intensive farming practices.

In the context of a legally-binding commitment to reduce total GHG emissions in the UK by 80% from the 1990 value of 13.5 t $CO_2e\ y^{-1}$ to 2.7 t $CO_2e\ y^{-1}$ by the year 2050, it is noteworthy that we estimate current food production, waste and consumption in the UK currently contributes 2.7 t CO_2e $person^{-1}$ y^{-1}, and that even the most GHG-frugal diet examined here, normalised to current FAOSTAT energy consumption of 3548 kcal day^{-1}, embodies 1.9 t CO_2e $person^{-1}$ y^{-1}.

It is also informative to compare possible GHG emissions reductions resulting from dietary choices with those achievable through other lifestyle choices. Taking the average GHG saving achievable from all six dietary scenarios compared with the UK-average diet (1.78 kg CO_2e $person^{-1}$ day^{-1} or 0.65 t CO_2e $person^{-1}$ $year^{-1}$) gives a potential national GHG saving of 40 Mt $CO_2e\ y^{-1}$. This is equivalent to a 50% reduction in current exhaust pipe emissions of CO_2 from the entire UK passenger car fleet.

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