

The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change

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Abstract The UK has committed to reduce greenhouse gas (GHG) emissions by 80 % relative to 1990 levels by 2050, and it has been suggested that this should include a 70 % reduction in emissions from food. Meeting this target is likely to require significant changes to diets, but the likely effect of these changes on population nutritional intakes is currently unknown. However, the current average UK diets for men and women do not conform to WHO dietary recommendations, and this presents an opportunity to improve the nutritional content of diets while also reducing the associated GHG emissions. The results of this study show that if, in the first instance, average diets among UK adults conformed to WHO recommendations, their associated GHG emissions would be reduced by 17 %. Further GHG emission reductions of around 40 % could be achieved by making realistic modifications to diets so that they contain fewer animal products and processed snacks and more fruit, vegetables and cereals. However, our models show that reducing emissions beyond 40 % through dietary changes alone will be unlikely without radically changing current consumption patterns and potentially reducing the nutritional quality of diets.

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1 Introduction

The UK has committed to reduce its greenhouse gas (GHG) emissions by 80 % relative to 1990 levels by 2050 under the Climate Change Act (CCC 2008), and WWF-UK and the Food Climate Research Network have suggested that this should include a 70 % reduction in emissions from food (Audsley et al. 2009). Since agriculture contributes 18–20 % of GHG emissions in the UK, meeting this target is likely to require significant changes to diets. The production of food gives rise to GHG emissions (largely in the form of carbon dioxide, methane and nitrous oxide) from the processes of agricultural production, processing, transport, storage, cooking and disposal of waste (Foster et al. 2006), and it has been shown that more developed countries tend to consume diets that produce more GHG emissions (Pradhan et al. 2013). Globally, agricultural production itself contributes 80–86 % of total food-related emissions, with emissions from other processes being small (Vermeulen et al. 2012). However, in net food importing countries such as the UK (Fader et al. 2013) where consumption of highly processed food is also common, emissions from other parts of the food life cycle tend to be much higher. In addition, the UK diet is relatively high in animal source foods, which have been estimated to account for over half of UK food-related emissions (Audsley et al. 2009). Taken together, these factors make it clear that some changes to food consumption patterns in the UK (in addition to increased production efficiency and waste reduction) will be necessary in order to meet emissions reduction targets.

Dietary change is also desirable from the standpoint of good nutrition. Current average diets in the UK fail to meet the UK recommendation for five portions per day of fruit and vegetables, and also do not contain the recommended daily amounts of many micronutrients (Bates et al. 2012). The consequent burden of food-related ill-health on the UK's National Health Service has been estimated to be around £6 billion annually (Scarborough et al. 2011). The possibility that diets lower in GHG emissions may also have improved nutritional content has been identified (Stehfest et al. 2009; Tilman and Clark 2014), but the degree to which these dietary changes are realistic is thus far unknown.

Several previous studies have proposed diets for UK populations that would reduce GHG emissions (Scarborough et al. 2010; Aston et al. 2012; Berners-Lee et al. 2012; Macdiarmid et al. 2012; Scarborough et al. 2012; Scarborough et al. 2014), although most of these studies have not explicitly addressed whether these diets are realistic given current dietary patterns in the UK. Many such studies postulate hypothetical policy scenarios such as a diet low in animal products (Friel et al. 2009; Aston et al. 2012; Berners-Lee et al. 2012) or a Mediterranean dietary pattern (Tukker et al. 2011) and calculate associated GHG emissions. Studies such as these tend to assume that changes to national diets will be acceptable and therefore politically implementable, without actually explicitly modelling this aspect using the available data. This is clearly important since a few studies have identified acceptability of the diet as a major limitation of the degree of dietary change that can be achieved when attempting to reduce GHG emissions (Macdiarmid et al. 2012; Wilson et al. 2013; Masset et al. 2014).

Studies to-date modelling dietary change have also rarely considered food substitution, i.e., when a particular food is reduced in the diet, what is this food replaced with (if anything)? There is a paucity of evidence on this topic, although a recent review has begun to summarise worldwide evidence on food substitution (Green et al. 2013). Many previous studies in the literature assume that reductions in consumption of one food group (e.g., meat) will automatically be substituted by increases in another (e.g., cereals or fruit and vegetables) (Berners-Lee et al. 2012; Scarborough et al. 2012; Vieux et al. 2012; Hedenus et al. 2014), but the current evidence on food substitution indicates that

the reality is likely to be much more complex, and accounting for this complexity may drastically alter the results of such studies.

Given the acknowledged weaknesses of earlier estimates of the effect of dietary change on GHG emissions, our study takes the innovative steps of constraining changes in the average diet to reflect current food consumption patterns, as well as incorporating the available evidence on substitution between different food groups (through the inclusion of responsiveness to food price changes and expenditure share for different food groups). The method adopted thus constrains dietary changes in a way that reflects individual preferences for certain kinds of foods. Using a recent and representative UK dietary survey, the aim of this work was to model the specific reductions in food-related GHG emissions that could be achieved while meeting international dietary recommendations and minimising deviation from the current diet.

2 Data and methods

2.1 Dietary data

The UK National Diet and Nutrition Survey (NDNS) is a rolling programme of cross-sectional surveys using a 4-day food diary (Bates et al. 2012). We used data from Waves 1–3 (2008–2011) of the survey, which includes nutritional data from 1571 adults, to estimate the composition of current UK average diets for men and women. The raw dietary data were used to obtain nutritional information for each food entry on each day of the NDNS using UK food composition tables (<http://www.ifr.ac.uk/fooddatabanks/nutrients.htm>). Foods were aggregated into sub-groups according to the NDNS classification (148 sub-groups). The nutritional information for each food entry within a sub-group was then averaged to achieve a nutritional classification for each sub-group, along with the mean grams of each food consumed per sitting and the number of sittings for each sub-group in the dataset. This information was then used to calculate the average nutritional content of each of 42 main food groups used in the analyses (details of the individual foods contained within each group and sub-group can be found in the Supplementary Materials Table S1). This was done by calculating proportional weights for each sub-group within a food group (e.g., the weight for cream within the ‘milk and milk products’ group) using the portion size (in grams) and the number of portions of the sub-group that were eaten in total. Finally, these weights were applied to all nutritional information in order to calculate weighted averages of nutritional content for each food group. We calculated nutritional content for all nutrients included in the WHO dietary recommendations (carbohydrate, total fat, saturated fat, N6, N3 and total polyunsaturated fat, trans fat, monounsaturated fat, free sugars and sodium).

The raw dietary data were also used to obtain the total consumption of each food sub-group over the 4-day diary period for all individuals. These sub-groups were then combined (separately for males and females) into the 42 groups used for analysis, and the total consumption was divided by four to give the daily average consumption of each food group. Non-consumers of each food group were included in the averages. Average consumption of nutrients for each individual was taken from the individual-level consumption data. For macronutrients (carbohydrate, protein and fat), World Health Organization (WHO) nutritional recommendations state that intake should be as a proportion of total calories, and we therefore converted grams of macronutrients consumed into calories as a proportion of total calories, using the accepted content figures of 9 kcal per gram of fat, 4 kcal per gram of protein and 4 kcal per gram of carbohydrate.

2.2 Greenhouse gas emissions data

Estimates of GHG emissions associated with each of the 42 food groups were calculated using Life Cycle Analysis (LCA) compiled from the relevant literature in the UK and Europe (Audsley et al. 2009; Hammerschlag and Venkat 2011; Berners-Lee et al. 2012; Vieux et al. 2012; Weiss and Leip 2012). In some cases a full LCA of emissions was not available (Berners-Lee et al. 2012; Vieux et al. 2012; Weiss and Leip 2012), so extrapolations from the literature (Foster et al. 2006; Audsley et al. 2009; Garnett 2011; Hammerschlag and Venkat 2011; Berners-Lee et al. 2012) were used to extend the estimates across the full life cycle of the food. We also estimated food losses from production, handling and sales, from cooking meals and from consumer waste, extrapolated from estimates of waste in the US (Venkat 2011). For food groups where specific emissions estimates were not available in the literature, representative items included in the food group for which emissions data were available were used as a reference point for all foods within the group. Complete information on how GHG emissions were estimated for each food group can be found in the Supplementary Materials Table S2.

2.3 Optimisation modelling of diets

We used a mathematical programming method (optimisation) to design nutritionally optimised diets for men and women in the UK that conformed to WHO nutritional recommendations (WHO 2003) but with minimal deviation from the current diet. The optimisations were performed in the statistical software R (R 2012) using the package Alabama (Varadhan 2012), which optimises smooth nonlinear objective functions with constraints using an Augmented Lagrangian method. Each simulation attempted to minimise the sum of squared deviations for each food group from the current diet (see Text S1 and Figure S1a and S1b in the Supplementary Materials for more details). For a given food group i , the loss of welfare W_i resulting from consumption greater or less than the ideal level for health can be shown to be proportional to the share of expenditure for that food group s_i and inversely proportional to the price elasticity of demand ε_i

$$\Delta W_i \propto \frac{s_i}{\varepsilon_i} \left(\frac{\Delta X_i}{X_i} \right)^2$$

where X_i is the current consumption for food group i and ΔX_i is the difference between current and ideal consumption for food group i (details of expenditure shares and own-price elasticities used in the analysis can be found in the Supplementary Materials, Table S3). The ratio of s_i/ε_i acts as a proxy measure of how likely people would be to modify their consumption of that food group. The analysis therefore seeks to find the combination of foods that minimizes the weighted deviations of squared percentage consumption from the desired levels, where each deviation is weighted by s_i/ε_i . For the 42 food groups identified from the NDNS, we attempted to find the solution of

$$\min_{\{\Delta X_i; i=1..42\}} \left[\sum_{i=1}^{42} \frac{s_i}{\varepsilon_i} \left(\frac{\Delta X_i}{X_i} \right)^2 \right]$$

whilst ensuring that the resultant diet complied with WHO recommendations and maintained the total calories and proportion of liquids in the diets. The ideal consumption of food i is given by $X_i^* = X_i + \Delta X_i^*$ where ΔX_i^* is the solution for food i . Initial estimates of future consumption for each food group (i.e., initial estimates of the solution of the

above equation) were generated randomly. The values of s_i were determined directly from the NDNS dietary survey, while the price responsiveness (ϵ_i) for each food group was obtained from (Tiffin et al. 2011).

Constraints were added to each simulation to ensure that the modelled diets complied with WHO guidelines (e.g., total fat had to be between 15 and 30 % of calories and there had to be a minimum of 400 g of fruit and vegetables consumed – see Table 1 for details). We added further constraints specifying that the total calories and volume of liquids consumed should remain equal to the current diet, and that consumption of each food group must be ≥ 0 . These constraints also acted to keep the new diets similar to current diets. Alcohol consumption was kept constant, since alcohol is associated with specific public health issues which were considered to be beyond the scope of this work.

To reduce the GHG emissions associated with the nutritionally optimised diets, we added an additional constraint to each optimisation model that progressively reduced the maximum allowed emissions by 10 %. We therefore produced a total of 16 models for men and women (one nutritionally optimised diet with no specified reduction in emissions, and then models with 10, 20, 30, 40 50, 60 and 70 % reductions in emissions in addition to the nutritional constraints – only the models with 0, 20, 40 and 60 % reductions are presented in the main results).

Each simulation was repeated 100 times to increase the probability of finding an overall minimum solution rather than local minima.

Table 1 Nutritional composition of current UK average diet for males and females compared to WHO dietary guidelines

Food group / nutrient	WHO dietary guideline+	Current UK diet#	
		Males	Females
Total energy (kcal)	–	2098	1578
Total fat (% total energy)~	15–30	33.4	33.5
Saturated fat (% total energy)	<10	12.3	12.5
Polyunsaturated fat (% total energy)	6–10	5.8	5.1
N6 polyunsaturated fat (% total energy)	5–8	4.8	4.2
N3 polyunsaturated fat (% total energy)	1–2	1.0	0.9
Trans fat (% total energy)	<1	0.7	0.7
Monounsaturated fat (% total energy)	(remaining)	12.1	11.8
Carbohydrate (% total energy)~	55–75	44.4	46.1
Free sugars (% total energy)	<10	11.9	11.1
Protein (% total energy)~	10–15	16.2	16.7
Cholesterol (mg)*	<300	–	–
Sodium (g)	<2	2.6	1.9
Fruit and vegetables (g)	≥ 400	285	288

+Dietary guidelines taken from World Health Organization. Diet, Nutrition, and the Prevention of Chronic Diseases: Report of a Joint WHO/FAO Expert Consultation. Geneva, Switzerland: 2003

#Nutritional data taken from the National Diet and Nutrition Survey

*Not included in analyses because information is not available from the National Diet and Nutrition Survey

~% total energy from fat, carbohydrate and protein are averages across individuals and therefore these do not add up to 100 %

3 Results

3.1 Nutrient content and GHG emissions of the current UK diet

Average nutritional intake is described in Table 1, along with the WHO nutritional recommendations. No individuals were found to have diets that conformed to all of the recommendations, and it can be seen from the table that average diets exceed the recommendations for saturated fats and free sugars, and do not meet the recommendations for polyunsaturated fats, carbohydrates, fruit and vegetables. Women's diets tended to be slightly higher in saturated fats and lower in polyunsaturated fats than men's, but men's diets tended to be higher in sugars and sodium, and lower in fruits and vegetables.

Estimated GHG emissions for each of the 42 food groups included in our models are presented in Fig. 1. It can be seen from the chart that red meats and butter have by far the highest estimates of GHG emissions, followed by cheese and margarine. Other meats and fish have moderately high emissions, as do ice cream, eggs and processed foods such as pizza and pasta, crisps and soups. The lowest emissions came from tea, coffee and water, with bread, potatoes, beans and breakfast cereals also having low emissions. It is worth noting from the chart that some healthy foods that are desirable in the diet have higher emissions than unhealthy foods (e.g., tomatoes, fruits and vegetables have higher emissions than sugars and sweet spreads).

3.2 GHG emissions consequences of adopting a healthy diet

The results of the dietary optimisations for selected food groups are shown in Fig. 2. It can be seen from the figure that the nutritionally optimised diet shows a considerable deviation from the current average diet even with no constraints to reduce emissions. The nutritionally optimised diet reduces GHG emissions by just over 17 %, even though no reduction was formally required by the model (see Supplementary Materials, Text S1 and Figure S1a and S1b). The diet is lower in red meat, and much lower in dairy products and eggs (particularly among men). There is an increase in the consumption of cereals, and consumption of vegetables (including potatoes, beans and pulses) and fruit is also increased, whereas consumption of both sweet and savoury snacks is reduced. Soft drink consumption is vastly reduced, with the volume of liquids in the diet being mostly replaced by water and tea (complete data on the changes to all food and beverage groups can be found in the Supplementary Materials, Table S4a and S4b).

3.3 Further optimisation for reduction of GHG emissions

In order to reduce GHG emissions, further dietary changes would be required, and these were calculated for 10 % increments in emissions reduction (Fig. 2 – only results for 20, 40 and 60 % reductions are presented). A diet involving a 20 % reduction in emissions is very similar to the basic nutritionally optimised diet, confirming that a considerable reduction in food-related GHG emissions could be achieved simply by adopting a healthier diet. To achieve a 40 % reduction in emissions requires slightly more change to the diet, mostly in the form of reducing meat and dairy intake further, slightly reducing fruit consumption, and increasing the consumption of sugary snacks (which are energy-dense but have low emissions).

At this point there are clear trade-offs between environmental and nutritional impacts (since consumption of healthy foods such as fruit is reduced and sweet processed foods are increased), but the diet still conforms well to nutritional recommendations and is highly varied.

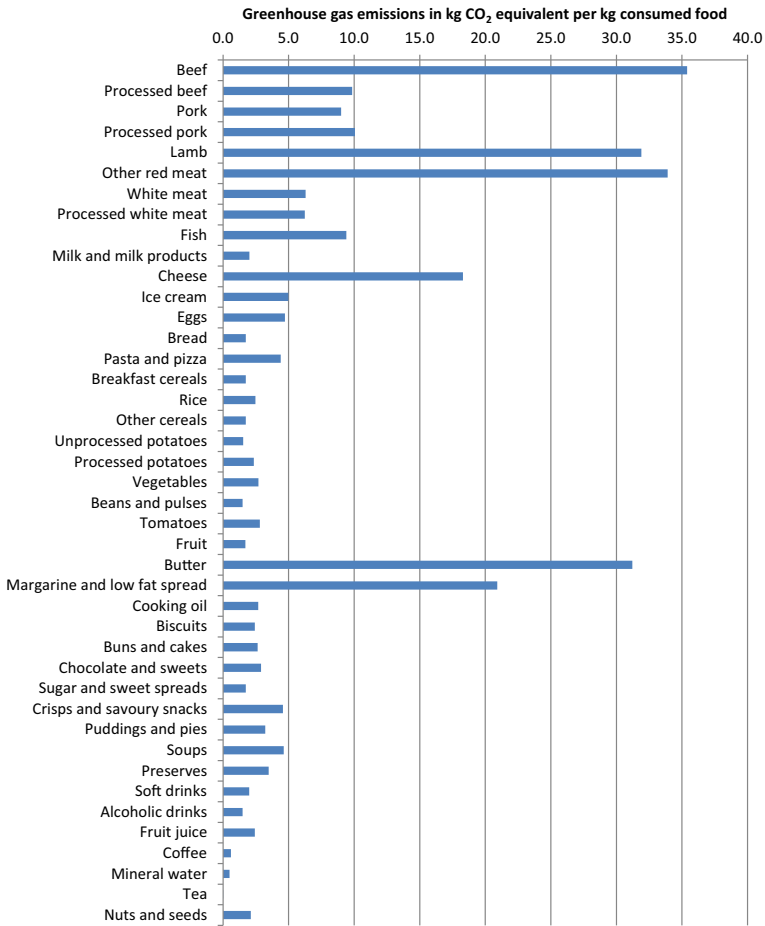
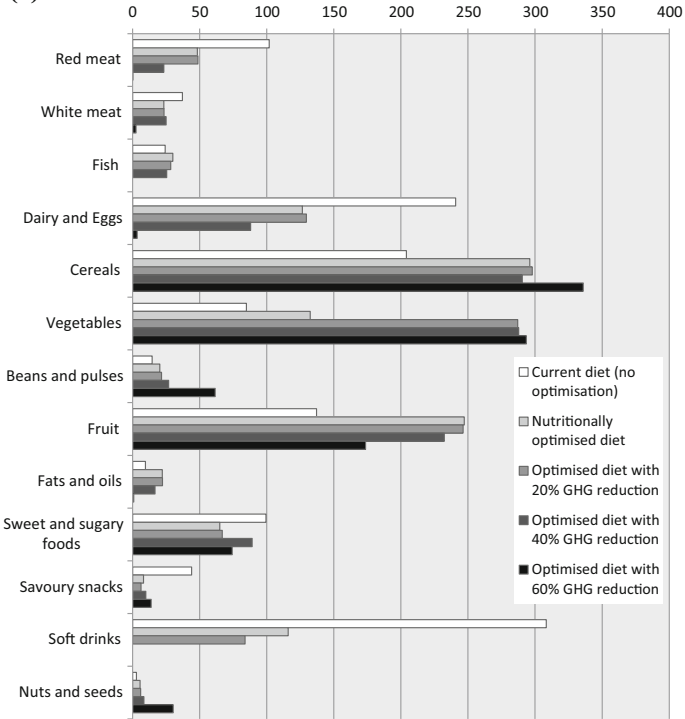


Fig. 1 Estimates of greenhouse gas emissions associated with 42 food groups in the UK National Diet and Nutrition Survey

The 60 % reduction scenario involves major dietary change and is a much less balanced diet (although it also still conforms to WHO recommendations, albeit barely meeting the requirement for protein intake). This diet is almost entirely vegan, with added sugary snacks. There is a fairly large increase in consumption of nuts, seeds, beans and pulses, but these are still a relatively small part of the diet. We also modelled diets with up to a 70 % reduction in GHG emissions, but these models failed to converge, indicating that such diets could not be made to conform to the nutritional guidelines.

We plotted the level of GHG emissions reduction in each of our dietary scenarios against the sum of squared percentage deviations from the current average diets for men and women (see Fig. 3). According to this figure, there appears to be a clear point in the reduction of GHG emissions at which deviations from the current diet become extreme. This point occurs at around a 40 % reduction in GHG emissions, and is more marked in men than in women since male diets would need to be modified more to fit with nutritional and environmental recommendations. Up to this point, considerable environmental benefits can be achieved with relatively small changes to the current diet (up to a 50 % deviation for men and a 40 %

(a) UK adult men



(b) UK adult women

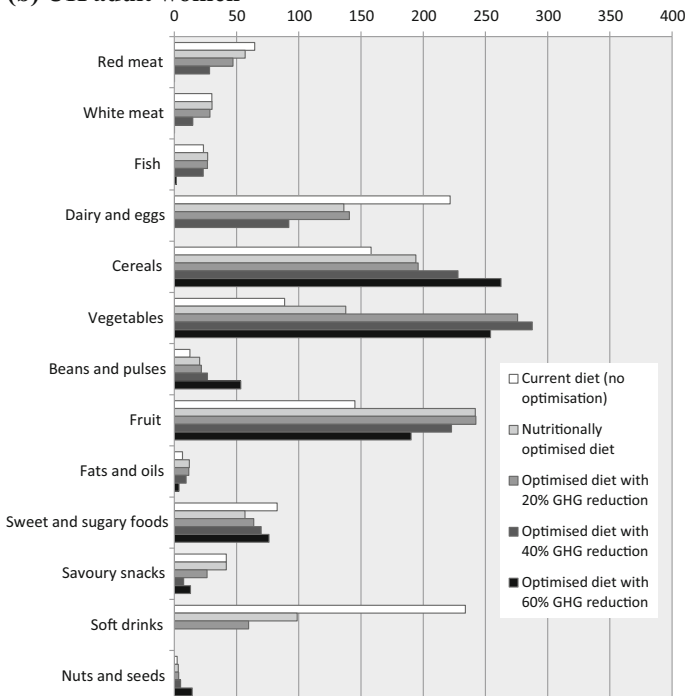


Fig. 2 Optimised diets for UK adult men and women conforming to WHO nutritional guidelines, incorporating reductions in GHG emissions (consumption of selected food groups in g per day). **a** UK adult men. **b** UK adult women

deviation for women). Above a 40 % reduction in GHG emissions, the diet may become too limited and unacceptable for the population (e.g., a 60 % reduction in GHG emissions requires around a 200 % deviation from the current diet for men and a 150 % deviation for women), though the environmental benefits would continue to increase.

4 Discussion

4.1 Strengths and limitations

A major strength of this study is that it is the first to use UK data to specifically model the health co-benefits that would be attained by reducing GHG emissions by defined amounts. The results can therefore be used to balance the need to reduce food-associated emissions against the need for diets to be diverse, healthy and acceptable to the population. However, studies focusing on diets and GHG emissions must necessarily rely on approximate data, since these areas are notoriously difficult to measure accurately. Food consumption is likely to be slightly under-reported in the NDNS, as in all self-reported dietary surveys, so the total calories consumed are likely to be an underestimate of actual intake (Macdiarmid and Blundell 1998). However, other available data tend to focus on expenditure (e.g., the Family Food Survey) or food availability (e.g., FAOSTAT Food Balance Sheets), and are therefore likely to be less reliable in terms of the nutritional content of diets eaten by individuals. We chose to analyse the NDNS because of the need to focus on nutritional content of the diet in our analyses, which we believe requires the use of actual consumption data rather than a proxy for consumption. We have used the most recent and accurate data available for the UK, and the fact that consumption of unhealthy foods is more likely to be under-reported than consumption of healthy foods means that we are likely to have underestimated the unhealthiness of the UK diet, making our findings somewhat conservative.

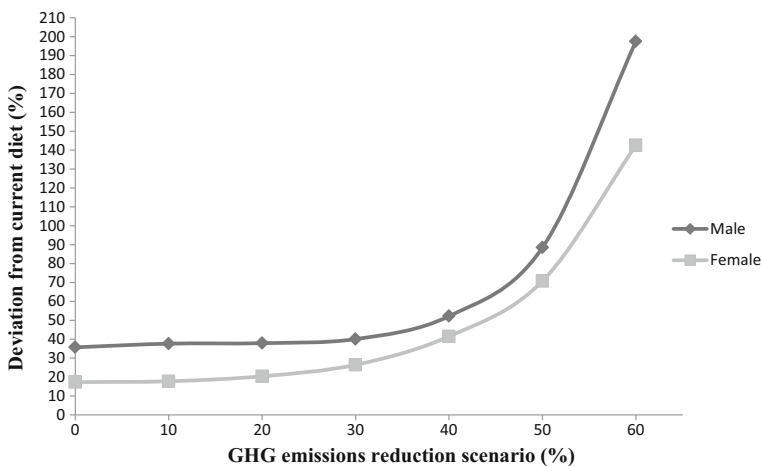


Fig. 3 Deviations of optimised diets from current average diet, with associated reduction in greenhouse gas emissions

Few other studies have produced estimates of GHG emissions from food items in the UK, but where these have been produced our estimates are largely similar (in many cases they are partially derived from these previous studies). Where our estimates differ – for example, our estimates of meat and dairy emissions are somewhat higher than those from other UK sources (Audsley et al. 2009; Berners-Lee et al. 2012) this is likely to be due to the methods used. We used a complete Life Cycle Analysis (LCA) of emissions specific to the UK where possible, and where only partial estimates were available we extrapolated data from similar food groups and countries. Our estimates therefore incorporate emissions from food production, processing, packaging, transport, storage and waste, whereas most other studies do not include all of these elements. Despite attempts to use the highest quality data, our optimised diets are necessarily based on estimates and should therefore be taken as an approximate guide to dietary modifications rather than an exact specification. In particular, estimates of food waste can only be approximate, and we have used scaling factors to estimate how these may have affected the different food groups used in our analysis. For this reason we have produced the results in chart form to enable readers to gain a general sense of comparative relationships rather than tables presenting exact figures (although a table showing the estimates and how they were derived is available in Table S1 in the supplementary materials). Finally, we are aware that substitution between different food groups would affect the supply–demand structure on which we have based our assumptions, so that for example if UK consumers switched from fresh beef to processed beef (which has lower emissions as shown in Fig. 1) this would increase the price of processed beef and therefore change the baseline assumptions of our models. Future analyses could take account of this issue by creating dynamic models that are responsive to such changes in assumptions.

4.2 Comparison with previous studies

Previous studies of diets in the UK have not attempted to explicitly optimise diets to reduce their associated GHG emissions to specified levels. Most previous studies have concentrated on modifying specific aspects of the diet (e.g., reducing meat consumption and replacing this with consumption of fruit and vegetables) and have calculated the associated reduction in emissions (Aston et al. 2012; Berners-Lee et al. 2012; Macdiarmid et al. 2012; Scarborough et al. 2012), which ranges from 3 % for reduced red and processed meat consumption (Aston et al. 2012) to 90 % for a healthy but unrealistic diet containing only seven food items (Macdiarmid et al. 2012). However, these studies face the problem of having to assume what foods would be substituted for the food groups being reduced, and often it is unknown whether these substitutions would be realistic or acceptable to consumers.

Our study has taken a different approach and modelled the specific reductions in emissions that can be achieved while still meeting nutritional recommendations and minimising deviation from the current diet (using the expenditure share and price elasticity of each food group as a proxy for how acceptable changes to the consumption of each food would be to the UK population). As such, we have explored dietary modifications that are more complex than merely reducing intake of animal products and increasing intake of fruit and vegetables, and have thereby been able to model larger reductions in food-based emissions while making less extreme modifications to the overall diet. For example, one previous study found that switching to a vegan diet in the UK would result in a 26 % reduction in GHG emissions (Berners-Lee et al. 2012). However, our models show that a 40 % reduction in emissions can be achieved without consuming an entirely vegan diet, due to switching to types of animal products with lower associated emissions, and reducing consumption of other foods such as pasta, pizza and savoury snacks, which have relatively high emissions and are also unhealthy.

4.3 Policy implications of the findings

The results show that by adopting a diet optimised to conform to WHO dietary guidelines, the GHG emissions associated with diets in the UK would be substantially reduced. Further reductions in GHG emissions appear possible while maintaining a healthy and balanced diet which does not deviate too greatly from the current average diet. The results of this study therefore indicate that a set of relatively subtle dietary changes would be beneficial not only for the nutrition of the UK population, but also for the climate.

However, reductions in emissions of over 40 % will produce radically altered and narrow patterns of food consumption which are highly unlikely to be acceptable to the UK population. Since current targets indicate that the UK GHG emissions should be reduced overall by 80 % by 2050 (CCC 2008), our results suggest that changes in food consumption cannot contribute their full share of emissions reductions to achieve this target. This study therefore supports the findings of previous research indicating that other measures such as waste reduction and increased production efficiency must also play their part (Audsley et al. 2009). Since the UK is a net importer of food and is projected to become more so in future (Fader et al. 2013), these other measures will also be vital for ensuring that diets are sustainable. However, the results of the present study indicate for the first time the level of reduction in emissions that can be achieved without resulting in dietary changes that are likely to be unacceptable to the UK population.

5 Conclusions

This study has shown that considerable reductions in the GHG emissions associated with diets can be achieved while still maximising the nutritional content and acceptability of the diet. However, the dietary changes required to achieve these co-benefits may be more complex than many studies assume. Our dietary optimisations show that emissions reductions can be achieved by reducing consumption of animal products, switching to meats and dairy products with lower associated emissions (e.g., pork, chicken and milk), reducing consumption of savoury snacks, switching to fruits and vegetables with lower emissions, and increasing consumption of cereals. The optimised diet stops short of suggesting that the universal adoption of vegetarianism or veganism is essential (which will not be currently acceptable to large sections of the population). However there are limits to the extent of cuts in emissions that can be achieved and our findings indicate that additional strategies such as reducing food waste and increased efficiency will be essential if the food and agricultural sector is to play its full part in contributing to national GHG reduction targets, especially as increased cereal crops will also be required in order to meet the global demand for animal products in future (Pradhan et al. 2013). This information will be of use to public health, food and environment policy makers, as they suggest that benefits to both health and the environment could be considerable if such policies can be successfully implemented.

Contributors RG contributed to the study design, conducted data management and analysis, and drafted the paper. She is guarantor. JM contributed to the study design, analysed the data, and revised the paper. AD, AH and AM assisted with study design and revised the draft paper. ZC advised on modelling and revised the draft paper. JS provided data, conducted data management and analysis, and revised the draft paper. PW initiated the project, designed the study and revised the draft paper.

This study is a secondary analysis of publicly available data, and as such does not require ethical approval.

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