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Healthy and sustainable diets that meet GHGE reduction targets and are affordable for different income groups in the UK.

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A shortened version of the title: Healthy sustainable diets for UK incomes

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Conflict of Interest

There are no conflicts of interest.

Authorship

JM, GH formatted the research questions, CR, JM, SW, and GH contributed to the study design and analysis. CR and JM drafted the manuscript. CR had primary responsibility for the final content. All authors contributed to the final version and read and approved the final manuscript.

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Abstract

Objective: To model dietary changes required to shift the UK population to diets that meet dietary recommendations for health, have lower greenhouse gas emissions (GHGE) and are affordable for different income groups.

Design: Linear programming was used to create diets that meet dietary requirements for health and reduced GHGE (57% and 80% targets) by income quintile, taking into account food budgets and foods currently purchased, thereby keeping dietary change to a minimum.

Subjects: Nutrient composition, GHGE and price data were mapped to 101 food groups in household food purchase data (UK Living Cost and Food Survey (2013), n=5144 households).

Results: Current diets of all income quintiles had similar total GHGE, but the source of GHGE differed by types of meat, and amount of fruit and vegetables. It was possible to create diets with a 57% reduction in GHGE that met dietary and cost restraints in all income groups. In the optimised diets, the food sources of GHGE differed by income group due to the cost and keeping the level of deviation from current diets to a minimum. Broadly, the changes needed were similar across all groups; reducing animal-based products and increasing plant-based foods but varied by specific foods.

Conclusions: Healthy and lower GHGE diets could be created in all income quintiles but tailoring changes to income groups to minimise deviation may make dietary changes more achievable. Specific attention must be given to interventions and policies to be appropriate for all income groups.

Introduction

Dietary intakes in the UK vary by income and socio-economic group [1–3], yet the majority of the current literature on dietary change towards healthy, low greenhouse gas emission (GHGE) diets tends to focus on population level studies and solutions[4–7] rather than exploring the differences within the population[8]. Dietary intakes need to improve across all income groups in the population since they are not meeting the dietary recommendations for health and are contributing significantly to climate change. Dietary habits, however, vary across income group, therefore the changes needed may differ from the general population level solutions that have been proposed. These changes include, for example, increasing consumption of fruit, vegetables, and starchy foods and reducing consumption of high-fat/high-sugar foods and animal products.

Dietary differences have been shown to be associated with the cost of food and the amount of money available to purchase food[2,9]. In previous studies in the UK, low income groups have reported consuming greater quantities of processed meat and sweet snacks or processed potato products (e.g. chips, crisps), while higher income groups report consuming greater quantities of fruits and vegetables, and high-fat dairy products (e.g. cheese)[1,10–12]. These dietary differences across income groups have been associated with health inequalities such as obesity, type 2 diabetes and cardiovascular disease[13–15].

Cost is often perceived as a barrier to the uptake of healthy, low GHGE diets[16]. However, some studies have shown that all income groups can afford a nutritionally adequate diet without increasing cost, though this became difficult with lower food budgets[17]. While a UK study has found that expensive, recommended ‘healthy’ diets (i.e. Dietary Approaches to Stop Hypertension (DASH)) can have lower GHGE than cheaper, ‘unhealthier’ diets[18] because they have larger amounts of lower GHGE foods (e.g. fruit and vegetables). In contrast, an Australian study showed that a typical diet actually eaten by high income groups tends to be associated with higher GHGE than a typical diet consumed by low income groups[19]. This was because higher income groups spent more on food, and on some higher environmental impact foods (e.g. meat, dairy and meals out). This study, however, did not examine the nutrient composition of the diet for health and, as previous studies have shown that while comparable, a healthy diet does not always have a lower GHGE[20–24]. Van Dooren[25] examined GHGE and dietary requirements across Dutch sub-populations, finding those with high income and social economic status (SES) had higher dietary GHGEs than those on a low income and lower SES. Van Dooren concluded that these unsustainable dietary practices of specific subgroups require dedicated transition strategies, and provided examples for specific sub-groups (including replacing snacks with fruit, replacing cheese with vegetables, partly replacing meat with fish, changing beverage consumption, and halving the daily portion of meat).

Other barriers to dietary change include a resistance to reduce higher GHGE foods (e.g. animal products)[16,26], perceived time constraints for food preparation[16,27] and a lack of knowledge about what constitutes environmentally friendly diets[16,26,28]. To encourage a shift towards healthy, low GHGE diets, these barriers could be mitigated by proposing healthy, low GHGE diets that align more closely with current diets, that keep dietary change to a minimum.

It has been shown that across European populations, change at a national dietary level towards a healthy low GHGE diets is feasible[29]. Though the changes required in the consumption of animal-based products across countries and genders are similar, other dietary changes differed (such as consumption of fish, poultry, and non-liquid milk dairy). However, there is not one ideal diet or set of policy advice to move towards a lower GHGE diet.

Change towards lower GHGE diets is necessary to meet the UK's GHGE reduction targets[30]. GHGE reductions are planned to be evenly distributed across the food system, which contributes an estimated 20% of total UK GHGE [5,31,32]. Reductions in food system associated GHGE will need to come from agriculture, processing, retail and waste management practices (supply side change), as well as changes to diet to successfully transition to a lower GHGE economy[33,34].

Household food budgets vary across the population, and this needs to be factored in to recommended dietary changes. Through dietary modelling it has been shown that healthy, affordable and low GHGE diets are feasible at the population level[35–43]. However, to shift to the types of diets proposed, lower income groups would need to spend between 18% and 74% of their total household income on food, while high income groups would only have to spend between 6% and 10% to achieve a similar diet[44–46].

The aim of this study was to model healthy, low GHGE diets that takes into account current dietary habits and food budgets by income quintile. Using data from the Living Cost and Food Survey (LCFS) this study compared current household purchases, used as a proxy for diets, with optimised diets for different income groups.

Method

Study design

Linear programming was used to create low GHGE diets that met dietary requirements, and were no more expensive than existing spend on diets, while keeping the deviation from current intakes to a minimum. While linear programming has been previously used to calculate healthy, lower GHGE and affordable diets at the population level [4,7,22,29,47–63], this study extends the research to optimised diets for the different income quintiles and keeping dietary change to a minimum in each group. By keeping the change to a minimum, multiple diets were generated that varied the minimum amount of each food that made up the current diet. The UK's GHGE target at the time of this study, a 57% reduction from 1990 values by 2032, was used[32]. Income was based on gross income reported in LCFS, the income quintile boundaries were taken from the Office for National Statistics, and generated using weighted income data to represent the UK population [64]. In the manuscript current diets are referred to '2013 diets', which provide the baseline for the optimised diets.

Data Sources

The 2013 Family Food module of the Living Costs and Food Survey

The 2013 Family Food Module of the LCFS includes purchase data of 5,144 households across the UK. Households recorded all purchases of food and drink over two weeks, including those eaten in the home and those out of the home[2]. The LCFS collected data on weights of all foods purchased and the amount spent (£) on each food and drink item per person per week, which was reported at the amount per individual, per week level by the LCFS.

Quintile household gross income boundaries range from less than £265.18 per household, per week in the lowest income (Q1) to more than £1077.97 per household per week in the highest (Q5). Individual incomes were not reported by the LCFS. Foods eaten in and outside the home were both included in the linear programming, but the foods were kept as separate to allow for analysis of these differing types of purchases and food budgets.

The 337 (eaten at home) and 316 (eaten out) LCFS food categories were matched to 101 food item categories in a pre-existing dataset mapped to nutrient composition and GHGE data (see Table 1 for list of the 101 food items used in the linear programming). Drinking water was excluded from this mapping, and purchased drinking water was excluded from total spending. The nutrient composition of the foods, associated GHGE data, and the purchase weights of the foods were converted to represent the edible portions (g/day)[65]. This included, for example, weight changes with cooking (e.g. rice, meat) and unavoidable wastage (e.g. banana skins). Nutrient data were taken from the National Diet and Nutrition Survey databank[66]. Both the LCFS and nutrient data were obtained from the UK Data Archive.

Composite meals in the LCFS were disaggregated into individual components, based on recipes from UK food composition tables and portion sizes[65,67] and cookbooks[68–70]. For food categories with multiple composite dishes (e.g. takeaway and ready meals) a two-step disaggregation was used. First, composite dishes were disaggregated into the Eatwell Plate food groups proportions[71]. Second, within each of the Eatwell Plate food group, ingredients (in proportions based on the frequency of purchasing (in Scotland between 2006 and 2012) recorded by Kantar Worldpanel (www.kantarworldpanel.com/en)) were matched to one of the individual food items in the linear programming dataset.

For example, for the category of takeaway meat based meals (e.g. curries, meat pies) it was estimated that these dishes comprised 28% protein on the Eatwell plate. The protein category was then disaggregated into the food groups of beef (14.34%), lamb (1.83%), pork (1.58%), chicken (9.38%), and turkey (1.35%) based on the frequency of purchase of these types of meat. The amount of each ingredient was then assigned to one of the food in the linear programming dataset.

Price data

The total spend per person was calculated by multiplying the weight of food consumed by a price vector. The price vector (£ per 100g for all 101 food groups) was estimated using price and weight data from the 2013 LCFS to create an average price for each food item. Six food categories (i.e. pepper, sweetcorn, pumpkins, squash, kiwi, fried white fish and mayonnaise) did not have direct price information, and so they were matched to similar products. The LCFS supplied no food item level price data for foods eaten out of the home, and therefore in the absence of this information these were set the same as food eaten at home. It is recognised that this has limitations as eating food out can be more expensive.

Greenhouse gas emissions data

GHGE data (kgCO_2e /100g product) for each of the 101 food items were based on data published by Audsley et al.[31]. These values are average emissions for the production of primary food commodities up to the point of the regional distribution centre (RDC) in the UK (this excludes processing, retail, household use and waste). The RDC is described as a nominal boundary of primary production to the point of distribution for primary commodities in the UK. Audsley et al.[31] estimates that 56% of

GHGEs are accounted for up to the RDC. For foods with multiple ingredients, such as cakes, biscuits, bread, the GHGE were estimated based on the ingredients making up the food.

Audsley et al.[31] estimated that in 1990 the GHGE of food supplied and consumed in the UK was approximately 152 Mt CO_2e/year, or 7.38 kgCO_2e/person/day (based on the UK population by age and sex in 1990[72]), or 4.14 kgCO_2e/person/day to the point of the RDC. At the time of the study the UK had targets to reduce GHGE by 57% from 1990 values by 2032, and an 80% reduction by 2050[32]. These GHGE reduction targets take account of population growth. Using the Audsley et al. 1990 value as a baseline, the 57% and 80% GHGE reduction targets are estimated to be equivalent to 1.78 and 0.83 kgCO_2e/person/day respectively (to the point of the RDC).

Analysis: Linear programming and constraints

Linear programming is a mathematical technique used to minimise or maximise a linear function, subject to a series of constraints that defines a set of linear relationships between variables and limiting resource, which has been used in other studies to optimise diets [17,48,59,63,73–76]s. In this study it was used to construct nutritionally complete diets while optimising another variable (e.g. minimising GHGE), while being constrained by other factors (e.g. cost, energy, nutrients). The constraints are expressed in terms of linear combinations, with minimum requirements, upper limits or equality imposed on each item based on dietary recommendations (see Table 2 for constraints included in the models) [77–81]. In this study constraints comprised meeting dietary recommendations, not exceeding the budget spent on food (by quintile group) and limiting deviation from current purchases. The amount spent on each food item is based on the item as purchased, and is recorded at the household level but reported in the Family Food Report[2] as amount per person per week., The objective function was the associated GHGE of the diet, which was minimised. An additional constraint for GHGE was used in later models to impose the UK GHGE reduction targets (see Table 2). More details of linear programming is given in the supplementary material (S1).

The energy and nutrient recommendations were weighted to reflect dietary recommendations for the current UK population (by age and sex, excluding those younger than 1 year) using the same methodology described in the LCFS [82]. The price constraint was set at the maximum amount that could be spent on food per day, which varied by income quintile based on their current spend.

This study used constraints of maximum upper and variable lower boundaries for all food items to limit the deviation from the current dietary habits of each income quintile. This approach to minimise the deviation from habitual diets was used by Horgan et al [8] (who used fixed upper and lower bounds).

The maximum upper boundary meant that the weight of any food item from the 2013 diet could only double (200%), which was considered a reasonable and realistic increase, and in line with previous studies[7,22]. Oily fish was the exception because 2013 amounts were less than half that recommended. Alcoholic beverages could not exceed current household's purchase and an upper limit was set at the average LCFS alcohol consumption per day of 8.9g/day. This is below the national maximum recommendation for alcohol consumption[83]. This meant that the amount of alcohol could not increase.

A lower boundary was the minimum deviation per food item from the 2013 diet that could be found for each modelling scenario, while meeting dietary recommendations, cost and GHGE constraints. The lower boundary was set initially at 0% of the weight of all food items in the 2013 diet (i.e. 0% is the greatest deviation from the diet), and the percentage increased over successive iterations of linear programme runs (in steps of 1%), until no feasible diet could be found to meet the constraints (i.e. dietary requirements, price, GHGE). For example, iteration with a lower boundary of 60% meant that all food groups had at least 60%, by weight, of that food in the optimised diet. The iteration that met the constraints with the highest percentage 'lower boundary' is referred to as the 'final optimised diet'. This is the diet that meets all the constraints, with the smallest change from the 2013 diet that is possible using discrete linear constraints rather than an objective function, and is the diet reported in the paper.

A population weighted minimum fruits and vegetable constraint of 380g/day was set, with 2 fruit portions and 3 vegetable portions to ensure a mix of fruit and vegetables in the optimised diet[80]. Foods with no direct cost to the household (i.e. free school milk or free school fruit) were set at fixed weights and included in the diet.

Three scenarios were run, the first only included the dietary constraints and minimum and maximum boundaries (M1), and the second added the cost constraint (M2), while the final scenario rejected any solutions where the GHGE minimum was not low enough (M3). In all the scenarios GHGE were minimised.

Linear programming was carried out by using the GNU Linear Programming Kit as implemented in the Rglpk (0.3–5) package of the R (3.20) statistical software environment[84].

Results

For all income quintiles, the linear program found a range of optimised diets with lower GHGE than the 2013 diets that met dietary and cost constraints. However, it could not find any diet to meet the 80% GHGE reduction target with a 200% upper limit on food weights in place.

For the average UK diet the greater the lower boundary constraint achieved (i.e. keeping dietary change to a minimum, the higher the associated GHGE of this diet (Figure 1a). Figure 1b shows that the average optimized diets with (M1) and without (M2) a cost constraint are the same up to until the cost constraint is met. Once the maximum cost is met the constrained diet ‘flat lines’ cost), but increases in GHGE more quickly than the diet with no cost constraint .The cost and GHGE impacts of the diets are identical in both up to the constraint being met (at 52%).

Income level affected the number of lower boundary iterations that could be completed by the linear program, varying from 57% to 62% (quintile 1 to 5) when there was no cost constraint (M1), and when cost constraint included, 53% to 60% (M2) (Table 3). This meant the higher income group could retain more of the foods in the diet than lower income groups. When the additional GHGE constraint was added (M3), all quintiles were reduced to similar lower boundaries (34%-35%). These final optimised diets had an average saving of £0.21 per day (£0.23 to £0.47 quintile 1 and 5 respectively). The greatest GHGE reduction was in the highest income group (M3), this is due to the highest income group having the highest 2013 GHGE and the largest capacity for reduction due to their high income and high consumption of fruits and vegetables.

When there was no cost constraint, in order to meet the other constraints, the cost of the diets increased and GHGE decreased marginally. As more constraints were applied the further the optimised diets departed from the 2013 diets. At the lower boundary scenario, where the cost constraint is reached (in Figure 1 this is 52%), the linear program begins to select cheaper but higher GHGE intensity foods, to further increase the minimum amounts of the foods from the 2013 diet included in the optimised diet. These trade-offs lead to a divergence of the GHGE impacts for diets with and without cost constraints (as shown in Figure 1a and 1b above the 52% lower boundary). In Figure 1b this divergence can also be observed, with the daily price of the cost constrained diet ‘flat lining’ at £4.47 from the lower bound of 51% (2.18 kgCO_2e/ day) to 57% (2.55 kg CO_2e/day), while the diet without a price constraint continues to increase to lower bound of 62% (£5.06 and 2.70 kg CO_2e/day). This illustrates a trade-off being made between higher cost diets and healthy, lower GHGE diets. At greater the deviation from the current diet (ie at lower bounds) the diets costs less than the current spending.

The variability of GHGE in 2013 and final optimised diets is due to the different dietary composition and cost constraints of each quintile. For example, in 2013, the lowest income quintiles purchased less fruit and vegetables and different types of red and processed meats, while higher income quintiles purchased more dairy in the 2013 diets. These initial differences carried over to the optimised diets because of the lower boundary constraint. Detailed diets for all lower boundaries are provided in the online supplementary material (S2, Tables 2-7).

Substantial dietary change must occur in all income quintiles to meet the UK's 2032 57% GHGE reduction target, with 58 of the 101 foods reduced to 34-35% of their 2013 diet weights, and 29 foods double their 2013 diet weights (Table 4). As shown in Table 1, there were specific food items for all linear programme iterations, for all quintiles, that were maximised or minimised, i.e. oily fish was quadrupled when compared to 2013 diets in all quintile groups. While differences were seen between income groups with the amounts and types of individual foods that needed to change, the overall direction of dietary change needed was similar in all income groups: increase fruit, vegetables and starchy food, reduce animal products, non-alcoholic beverages and high-fat/high-sugar foods. The food groups where the magnitude of change between quintile groups were highest included a greater reduction in alcohol in higher quintile groups and in high-fat/high-sugar foods and milk in lower quintile groups. A greater increase in fruit, vegetables and starchy foods was observed in lower quintile groups. In optimised diets GHGE differences between quintile groups mostly decreased as they shifted towards similar diets as a result of the optimisation. Some food categories (e.g. cereals) had increases in differences in GHGE between quintiles due to changes in the types/quantities of foods purchased (Table 4). Similarly, the difference between quintile groups reduced for fruit and vegetables, and seafood because of differences in the original diets.

Results show that there is a greater than 20% difference in GHGE between the lowest and highest GHGE quintiles for the food categories of rice, potatoes, fruits and vegetables, milk, beans, pulses, nuts, seeds, alcoholic beverages, low calorie/sugar non-alcoholic beverages, and hot beverages in 2013 diets. GHGE differences are not specifically linked to income, with the highest and lowest GHGE per category not mapping directly to income quintiles for all foods. Further information on GHGE differences can be found in online supplementary materialS4, Tables 1 and 2.

Discussion

This study shows that all income quintiles' diets must change in broadly similar directions, with some variation resulting from differences in the foods contributing to GHGE in the 2013 diets. The degree of possible dietary change in each quintile was restricted by the amount of money available to purchase food and the composition of the 2013 diet. The highest income quintile achieved an optimised diet and retained greater amounts of its 2013 diet than did lower income quintiles, but were also able to spend more on their diet. If the highest income quintile preserved the same amount of its 2013 diet as lower income quintiles they achieved lower GHGE (Figure 1). This result confirms the existence of trade-offs to balance healthy, low cost and low GHGE diets observed in other studies[18], and illustrates that the trade-offs shift with income, as higher incomes can buy their way out of the trade-off until cost is a constraint (Table 3). The existence of trade-offs across income implies that attention should be given to developing interventions and dietary policies that can be achievable and effective for both lower and higher income quintiles.

The GHGE contribution of specific food categories differed across income quintiles in the 2013 and optimised diets. This is due to the 2013 dietary habits of each income quintile differing (and thus constraining the optimised diets). For example, although amounts of fruits and vegetables increased in all optimised diets lower income quintiles consumed less fruit and vegetables in 2013 (in number of types and absolute weight), and so were constrained in the types and quantities of fruit and vegetables available in optimised diets. This is similar to the finding (at a sub-national level) that low GHGE diets differed across European national diets due to current dietary habits[29].

Many of these differences between quintiles are passed through into the optimised diets. Retaining these dietary differences in optimised diets illustrates that population level modelling studies have missed the distinction that healthy sustainable diets will contain different foods in different quantities at high and low incomes. This is particularly relevant as the food categories that have variations between quintiles feature in current healthy and sustainable eating guidelines[85–90] (i.e. increasing fruits and vegetables or reducing animal products). Shifting to the more sustainable healthy diet may result in different impacts for different income quintiles. This is significant when discussing the types of foods eaten within each category with lower income groups eating a smaller range of fruit and vegetables, and different types and weights of processed meats. If population studies alone are used to design interventions this could mean only larger dietary changes are advised, such as changing what is consumed to new, more sustainable, foods; trading in a portion of meat for a portion of fish, for example [25,91]. Introducing or trading to new foods may not prove as effective as tailored advice that shifts amounts of what is already eaten, but may be seen as more achievable as deviation from current diets is less.

Our results suggest that, at an aggregated food group level, population modelling in some cases is sufficient, for some general food groups and categories. For example, the largest GHGE contributor in all diets was the food group of red meat, the 2013 amount purchased by each quintile, and reduction required in all diets is similar. Implying a population level (society wide) dietary change is required, rather than a change at one specific quintile level. However, this study highlights that the types of red (and processed) meat reduction is different for each quintile. For example, the consumption (and associated GHGE) of beef, lamb and pork is highest in Q1, while Q2 has the highest consumption of ham, and Q5 has the highest consumption of chicken and bacon. Shifting to sustainable consumption patterns will involve different decisions for each quintile as well as population level shifts of social norms and practices. Interventions and policy must recognise the differences in diets throughout society, and provide advice for shifting towards realistic healthy low GHGE diets for these different sectors of the population. The linear programme could not find a diet that met the UK's 2050 80% GHGE reduction target with the constraints used. This is consistent with previous population studies that show GHGE reductions above 74% were not possible no matter the deviation from the diet[22], while up to 60% GHGE reductions were possible only if some foods deviate from the current diet by up to 200% [7]. In this paper, GHGE reductions were modelled from the demand-side, with no changes to the GHGE intensities of food products, or the food system (supply-side) via new technologies or increases in efficiency. If the currently unobtainable 2050 80% GHGE reduction target is to be met, change from both demand and supply sides will be required[33,34]. However it is also unknown how diets may change over the next few decades. This study used a low GHGE diet as a proxy for a sustainable diet, but it is recognised that there are other indicators of sustainability such as water, waste, land, or energy use that could be included. Further research could analyse the trade-offs between these different diets with different income groups.

The optimised diets save between 18p and 47p a day across income quintiles. However, studies have shown that reducing dietary cost can result in rebound effects, where money saved in one part of the household budget (e.g. food) is spent on more GHGE intensive items elsewhere (e.g. travel, entertainment)[92–95]. To reduce rebound effects, dietary change must be accompanied by broader transitions in consumption to a healthier, lower GHGE lifestyle.

The monetary savings of the diet represent changes in energy to cost density, and energy to weight density, with all increasing the energy from the 2013 levels to 9250 kJ. It is well recognised that self-reported dietary records tend to be lower than actual consumption, or even requirements[96]. Purchase data may be similarly under-reported[97–99]. This increase in energy is a direct result of the constraints used, with the 2013 diets having lower energy values than estimated requirements. Additional linear program runs were carried out with energy constraints matched to 2013 energy values, and the results of these were that similar dietary shifts were required as in optimised diets. However, the cost of the final optimised diet decreased (to between £3.99 (Q1) and £4.10 (Q5) – see cells J41 to N41 in the online supplementary material S3 Energy Comparison), and the lower boundary reached increased (40%-42%). Furthermore, quintiles 3 and 5 did not meet their cost constraint for any diet, with health constraints taking effect first. This implies that the fixed energy constraint forced the LP to purchase more healthy and sustainable foods that cost more.

This study adds to the growing evidence that income quintiles have diets that are associated with differing amounts of GHGE emissions. Previously Reynolds et al.[100] and Van Dooren et al.[25] have found 66% and 9% GHGE differences, respectively between high and low income diet related GHGE emissions. The baseline difference of 3% in this study is smaller than previous studies, possibly because of a greater similarity of diets across the UK population. The larger GHGE impacts of Dutch and Australian diets can be explained by the differences in household diet composition between countries, such as higher consumptions of meat, poultry, fruit and discretionary foods[25,91,101,102]. All studies however agree that moving towards sustainable diets will impact income quintiles in different ways due to the different income based dietary habits. A recent US study has also looked at different households and GHGE emissions finding higher GHGE diets correlated with higher spending patterns [103]. However the paper analysed GHGE quintiles not income quintiles and did not perform any optimised diet modelling.

The types of foods selected for increase and reduction are consistent to previous population level linear programming studies [7,22,49,52], with starchy food, fish, fruit and vegetable consumption increasing to replace the decreases in animal products and high-fat/high-sugar foods. This is in part driven by food based guidelines, such as for fruit, vegetables, fish and red meat. However, this is not consistent with current dietary trends where purchases of starchy foods have been decreasing since 2010[2], while the consumption of fish, fruits and vegetables is static[2]. Encouraging increased consumption of these foods will pose its own set of challenges. Current dietary trends indicate reductions in meat consumption, particularly red meat,[2] which are consistent with the recommended direction of travel, but to meet GHGE targets, reduction needs to be accelerated.

The data used in this study have some limitations. Firstly, the LCFS is a purchase based survey at the household level, with no adjustment for avoidable food waste, or account of which household member consumes the food [104]. Future research could incorporate average avoidable waste (i.e. food waste that would be edible) fractions into the linear programme as per WRAP or Food Standards Scotland data[105,106].

Second, the disaggregation of composite dishes into raw ingredients means that the edible weights presented in Table 3 are in total 1.1kg per week (~9%) higher than the purchased weights in the LCFS. Furthermore, though our composite dishes were disaggregated to component food items using standardised recipes, this may not represent the full range of dishes purchased. Both these factors could affect the energy density and processed/fresh food composition of the optimised diets.

Third, the prices used are an average price for each food item, calculated using average price paid price and average weight purchased for each food item from the 2013 LCFS. Though commonly used in dietary modelling [52,107,108], different income quintiles may purchase similar foods at different price points. This can lead to underestimating diet cost in high incomes quintiles and overestimating in low income quintiles. The former was supplied as raw data from the LCFS, while the latter is calculated by multiplying the average prices of food items by the weights from the LCFS. As shown in Figure 1 and Table 3, cost constraints did not take effect until the 47%(Q1) to 54% (Q5) lower boundary scenario. Changes to food prices would result in this constraint coming into effect earlier and further modifying the optimised diet. Future research could use individual prices, and optimise each diet per quintile's average price paid, rather than at a population average.

Fourth, due to insufficient information regarding the price of food eaten out of the home, prices for foods eaten in the home were used throughout. The result of this was that the absolute spend per household was lower than in the LCFS, but the ratio of spending (and prices) were kept constant. Although the proportion of food purchased outside the home is not large (only 10% of total energy and 11% of the associated GHGE), this is important to note as foods eaten out of the home are typically higher cost, and the types and quantity of foods eaten outside the home changed with income (higher income households purchasing greater amounts of food outside the house than lower income households), the average UK household spending 30% of its food and drink spending outside the home in 2013. The models were run excluding eating out of home, with similar results (see supplementary material S3 Tables 1 and 2). Eat out costs results should be taken as minimum cost, and could be higher for the reasons stated above. Further research is needed into the sustainability and health implications of food eaten away from home.

Fifth, the method used to keep dietary change to a minimum is a slightly crude percentage deviation to the current diet. To achieve a closer match to the current diet, a modified objective function focused on keeping dietary change to a minimum could be used in future research.

In addition, the optimised diets found this study are based on population level food purchase data, and so are not suggested as diets on an individual, daily basis. To create individual diets that could be realistically followed, individual diets from the LCFS could be modelled in a similar method to Horgan et al.[8]. In this study, gross income was used rather than equivalised income due to data availability, however equivalised income quintiles can be calculated[109]. It is recognised that equivalised income quintiles may alter the finding slightly because this takes into account the composition of the household. Future research could investigate the differences in results between gross and equivalised income quintiles.

Finally, there is no statistical comparison of the optimised dietary results. Though not common in the optimised dietary literature to date, this limitation could be addressed in future studies using Monte Carlo and sensitivity analysis. It is also acknowledged that there are limitations due to the precision of the GHGE data, and using the Audsley et al.[31] data as the baseline in this study against the percent reduction targets may not give the exact reduction required. However, in the absence of other data these were used as the baseline for the UK diets. Future research might use Monte Carlo methods to incorporate the wider UK and global[110] variability of GHGE estimations into the linear programme.

Conclusion

In conclusion, this study has modelled healthy, low GHGE diets in each income quintile that did not exceed the current household food budget by altering the amounts of different foods (but not eliminating foods) currently consumed. The more of the foods from the current (2013) diet retained in the optimised diet, the higher the GHGE associated with the optimised diet. It was found that although all incomes had similar total GHGE impacts, there were differences in the foods within categories consumed in both 2013, and optimised diets. The results highlight that different dietary trade-offs are needed by different income quintiles, but these are generally in the same direction to be shifts towards healthy sustainable diets. This implies that though population dietary targets are sufficient, population level sustainable dietary advice or interventions may not produce the same effects in high or lower income groups. Tailored dietary advice or interventions that keep dietary change to a minimum may be more effective to shift income groups to healthy and sustainable diets

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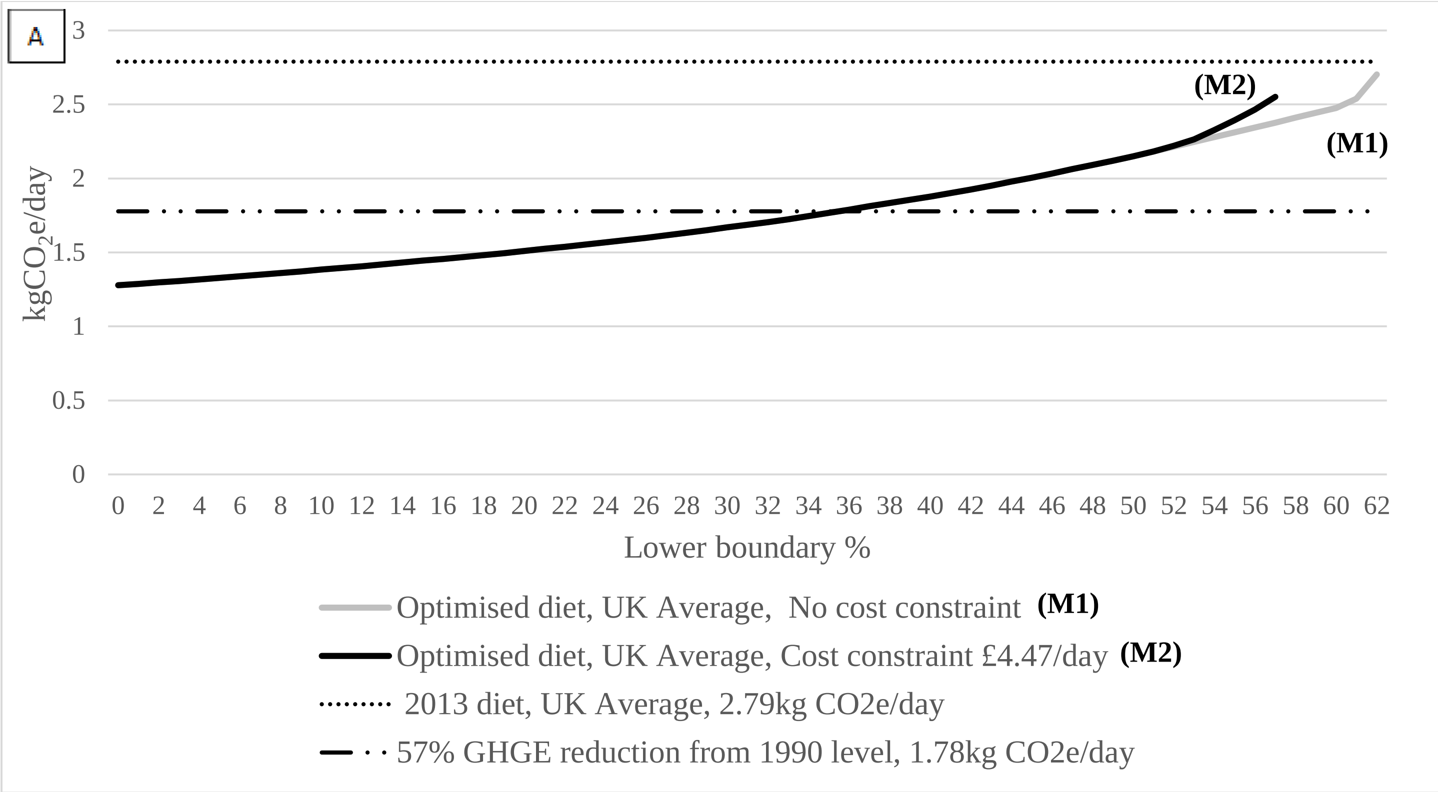

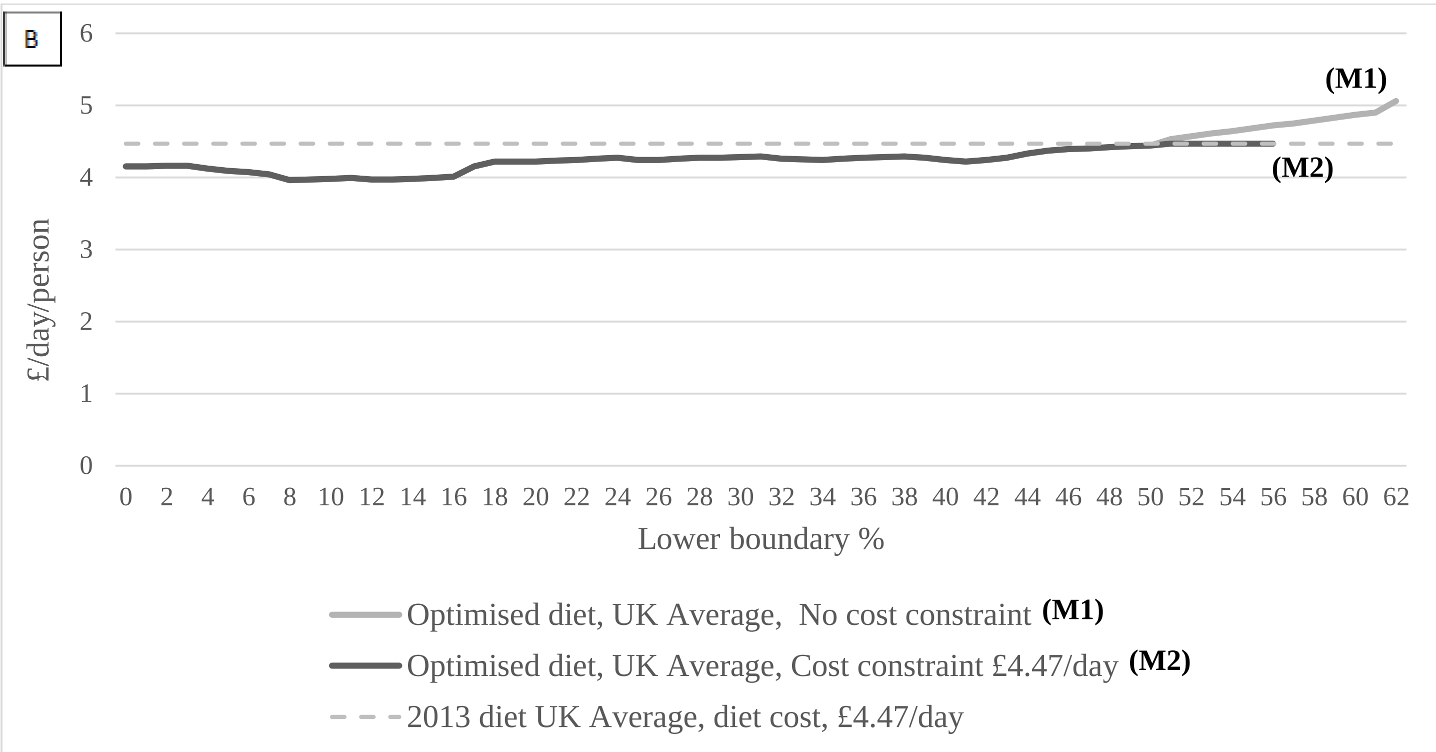

Figure 1. Impact on GHGE and cost associated with lower boundaries of the different diets. A) GHGE associated with different lower boundary iteration optimised diets. B) Cost associated with different lower boundary iteration optimised diets

Table 1 Food groups used in the linear programme, indicating if they were selected at the maximum weight limit, varied weight or at the minimum lower boundary for all linear programme iterations, for all quintiles.

Food category	**Food selected at their maximum weight limit (200%), in all linear programme iterations.**	**Food that varies depending on linear programme iteration.**	**Food selected at their minimum lower boundary, in all linear programme iterations.**
Starchy foods	Brown, granary, rye bread Pasta, noodles, couscous Wholegrain and high fibre breakfast cereals Muesli Potato products grilled or oven baked (not fried) Potato (boiled, baked, no fat)	White bread Wholegrain bread Other breads Other breakfast cereals Porridge oats Rice	
Fruit and Vegetables	Apples, pears Grapes, cherries Kiwi Peaches, nectarines, apricots Plums Peas Onions Sweetcorn	Citrus fruit Bananas Melons, pineapple, watermelon, mangoes Raspberries, strawberries Dried fruits Carrots/ turnips Tomatoes Cabbages, brussel s, other brassicas Cucumbers Lettuce Mushrooms Pumpkins, squash	Fruit juice Tinned fruit Free Fruit† Green beans Cauliflowers, broccoli, spinach Pepper
Milk and dairy foods	None	Whole milk Semi-skimmed milk Skimmed milk Yoghurt / fromage frais (full fat)	Cottage cheese Cheese (full fat) Cheese (reduced fat) Yoghurt / fromage frais (low fat) Free milk†
Non-dairy protein sources	Mixed nuts Mixed seeds Beans e.g. kidney, chickpeas Lentils Oily fish*	White fish (coated, fried) White fish (not fried) Shellfish Tinned tuna Eggs Soya milk Quorn	Beef Lamb Pork Bacon Ham Sausages (pork) Baked beans Soya mince
High fat/ high sugar foods	Fried, roast potatoes and fried potato products (incl. chips)	Biscuits Soft margarine (not low fat) Reduced or low fat margarine Crisps & savoury snacks Sugar Preserves (jam, honey etc.) Sweets	Buns, cakes and pastries Milk & dairy puddings Sponge & cereal based puddings Cream Ice-creams Butter Spreadable butter

		Chocolate Mayonnaise Oil	Reduced or low fat spreadable butter Bottled sauces (e.g. ketchup, brown sauce) French dressing
Non Alcoholic beverages §	None	None	Carbonated soft drinks Non-carbonated soft drink Carbonated soft drinks (low calorie/sugar) Non-carbonated soft drink (low calorie/sugar)
Alcoholic beverages		Beer‡ Wine‡ Spirits‡	
Hot beverages	None	Hot chocolate	Tea (no milk) Coffee (no milk)

* Oily fish had a minimum consumption of 19g per day, this is a minimum increase of 400% of 2013 consumption rates.
† These foods were fixed at 100% of their 2013 weights as they were 'free' foods and not purchased.
‡ Alcoholic beverages had an upper limit set at the average LCFS alcohol consumption (8.9g/day), this means there was some alcohol reduction in some diets.

Table 2 Dietary constraints based on population weighted dietary recommendations used in the linear programming compared with energy and nutrients reported in the 2013 diet by income quintile.

			2013 Diets					
			Low income 1 (n= 1014 households)	**2** (n= 1085 households)	**3** (n= 1058 households)	**4** (n= 1015 households)	High income 5 (n= 972 households)	**Population Average UK** (n=5144 households)
Income boundaries (£, per week, per household)			**< 265.18**	**265.18 - 461.89**	**461.9 - 695.5**	**695.51 - 1077.97**	**>1077.97**	—
Average income (£, per week, per household)			**170.06**	**362.02**	**572.56**	**864.27**	**1739.27**	**726.83**
% of gross normal weekly household income spent on food & drink			**28.32%**	**20.41%**	**17.27%**	**14.59%**	**10.17%**	**23.01%**
Population weighted dietary recommendations (per day)	**Constraints**							
Energy (MJ)	=9.25	(a)	8.95	8.88	8.74	8.58	8.70	8.74
Fat (g) *	≤ 82.50	(b)	92.81	91.40	89.98	87.92	88.92	89.81
Carbohydrate (g) †	≥ 272.10	(b)	252.56	250.15	244.15	237.40	237.55	242.90
Protein (g) ‡	≥ 46.20	(b)	75.60	75.45	74.36	73.86	76.19	75.06
Nonstarch polysaccharides (g)	≥ 16.90	(d)	13.22	13.22	12.94	13.01	13.56	13.20
Non milk extrinsic sugars (g) ‡	≤ 54.40	(b)	82.41	82.09	80.38	75.92	75.05	78.47
Saturated fat (g) §	≤ 25.00	(b)	34.73	33.47	32.75	32.04	32.59	32.91
Sodium (mg)	≤ 2115.00	(c)	2292.55	2275.05	2218.55	2238.99	2276.66	2257.46
Potassium (mg)	≥ 3.20	(b)	2.79	2.82	2.73	2.70	2.81	2.77
Calcium (mg)	≥ 693.30	(b)	923.84	914.98	874.61	845.44	868.64	879.17
Iron (mg)	≥ 10.90	(b)	11.79	11.67	11.52	11.66	12.10	11.77
Zinc (mg)	≥ 8.00	(b)	9.39	9.32	9.13	9.10	9.50	9.29
B12 (ug)	≥ 1.40	(b)	6.20	6.34	6.12	6.08	6.23	6.19
Folate (ug)	≥ 190.10	(b)	248.04	247.75	242.07	243.45	251.93	246.69
Vitamin A (ug)	≥ 624.90	(b)	1492.70	1551.80	1523.61	1494.10	1518.19	1516.18

Thiamin (mg)	≥ 0.85	(b)	1.65	1.65	1.61	1.61	1.63	1.63
Riboflavin (mg)	≥ 1.15	(b)	1.88	1.88	1.81	1.77	1.78	1.81
Niacin (mg)	≥ 14.10	(b)	14.60	14.65	14.96	15.15	15.18	14.97
Vitamin C (mg)	≥ 38.50	(b)	76.37	78.64	80.75	83.11	90.02	82.83
Magnesium (mg)	≥ 267.90	(b)	255.67	258.68	253.14	254.25	266.85	258.26
Alcohol (g)	≤ 8.90	(d)	6.55	7.17	8.21	9.25	10.82	8.76
Red & processed meat (g)	≤ 66.60	(e)	65.89	63.13	62.15	62.56	64.02	63.37
Fruit and vegetables (g)	≥ 380.50	(f)	269.47	273.61	282.70	289.77	330.94	293.82
Total Fish	≥ 38.05	(g)	14.01	14.58	13.90	14.45	15.72	14.64
(of which oily fish)	≥ (19.03)		4.56)	(4.28)	(4.17)	(5.21)	(5.21)	(4.79)
Total cost (£)‖	≤ current spend	(h)	4.24	4.29	4.38	4.46	4.76	4.47
Cost eat in (£)‖	≤ current spend	(h)	3.97	3.91	3.96	3.95	4.12	3.99
Cost eat out (£)‖	≤ current spend	(h)	0.27	0.38	0.41	0.51	0.64	0.47
GHGE (kg CO_2e /day)iii	≤ 1.78 kg CO2e/person /day	(i)	2.80	2.76	2.76	2.74	2.88	

Source a= Scientific Advisory Committee on Nutrition 2011[(77)], b= Department of Health 1991[(78)], c= Scientific Advisory Committee on Nutrition 2003[(111)], d= Intake of alcohol in average UK household, not to be increased DEFRA 2014[(2)], e= Scientific Advisory Committee on Nutrition 2010[(112)], f= Public Health England 2014[(80)] g= Scientific Advisory Committee on Nutrition and Committee on Toxicity 2004, and Public Health England 2014[(80,81)], h= DEFRA 2014[(2)] (i)= Audsley et al. and UK GHGE reduction targets [(31)(32)]

*based on ≤ 33% fat of total energy, † based on ≥50% CHO of total energy, ‡ based on ≤10% NMES of total energy, § based on ≤10% saturated fat of total energy

‖cost constraints calculated by multiplying an average price for each food by the weight of each food purchased.iii this constraint was not used in every model.

Table 3. The estimated GHGE and cost of the diet by household income quintiles for 2013 diets and optimised diets for health

	Low income 1 (n= 1014)	**2** (n= 1085)	**3** (n= 1058)	**4** (n= 1015)	High income **5** (n= 972)
2013 diets					
GHGE, (kgCO_2e/ day)	2.80	2.76	2.76	2.74	2.88
Energy (kJ/day)	8951	8876	8739	8576	8701
Cost (£/day)	4.24	4.29	4.38	4.46	4.76
Weight (g/day)	1979	1964	1919	1873	1939
M1 Optimised diet for health, with no cost constraint*					
Final optimised diet					
Lower boundary for any food group	57%	60%	62%	62%	62%
GHGE (kgCO_2e /day)	2.46	2.68	2.57	2.61	2.79
Cost (£/day)	4.61	4.87	4.83	5.00	5.25
Weight (g/day)	1870	1973	1927	1903	1963
M2 Optimised diet for health, with cost constraint					
Final optimised diet					
Lower boundary for any food group	53%	54%	57%	56%	60%
GHGE (kg CO_2e /day)	2.43	2.49	2.52	2.58	2.56
Cost, £/day	4.24	4.29	4.38	4.46	4.76
Weight (g/day)	1836	1908	1847	1886	1852
Lower boundary where cost constraint takes effect					
Food groups retained	47%	47%	52%	48%	54%
GHGE (kg CO_2e /day)	2.11	2.09	2.20	2.10	2.29
M3 Optimised diet for health, with cost constraint and maximum GHGE1.78 kg CO_2e/person /day target					
Final optimised diet.					
Lower boundary for any food group	34%	35%	35%	35%	35%
GHGE (kg CO_2e /day)	1.78	1.78	1.78	1.78	1.78
Cost (£/day)	4.01	4.03	4.20	4.25	4.29
Weight (g/day)	1599	1627	1617	1591	1570

Note: the lower boundary iteration refers to the minimum percentage of any food item (g/day) from the 2013 diet to be included in the optimised diet. The ‘final optimised diet’ is the iteration with the highest limit found by the linear programme to have a feasible diet. *the energy constraint for all the optimised diets was 9200kJ/day.

Table 4 Food purchases by household by income quintile for the 2013 diet and optimised diet with cost constraint and 1.78 GHGE kg CO_2e /day target.

	2013 diet							Optimised diet, with cost constraint GHGE of 1.78 kg CO_2e/day.						
Food purchases per day	Low Income 1	2	3	4	High Income 5	Population Average UK	Maximum difference in % GHGE between quintile groups	Low Income 1	2	3	4	High Income 5	Population Average UK	Maximum difference in % GHGE between quintile groups
Starchy foods (g)	269	264	254	251	248	255	4%	481	485	478	458	452	463	7%
Bread (g)	118	113	107	107	105	109	11%	205	204	215	201	195	197	9%
Cereals (pasta, breakfast) (g)	45	44	43	48	52	47	15%	68	66	68	76	85	74	21%
Rice (g)	23	21	27	25	24	24	21%	41	41	43	38	37	41	13%
Potatoes (g)	84	87	76	72	67	76	22%	168	173	152	143	135	151	22%
Fruit and vegetables (g)	269	274	283	290	331	294	22%	393	395	395	399	402	397	2%
Fruit (g)	115	122	125	131	153	132	25%	165	167	167	170	173	169	5%
Vegetables (g)	154	152	157	159	178	162	19%	228	228	228	228	228	228	0%
Dairy products (g)	304	305	273	250	254	272	8%	104	107	96	88	89	96	18%
Milk (ml)	258	258	222	197	199	221	24%	89	91	78	69	70	78	24%
Other dairy products (g)	46	46	51	53	55	51	17%	16	16	18	19	19	18	18%
Non-dairy proteins (g)	162	162	164	163	173	166	5%	105	107	117	106	116	110	10%
Total meat (g)*	101	101	103	104	106	103	4%	34	35	36	36	37	36	7%
Red meat (g)	42	39	39	38	39	39	9%	14	14	13	13	14	14	6%
White meat (g)	35	38	40	41	42	40	17%	12	13	14	14	15	14	18%
Processed meat (g)	21	21	20	21	22	21	6%	7	7	7	7	8	7	7%
Seafood (g)	16	17	16	17	19	17	16%	39	39	39	39	39	39	1%
Eggs (g)	16	14	15	14	17	15	14%	5	5	5	5	6	5	14%

Beans, pulses, nuts, seeds (g)	29	30	31	28	31	30	23%	26	28	37	26	34	30	30%
High fat/ high sugar foods (g)	240	242	233	225	217	229	9%	203	205	195	206	199	205	5%
Alcoholic beverages (ml)	96	118	134	155	175	142	48%	96	118	134	145	122	142	34%
Non-alcoholic beverages (ml)	212	226	256	262	258	247	19%	72	79	90	92	90	87	21%
Not low calorie/sugar (ml)	132	134	149	142	136	139	17%	45	47	52	50	48	49	14%
Low calorie/sugar (ml)	80	91	108	120	122	108	41%	27	32	38	42	43	38	36%
Hot beverages (ml)	426	374	322	278	283	323	21%	145	131	113	97	99	113	33%

* Total meat also includes red meat, white meat, processed meat and liver † The weights (g) of these food categories is similar however there is difference in the GHGE between quintiles due to the differing composition of each quintiles diet.