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Sustainable Diets in the UK—Developing a Systematic Framework to Assess the Environmental Impact, Cost and Nutritional Quality of Household Food Purchases

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Received: 1 August 2019; Accepted: 6 September 2019; Published: 11 September 2019

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Abstract: Sustainable diets should not only respect the environment but also be healthy and affordable. However, there has been little work to assess whether real diets can encompass all three aspects. The aim of this study was to develop a framework to quantify actual diet records for health, affordability and environmental sustainability and apply this to UK food purchase survey data. We applied a Life Cycle Assessment (LCA) approach to detailed food composition data where purchased food items were disaggregated into their components with traceable environmental impact data. This novel approach is an improvement to earlier studies in which sustainability assessments were based on a limited number of "food groups", with a potentially high variation of actual food items within each group. Living Costs and Food Survey data for 2012, 2013 and 2014 were mapped into published figures for greenhouse gas emissions (GHGE, taking into account processing, transport and cooking) and land use, a diet quality index (DQI) based on dietary guidelines and food cost, all standardised per household member. Households were classified as having a 'more sustainable' diet based on GHGE, cost and land use being less than the median and DQI being higher than the median. Only 16.6% of households could be described as more sustainable; this rose to 22% for those in the lowest income quintile. Increasing the DQI criteria to >80% resulted in only 100 households being selected, representing 0.8% of the sample. The framework enabled identification of more sustainable households, providing evidence of how we can move toward better diets in terms of the environment, health, and costs.

Keywords: diet quality; life cycle analysis; cost; food purchase

1. Introduction

Recent work has demonstrated the urgency of moving to a more plant-based diet combined with reductions in food loss and waste in order to keep within planetary boundaries [1,2]. However, the concept of healthy sustainable diets includes more than just the environment and nutrition and it has been postulated by the Food and Agriculture Organization of the United Nations (FAO) and others that they should also be both affordable and culturally acceptable [3,4]. Mertens and co-authors proposed the acronym SHARP to encompass environmental Sustainability, Health, Affordability, Reliability and Preference from the consumer [4].

Food production and distribution has a significant contribution to global environmental impacts. For example, the annual greenhouse gas emissions (GHGE) arising from agricultural production have been estimated to range from 7.3 to 12.7 Gt CO_2-equivalent, or 14–24% of total global emissions [5]. Additional environmental impacts in the form of energy use and greenhouse gas emissions arise from transport, processing and preparation of food. In addition to the harmful emissions to environment, food production is associated with the use of limited resources. For example, there are few opportunities to increase the land area available for agricultural production, despite the fact that the food requirement of growing global population is continuously increasing [6]. Although food production is a necessary activity, it is possible to mitigate its environmental consequences, for example, by reducing its greenhouse gas emission intensity [7]. Improving the efficiency of the production chain and directing consumption towards more environmentally friendly ingredients and production techniques provides an opportunity to considerably reduce the global environmental impacts associated with the food production chain [8–14].

Mathematical modelling has already been used to assess the environmental sustainability of different diets. For example, Macdiarmid et al. [15] applied modelling to generate combinations of foods which could form menus that are sustainable in terms of the environment, health, affordability and acceptability. However, the limitation of this work was that it used a database of only 82 food groups and did not account for GHGE beyond the primary production stage. Although such GHGE are more difficult to assess, estimates are available and can be incorporated. Saxe [16] compared a New Nordic diet (which meets nutrition and health guidelines) with the Average Danish diet and estimated the environmental impact in a terms of other environmental impacts such as respiratory organics, land use and global warming potential (i.e., greenhouse gas emissions). The study took different scenarios into account in terms of transport and use of organically produced food.

In recent studies (e.g., [17–24]), more detailed calculation methods have been applied to estimate the GHGE of actual and hypothetical diets. However, such analyses are still based on rather limited data on the emissions associated with specific food items, and the calculations are often based on rather generalized "food groups". Although such analyses can provide reliable overviews of the environmental consequences of dietary choices, there is also a need for exploring the effects of more detailed small-scale changes in dietary patterns. To achieve this, novel modelling approaches that can better utilize the available data are needed.

In order to achieve the shift towards healthy and environmental diets, such diets need to be affordable to the consumer. There is a general assumption and some evidence [25,26] that a higher quality diet costs more than a "normal" diet, but this is based on average current diets and the studies have not always fully explored possible examples where sustainable choices have resulted in a lower cost diet of adequate nutritional quality. The New Nordic diet was shown to be less costly than the average Danish diet [16], thus demonstrating that it is possible to have a nutritionally and environmentally sustainable diet at a lower cost than the average western diet.

In general, much of the existing research evidence on the sustainability of current diets, although useful, has been based on population data, and generalisations and simplifications of the environmental impacts of standard food commodities and a limited number of product groups, as stated above [15,27]. This is mainly analysed using publicly available "carbon footprint" information with only limited or no traceability, using data covering only a limited number of food items [18] and excluding parts of the food supply chain. This has been productive in indicating the type of diets needed for both health and sustainability but limited to producing idealistic diets designed by statistical models which may not be culturally acceptable or affordable [24–26]. Masset and co-workers [28], using data from the French national dietary survey (INCA2), selected real individual diets exhibiting less than the median GHGE and higher than the median for their diet quality measure. However, although they measured cost as an outcome, they did not incorporate it when selecting their "More Sustainable" category.

Our aim was to develop an improved novel modelling framework to enable quantification of real household level food choices for health, affordability and environmental sustainability;

while systematically accounting for the entirety of the food production, processing and supply chain, and using the actual disaggregated composition of food items rather than a limited number of food categories as a basis our analysis. Thus, our main objective was to develop a systematic, traceable, and comprehensive Life Cycle Assessment (LCA) framework to quantify the various dimensions of environmental sustainability of the main UK food items, taking into account the entirety of the food production, processing and supply chain. We also wanted to demonstrate how such methods can be used to assess the proportion and characteristics of households and/or individuals who purchase real diets (rather than idealistic diets that are sometimes produced by linear programming) that could be considered sustainable, healthy and affordable, and thus discover if such diets could be acceptable within the population. Hence, a further objective was to integrate LCA with measures of diet quality and cost of household food purchases and apply the framework to analyse a large-scale UK food purchase dataset in terms of environmental sustainability, healthiness and cost of household and individual diets. By doing this, we wanted to provide a method that could also be able to improve the evidence-based approach to assessing interventions and formulating sustainable dietary goals to improve the sustainability of household food consumption.

2. Materials and Methods

2.1. Data

The framework drew on data from multiple sources, and the Living Costs and Food Survey (LCFS) [29] was used as an example to demonstrate the use of the method in connection with a large food purchase dataset where purchases are recorded for each household in the survey. We constructed a database with all the requisite variables (type of food, weight, cost, greenhouse gas emissions, and land use) at the household level. This provided the desired resource that would enable future investigation of the relationship between environmental sustainability, healthiness and cost of household food purchases. We used the household as the unit of study, acknowledging the fact that purchases are frequently shared between the members of a household.

2.2. Living Costs and Food Survey (LCFS)

The LCFS is a continuous survey that is managed by the Office for National Statistics [29]. It is conducted throughout the year and collects data on income and expenditure from a representative sample of UK households. It provides a valuable source of information about household food purchases, from which estimates of food consumption and nutrient intakes can be derived [30,31]. The LCFS collects household food purchase data from every person over seven years of age over a 14-day period. Data is collected about foods bought for consumption at home, i.e., from supermarkets and takeaways, and bought for out-of-home consumption, i.e., from restaurants or sandwich shops. We used data from 2012, 2013 and 2014, downloaded under license from the UK Data Archive. Data from these three years combined together created a dataset of the food purchases of approximately 15,000 households with details on the quantity and price paid for 526 different foods or food groups (e.g., groups such as complete meat-based ready meals which included a range of items).

2.3. Life Cycle Assessment

The Life cycle assessment (LCA) method considers the environmental burdens and resource use in the production and exploitation of a commodity within defined boundaries. The commodity (or end product) considered in the analysis is called Functional Unit in the LCA terminology, and it must be clearly specified and consistently used (also in terms of quantity) throughout the assessment. The boundary can be from cradle to grave, which includes the production, retail, consumption, and disposal stages, but it is also common and pragmatic to stop the analysis at earlier stages, for example, in agricultural production at the farm gate [32], or in the case of a food supply chain, apply a boundary from cradle to plate. LCA can be considered to be the most holistic method available for environmental impact assessment [32,33], and therefore, it is the methodology favored by major organizations, such as the United Nations Environment Program [34].

We developed an LCA framework that was able to estimate the total greenhouse gas emissions (GHGE) and land use for any specific food product purchased. For use in connection with the LCFS data, the Functional Unit (or the end product) was specified as all food items obtained for consumption (i.e., eaten or disposed of) by a household during the period of 2 weeks. We therefore applied an LCA system boundary from cradle to plate. To achieve this, we established a calculation framework for the basic commodities (e.g., potatoes, sugar, wheat, rape and mustard seed oil) for which there are data on GHGE and land use that incorporate primary production of the raw materials, plus processing and transport. In total, these environmental variables were quantified for 129 commodities. This permitted each of the 526 food and drink codes in the LCFS to be allocated to one or more of these basic commodities (i.e., bread allocated to wheat, water, oil etc.) so that GHGE and land use could be calculated for each code (see details below). The main source of the GHGE and land use data for different commodities was from the report by Audsley and co-workers [35], together with other published data on UK food and drink production [36,37]. The use of carefully selected sources of the environmental data made it possible to ensure that possible methodological differences did not cause any bias to the results. For example, economic allocation was systematically used to distribute the environmental burdens between co-products, and a systematic method for accounting for the GHGE related to land use change was also applied (i.e., the *top-down* method which takes into account both direct and indirect land use change emissions [35]).

Although the LCA framework developed here can consider the exact origin of the commodity (where known) and related transport emissions, such a detailed analysis was not needed in this study, since the LCFS data does not indicate the origin of the purchased food. Therefore, a method based on weighted averages of the estimated proportions of commodities originating from the UK, the rest of Europe and the rest of the World was used instead. The GHG emissions for products from different origins were obtained from Audsley and co-workers [35] and the proportions of imported and domestically produced raw materials were estimated based on FAO production and import/export statistics [38].

Some of the 526 food and drink codes can be considered as "single-product codes" (consisting of one commodity, e.g., potatoes) and some as "multi-product codes" (e.g., chips assigned to potatoes and cooking oil). Single-product codes could easily be allocated to a single raw commodity, but multi-product codes presented a challenge when attempting to calculate estimates of GHGE and land use, because the constituent products that make up the code were often made up of different raw commodities. Therefore, we had to devise a method that permitted GHGE and land use calculations to take into account both the different proportions of foods coming from different commodities, and the different constituent products making up each multi-product codes. However, disaggregating all these multi-product codes and taking into account every possible constituent product was not feasible in this study due to the minimal contribution of some of the products to the overall food purchases. Therefore, we took a pragmatic approach to this exercise and prioritised the 202 codes that accounted for 95% of all purchases (by quantity). For the remaining 324 codes, the closest match amongst those products that had been already disaggregated was used (more details provided in Supplementary Material S1).

After a commodity allocation had been established for each of the 526 food and drink codes, GHGE and land use figures were calculated. These figures were calculated on a per 1 kg of the food item basis; this was done by using a weighted average based on GHGE and land use figures related to the production of the basic commodities and the proportions of these commodities needed for the production of each food code. In addition to the emissions arising from the basic commodities, additional GHGE were added to the final figures for each product to account for (1) additional processing not included in the GHGE figures for the raw commodities, (2) canning or freezing of products, and (3) cooking of products either by the consumer or by the retailer (for products bought ready-to-eat from out of the home, i.e., a takeaway or restaurant). In this study, we did not try to quantify the exact emissions related to processing and cooking for each product separately (although the framework would allow this option if such data are available). Instead, for each product, we specified whether or not it was likely to be processed and/or cooked, and then used typical GHGE values for processing, canning, freezing, drying and cooking as found in the literature [39,40].

Thus, the final product was a matrix of total GHGE and land use data for each of the 526 food and drink codes in the LCFS, that took into account:

- Primary production of the raw materials
- Processing
- Transport (including the raw materials and final products)
- Cooking

In mathematical terms, this can be expressed as follows, using the GHGE as an example:

$$GHGE_i = GHGEc_i + \sum_{j=1}^{n} p_j GHGE_j$$

where $GHGE_i$ is the total GHG emission associated with food item i, (kg CO_2e/kg) $GHGEc_i$ is the GHG emission associated with further processing and cooking of food item i (kg CO_2e/kg), $GHGE_j$ is the GHG emission associated with production, processing and transport of raw commodity j (kg CO_2e/kg, weighted average of different origins), p_j is the proportion of raw commodity j in food item i, and n is the total number of raw commodities included in the analysis.

2.4. Diet Quality Index

The Diet Quality Index (DQI) is a tool to assess the quality of the total diet and was devised in collaboration with Food Standards Scotland for the Scottish Health Survey and the Living Costs and Food Survey [41]. It is based on UK and global food- and nutrient-based dietary guidelines (see Supplementary Table S1) available at the time of the surveys. The scoring system created reflects the extent to which a household's diet conforms to these guidelines.

The scoring system is described in Supplementary Table S1, which provides details of the foods and nutrients that are included in the DQI, and the scoring methodology and rationale for each component. The definitive index comprises three food scores and six nutrient scores with a total score out of 85. The coding frames for each of the food groupings described in Supplementary Table S2 indicate which foods and drinks are included in each of the food groupings and list adjustment factors. Estimated waste figures [42] were applied to adjust purchases for waste prior to calculating the DQI as the DQI represents the quality of the diet as eaten not purchased.

To calculate the scores linked to food consumption, food purchase data (minus waste) from the LCFS 2012, 2013 and 2014 data were linked to the DQI coding frame; each food code was multiplied by the appropriate adjustment factor and summed by food grouping. Summed household data was then adjusted to an average adult consumption figure for the household as g/2000 kcal (8368 kJ) to standardise the data. This figure was used as it is the Reference Intake used on food labels across the EU for the average adult [43].

To calculate the scores linked to nutrient consumption, household consumption data minus waste (based on purchases) for each food code was multiplied by the appropriate nutrient content per gram (provided by the UK Department for Environment, Food & Rural Affairs) to provide the nutrient intake per food; this was then summed for each household. The individual nutrient intakes for each food were then summed and either expressed per 2000 kcal (8368 kJ) or as a percentage of food energy (with the exception of alcohol which was expressed as a percentage of total energy).

A score was assigned to each household for each of the three food and six nutrient elements as per the scoring system (Supplementary Table S1). These scores were then summed out of eighty-five and adjusted to a percentage score.

2.5. Cost

Using the total food-related expenditure derived from the LCFS raw unadjusted data for each household, the average cost of food per person within each household was calculated. Thus, we obtained the actual cost of food at the time of purchase regardless of where it was purchased or the time of purchase. Controlling for inflation was not necessary for our study as we based our results on the actual median expenditure specified separately for each year included in the dataset (see Section 2.6 below). We did not average over the population [26,44] as we wanted to record the actual price paid by individual consumers.

2.6. Database Variables and Integration

There were four groupings of variables (shown in Supplementary Table S3): LCFS-related variables (including weight of food purchased and expenditure); DQI variables; LCA variables; and Household Basal Metabolic Rate estimate [45]. The latter was developed in order to exclude households who purchased an amount food that would be unable to sustain energy requirements (see Supplementary Material S2 for calculation). In summary, food purchase data for 2012, 2013 and 2014 combined, from the UK LCFS, detailing food weights and costs, were mapped to the LCA variables of Greenhouse Gas Emissions (GHGE) (estimated for primary production, processing, transport and cooking of the individual food commodities and composite foods) and Land Use to produce estimates of the total GHGE and land use for any specific food product purchased by the consumer, calculated in a systematic and transparent method based on disaggregated food items. A DQI was assigned to each household in the survey [41].

2.7. Analysis

Using the framework described the median GHGE (kgCO_2), expenditure on food per person (£), land use (m^2) (all standardised per person and per week) and DQI were calculated for three years of data (2012, 2013 and 2014) from the LCFS. Households whose purchase patterns were unlikely to sustain estimated Basal Metabolic Rate of its members for the 2 weeks of data collection were removed (see method in Supplementary Material S2) to avoid underestimation of actual diet and environmental cost. Households were classified as having a more sustainable diet based on GHGE, expenditure and land use being less than the median and DQI being higher than the median, similarly to the procedure used by Masset and co-workers in France [28]. As median expenditure rose each year, the median cut off for expenditure was done on a yearly basis. There was no significant change in DQI, GHGE, or land use over the three years. The percentage of households exhibiting the more sustainable diet was compared by equivalised income quintile (calculated per year), and also household composition (for the 4 most common types of household, single man; single woman; one man and one woman; families with man, woman and one or two children) using the Chi-square statistic.

In addition, households were also selected as having more sustainable diets with excellent adherence (DQI > 80%) to the dietary guidelines. The average food purchases of this group were examined in more detail to demonstrate a pattern of diet relatively low in terms of GHGE, Land Use and cost but high in dietary quality. This was carried out by calculating means and medians of the foods purchased by this group (n = 100) and assigning a likely frequency to how much was eaten.

SPSS V24.0 (SPSS Statistics, IBM, New York, NY, USA) was used for all statistical analyses.

3. Results

3.1. Characteristics of Final Sample

The number of households, after removal of those who purchased a lower than feasible amount of food to maintain the Basal Metabolic Rate of the members of the household, was 12434. All had data on equivalised income and could be categorised into quintiles. The majority (72.2%; n 8982) could be categorised into four household types: single man (14.5%), single woman (21.7%), one man and one woman (48.4%), families of a man, woman and 1 or 2 children (15.5%). This was a pattern broadly similar to the UK population in 2011 [46].

3.2. General Findings

Median GHGE, Land Use, Expenditure and DQI are presented in Table 1. Inter quartile ranges are included (IQR) to show the range between the 25th and 75th percentile of the distribution. Median DQI was low, suggesting that population adherence to dietary guidance for health was poor and only 22% had a DQI above 50%. Median expenditure on food per person was almost £46 per week in 2014, comparable with that reported in the Family Food report for 2014 (£41.97) [47], which would include those excluded in our analysis due to a low purchase record.

Only 16.6% of the sample could be described as being more sustainable using the criteria based on GHGE, expenditure and land use being less than the median and DQI being higher than the median. When comparing within the equivalised income quintiles, it was the lower quintiles (i.e., those with the lowest incomes) that had a higher proportion (21–22%) of those with the more sustainable food purchase pattern (Table 2), with the higher quintiles 4 and 5 having a lower proportion (9–14%). For the four main types of household composition, where overall 14% exhibited the more sustainable pattern of food purchases, families with children tended to have a higher proportion (26%), whereas single men had the lowest proportion (just 10%).

Applying similar criteria for the more sustainable category but with a DQI > 80% only 100 households were selected, representing 0.8% of the sample (Table 3). The characteristics of this group (more sustainable, DQI > 80%) are provided in the following section. When the stricter criteria of DQI >90% only 16 households were selected, that is, 0.13% of the sample.

Table 1. Median and Inter quartile Range (IQR) of greenhouse gas emissions (GHGE), Land Use, Expenditure (per person per week) and diet quality index (DQI).

	Median (and IQR) All N = 12,434	**Median (and IQR) More Sustainable DQI% > median N = 2061**	**Median (and IQR) More Sustainable with DQI% > 80 N = 100**
DQI (%)	37.60 (28.57–48.51)	49.0 (42.25–59.56)	85.13 (82.65–88.50)
GHGE (kg CO_2e)	24.14 (18.75–31.43)	17.29 (14.36–20.20)	17.22 (14.13–20.30)
Land use (m^2)	26.27 (20.20–34.53)	18.56 (15.28–21.45)	18.62 (15.75–20.27)
Expenditure (£) (average of 3 years)	44.24 (31.43–61.99)	28.52 (22.18–35.32)	27.66 (22.22–34.38)
2012	42.83 (30.97–60.23)		
2013	44.60 (31.51–62.54)		
2014	45.67 (32.25–63.28)		

Table 2. Percentage (number) of households exhibiting more or less sustainable food purchase patterns within equivalised income quintiles and household type.

	More Sustainable	**Less Sustainable**	**Total**
Equivalised Income Quintile			
Lowest 1	21.9 (545)	78.1 (1942)	100 (2487)
2	20.9 (520)	79.1 (1967)	100 (2487)
3	17.2 (427)	82.8 (2060)	100 (2487)
4	13.6 (337)	86.4 (2150)	100 (2487)
Highest 5	9.1 (226)	90.9 (2260) *	100 (2486)
Household Type			
One man	10.0 (130)	90 (1170)	100 (1300)
One woman	15.2 (295)	84.8 (1650)	100 (1945)
One man and one woman	10.8 (468)	89.2 (3876)	100 (4344)
Family of man, woman and one or two children	25.7 (358)	74.3 (1035)	100 (1393)

* $p < 0.001$ using chi-square for group differences in proportions in more or less sustainable.

Table 3. Mean, SD, median, and inter quartile range (IQR) purchases per person per fortnight of different food groups by those exhibiting a more sustainable diet based on GHGE, expenditure and land use being less than the median and DQI > 80%.

Food Group	Mean (g)	SD	Median (g)	IQR	Likely Frequency
Bread and rolls	1588	1185	1337	813–2081	1.5–4 slices or 1–2 rolls per day
Breakfast cereal	666	709	500	0–1008	1–2 × 40 g portions per day
Pasta, rice and noodles	408	575	218	0–500	1–3 portions per week
Flour	470	1014	0	0–500	Around 250 g per week
Pizza	133	256	0	0–249	No more than 1 × 200 g portion per fortnight
Potatoes	1534	2323	998	37–2068	1 baked potato per month to 5 per week
Vegetables (not potatoes and includes pulses)	3184	2095	2632	1777–4161	2–4 portions per day inclusive of soup or dish with peas, beans or pulses every day
Beans, other pulses and peas	450	637	250	0–579	
Fruit	2707	1697	2325	1607–3483	1–3 portions per day
Fruit juice	434	730	0	0–705	1–2 × 150 mL glass twice per week
Liquid milk and yoghurt	3587	2214	3421	1881–5000	1 glass plus milk on cereals per day
Cheese	146	183	100	0–236	2–4 30 g portions per week
Unprocessed red meat	258	430	0	0–371	Up to1–2 portions per week
Processed meat	339	421	261	0–501	Up to 1–2 portions per week
All Red and processed meat	597	658	435	76–849	1–4 portions per week
Poultry	312	535	47	0–369	1–2 portions per week
Eggs (number)	11	15	6	0–14	3–7 per week
Fish	460	405	390	145–654	1–3 portions per week
Nuts and seeds	70	155	0	0–73	1–2 20 g handfuls per week
Total spreading and cooking fats	140	205	25	0–123	2–10 g per day
Crisps and savoury snacks	94	150	27	0–123	2–3 25 g packets per week
Cake, pastries, puddings, biscuits	758	573	636	306–1080	1–4 20 g biscuits or no more than one cake or pudding per day
Confectionery, sugar, jams	227	245	141	0–399	Chocolate, sweets, jam or honey equivalent of 2–6 teaspoons per day
Savoury sauces	25	348	160	0–382	
Soft drinks total	1219	2491	0	0–1303	No more than two 330 mL cans per week mixed or 1–2 per fortnight sugared.
Sugar containing	431	918	0	0	
Sugar free	788	2293	0	0	

3.3. Food Purchase Pattern for Households with High Diet Quality (More Sustainable DQI > 80)

The average food purchase pattern of the 100 households consuming a more sustainable diet with a DQI above 80% is summarised in Table 3 on a per person per fortnight basis. The households represented varied in size, from one person (25%) to seven people (1%) with a range of household types (26% being families with children) and spread evenly across all the equivalised income quintiles. The food purchases were characterised by a high quantity of fruit and vegetables (equivalent to 400 g/5 a day when pure fruit juices included). The most popular vegetables were carrots, those classified in the courgette, marrow and pepper group, closely followed by tomatoes and fresh onions and leeks, as well as baked beans. The most popular fruits were fresh bananas and apples.

About 1.5 L of milk (with semi skimmed being the most popular choice) and 2–4 portions of cheese were purchased each week. Red meat and processed meat were purchased but means and medians showed that intake was likely to be no more than four portions a week, 23% of households purchased no red meat at all but 18% purchased enough red and processed meat to consume a portion every day. A smaller amount of poultry was purchased, equivalent to up to two portions per week (48% non-purchasers) with fish up to three portions per week (19% non-purchasers) including tinned, fresh and frozen varieties of white fish and salmon. All households that purchased some animal protein, but 3% purchased no animal flesh in the form of poultry, fish or red and processed meat.

Starchy carbohydrate foods consisted of approximately 2–3 thick slices of bread or rolls per day, with wholemeal and brown types in the majority. In addition, around 2–3 portions of potatoes, and 2–3 portions of pasta or rice per week, and the equivalent of a portion of breakfast cereal per day was purchased, with higher fibre versions being more popular.

Purchases that needed further preparation were dominant, such as flour, fresh vegetables and fresh potatoes but frozen chips, soft drinks and ready meals were also purchased, as well as alcohol in the form of lager and wine.

4. Discussion

We showed that only a very small proportion of the UK population purchase a diet that is likely to be compatible with sustaining their own health or that of the planet. However, this proportion represented a range of household types and incomes and food was not restricted solely to items that would be considered healthy, with alcoholic beverages, cakes, sweets and soft drink being purchased in relatively small quantities to add variety to the diet.

Food and drink purchases and their cost over a 14-day period by representative households in the UK were combined with data on GHGE and land use to provide a workable framework from which to assess the sustainability of food purchase patterns. This was accomplished using a systematic methodology which could be extended to other scenarios and dietary data.

Several modelling frameworks aiming to quantify the environmental consequences of dietary choices have been presented in the literature. However, we believe that the novel approach to dietary LCA as presented in this study has several advantages compared to most of the earlier methods modelling the environmental sustainability of food [15,18–24]. The current model was specifically developed for use in connection with food survey data, and the systematic approach and flexibility makes its application possible in a range of studies using such datasets, and also provides a tool that can be used in scenario analysis exploring alternative diets.

A practical advantage of the framework developed here is related to the detailed disaggregation of the purchased food items. In previous studies [15,18–23], the environmental impacts of foods (mainly GHGE only) were usually based on "food groups", not on individual products. Relying on such relatively coarse categories can in the worst case led to insufficient or even misleading conclusions. In reality, the composition of a single food group can be highly variable. As a simplified example, foods classified as "meat products" can include items such as whole meat, meat pies (containing mainly cereals) and meat soups (containing mainly water). Therefore, shifting dietary habits between such products can have a high impact on the GHGE associated with the diet, yet it can be observed only with detailed disaggregation of the food items. In general, the disaggregation approach allows for identification of the effects of much smaller scale changes in diets than major dietary shifts, e.g., from meat-based diet to vegetarian diet [8,11,13,48]. However, it should be noted that the LCFS dataset applied in this study included some food categories that did not allow a detailed disaggregation (for example "complete meat-based ready meals"). However, a further advantage of our method is that such categories can be handled in systematic way, based on the weighted average of the actually consumed items belonging to that category (see Supplementary Material S1 and Table S2). Therefore, we believe that our framework can handle both very detailed and less accurately specified food categories without bringing any bias to the results. Furthermore, the tool can handle unlimited combinations of raw materials in food items. Therefore, any number of new foods can be included in detailed calculations, as far as their "recipes" are known.

In the current study, the GHGE related to processing and cooking of different food items was based on rather simplified assumptions and generalizations [39,40]. However, in future studies, the modelling framework can be utilised with much more item-specific processing data, if such data is available. In general, as the framework includes the whole food chain, it can be applied in future studies to explore scenarios with changes in different part of the chain, for example, raw materials produced either domestically or imported, organic vs. non-organic production, processed vs. non-processed food, the use of energy-efficient cooking methods, etc. In addition, since the framework allows a breakdown of the different components of the food chain, it can be used as an analytical tool when comparing existing diets; if there are differences between the GHG emissions associated with diets, the main sources of the differences can be identified, indicating the "hotspots" within the food chain.

The study used purchase data from a large representative sample of the UK population. It has been suggested that purchase data is less subject to bias than individual food diaries [31,49], but as it combines data from purchase diaries within households, it is not possible to see the individual diets of household members or adjust for household composition or ages within the household. In addition, it is not possible to determine how much, if any, food and drink may have been purchased for friends and family outside the household, or whether the purchases were consumed within the 2-week recording period. However, a method for checking that the food purchased was an adequate amount for the household was provided and excluded about 20% cases where it was unlikely. Wastage was accounted for in calculation of the DQI using average figures from the Waste and Resource Action Programme (WRAP) [42], but not in the calculation of GHGE and Land use as these will be appropriate for the actual food purchased.

The DQI used to determine the nutritional quality of the diet was constructed using widely accepted dietary guideline cut-off points at the time of the surveys, (for example those from the World Health Organization [50] and others detailed in Supplementary Table S2) and although there have been recent changes to recommendations for added sugars and fibre (with changes to definitions and cut-offs [51]), it was not possible or considered appropriate to compare with guidelines that were constructed after the dates of the actual surveys.

Currently, there is no "recommendation" for the ideal GHGE from food for individuals to limit climate change, but this is also hampered by the fact that reported GHGE figures are variable and not standardised, as pointed out by Clune and co-workers [52]. However, within our study, the figures were comparable with each other as a result of the systematic methods used. Results for different food items were fully consistent, traceable and transparent, and go beyond the "farm gate". The method used was flexible (for example could be used to compare different scenarios) and could be applied to any food item (with known composition).

Our research confirms previous work that the average UK diet does not meet dietary guidelines [31,53,54]. However, contrary to previous research, it would appear that it is possible to purchase a diet that is healthy and sustainable at a relative low cost. This would appear to contradict work that shows that the cost of a healthy sustainable diet is more expensive than a conventional diet [25,26,28]. It should be noted that a relatively low-cost high-quality sustainable diet was purchased by a very small proportion of survey participants but this does show that there is potential for a carefully chosen diet to be both affordable, sustainable and healthy.

5. Conclusions

Using a systematic methodology in which purchased food items were disaggregated into their components with traceable environmental impact data, we found that there were households who were purchasing a diet that was both low cost and had a lower environmental impact, combined with a higher quality in terms of nutrition. Using the higher criteria for DQI the diet of the 100 more sustainable households was not unlike that recently proposed by EAT-Lancet Commission [2]. The purchase patterns of the 100 households were not uniform and some purchased no red or processed meat or other types of animal protein. There has been criticism of the EAT-Lancet proposal on the grounds that it is not feasible nor practical [55], nor fits within the UK situation [56] but there seems to be no appreciation of the flexibility within the plan and that it represents an average. Some individuals and households choose to eat more of their protein from animal sources and others purely from plants. What is needed is a population shift towards lower meat and dairy consumption and higher consumption of wholegrains and fruit and vegetables—the point that nutritionists in public health have been making for over two decades.

There are several opportunities for further improvement of the methodology developed in this study. The results could be further enhanced with more detailed information on food purchased (including the exact origins of food items, their processing and cooking methods, etc.) and more accurate and specific information on GHGE, once available. This would allow a more detailed comparison of both actual diets and hypothetical diets in scenario analyses. Furthermore, although the current analysis on food cost did not take into account any environmental costs, such costs can be included in new versions of the framework. As the GHGE of different food items are already part of the model, it would be relatively straightforward to include carbon prices in the calculations to expand the analysis of the monetary effects of dietary changes. The carbon costs would also automatically handle both direct and indirect emissions arising from land use changes, due to the top-down methodology applied for land use changes applied in the modelling framework [35]. This would provide a link between the land use estimates, GHGE and food costs, all of which are all already included in the current framework.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/18/4974/s1, Supplementary Material S1. Disaggregation method. Supplementary Material S2. BMR calculation. Table S1: Table S1: Components of the Diet Quality Index and Scoring System Table S2 Coding frame for the Diet Quality Index Table S3: List of variables in the final dataset.

Author Contributions: Conceptualization, W.W. and I.L.; methodology, W.W., I.L., K.B.; formal analysis, W.W., I.L., K.B., J.H. and L.G.; writing—review and editing, W.W., I.L., K.B., J.H. and L.G.; project administration, W.W.; funding acquisition, W.W. and I.L.

Funding: This research was partly funded by Newcastle University Institute of Sustainability, but otherwise received no external funding.

Acknowledgments: This work was carried out using data from the UK Data Archive, University of Essex (http://www.data-archive.ac.uk/). We would also like to thank Luca Panzone and Henrik Saxe for their contribution to early discussions of this work, Jen Bradley for technical assistance with the manuscript and Christian Reynolds for ongoing interest.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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