

Scotland's Rural College

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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Published in:
Sustainability

DOI:
[10.3390/su11184974](https://doi.org/10.3390/su11184974)

Print publication: 01/01/2019

Document Version
Peer reviewed version

[Link to publication](#)

Citation for published version (APA):

Wrieden, W., Halligan, J., Goffe, L., Barton, K., & Leinonen, I. (2019). Sustainable Diets in the UK—Developing a Systematic Framework to Assess the Environmental Impact, Cost and Nutritional Quality of Household Food Purchases. *Sustainability*, 11(18), Article 4974. <https://doi.org/10.3390/su11184974>

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1 Article

2 Sustainable diets in the UK? Developing a systematic 3 framework to assess the environmental impact, cost 4 and nutritional quality of household food purchases

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15 Received: date; Accepted: date; Published: date (6 September 2019 revision 2)

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

34 **Keywords:** Diet Quality, Life Cycle Analysis, Cost, Food Purchase. (List three to ten pertinent
35 keywords specific to the article; yet reasonably common within the subject discipline.)
36

37 1. Introduction

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

45 Food production and distribution has a significant contribution to global environmental
46 impacts. For example, the annual greenhouse gas emissions (GHGE) arising from agricultural
47 production have been estimated to range from 7.3 to 12.7 Gt CO₂-equivalent, or 14-24% of total global
48 emissions [5]. Additional environmental impacts in the form of energy use and greenhouse gas
49 emissions arise from transport, processing and preparation of food. In addition to the harmful
50 emissions to environment, food production is associated with the use of limited resources. For
51 example, there are few opportunities to increase the land area available for agricultural production,
52 despite the fact that the food requirement of growing global population is continuously increasing
53 [6]. Although food production is a necessary activity, it is possible to mitigate its environmental
54 consequences, for example by reducing its greenhouse gas emission intensity [7]. Improving the
55 efficiency of the production chain and directing the consumption towards more environmentally
56 friendly ingredients and production techniques provides an opportunity to considerably reduce the
57 global environmental impacts associated with the food production chain [8-14].

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

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

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

82 In general, much of the existing research evidence on the sustainability of current diets, although
83 useful, is based on population data and generalisations and simplifications of the environmental
84 impacts of standard food commodities and a limited number of product groups, as stated above [15,
85 27]. This is mainly analysis using publicly available "carbon footprint" information with only limited
86 or no traceability, using data covering only a limited number of food items [18] and excluding parts
87 of the food supply chain. This has been productive in indicating the type of diets needed for both
88 health and sustainability but limited to producing idealistic diets designed by statistical models
89 which may not be culturally acceptable or affordable [24, 26, 28]. Masset and co-workers [29] using
90 data from the French national dietary survey (INCA2), selected real individual diets exhibiting less
91 than the median GHGE and higher than the median for their diet quality measure. However,
92 although they measured cost as an outcome they did not incorporate it when selecting their "More
93 Sustainable" category.

94 Our aim was to develop an improved novel modelling framework to enable quantification of
95 real household level food choices for health, affordability and environmental sustainability; while
96 systematically accounting for the entirety of the food production, processing and supply chain, and

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

111 2. Materials and Methods

112 113 2.1. Data

114 The framework draws on data from multiple sources, and the Living Costs and Food Survey
115 (LCFS) [30] is used as an example to demonstrate the use of the method in connection with a large
116 food purchase dataset where purchases are recorded for each household in the survey. We
117 constructed a database with all the requisite variables (type of food, weight, cost, greenhouse gas
118 emissions, and land use) at the household level. This provided the desired resource that would enable
119 future investigation of the relationship between environmental sustainability, healthiness and cost of
120 household food purchases. We used the household as the unit of study, acknowledging the fact that
121 purchases are frequently shared between the members of a household.

122 123 2.2. Living Costs and Food Survey

124 The LCFS is a continuous survey that is managed by the Office for National Statistics[30]. It is
125 conducted throughout the year and collects data on income and expenditure from a representative
126 sample of UK households. It provides a valuable source of information about household food
127 purchases, from which estimates of food consumption and nutrient intakes can be derived [31, 32].
128 The LCFS collects household food purchase data from every person over seven years of age over a
129 14-day period. Data is collected about foods bought for consumption at home, i.e. from supermarkets
130 and takeaways, and bought for out-of-home consumption, i.e. from restaurants or sandwich shops.
131 We used data from 2012, 2013 and 2014, downloaded under licence from the UK Data Archive. Data
132 from these three years combined together created a dataset of the food purchases of approximately
133 15,000 households with details on the quantity and price paid for 526 different foods or food groups
134 (e.g. groups such as complete meat-based ready meals which included a range of items).

135 136 2.3. Life Cycle Assessment

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

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

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

173 Some of the 526 food and drink codes can be considered as “single-product codes” (**consisting**
174 **of one commodity, e.g. potatoes) and some as “multi-product codes” (e.g. chips assigned to potatoes**
175 **and cooking oil).** Single-product codes could easily be allocated to a single raw commodity, but multi-
176 product codes presented a challenge when attempting to calculate estimates of GHGE and land use,
177 because the constituent products that make up the code were often made up of different raw
178 commodities. We therefore had to devise a method that permitted GHGE and land use calculations
179 to take into account both the different proportions of foods coming from different commodities, and
180 the different constituent products making up each multi-product codes. However, disaggregating all
181 of these multi-product codes and taking into account every possible constituent product, was not
182 feasible in this study, due to the minimal contribution of some of the products to the overall food
183 purchases. We therefore took a pragmatic approach to this exercise and prioritised the 202 codes that
184 accounted for 95% of all purchases (by quantity). For the remaining 324 codes, the closest match
185 amongst those products that had been already disaggregated was used (more details provided in
186 Supplementary Material 1).

187 After a commodity allocation had been established for each of the 526 food and drink codes,
188 GHGE and land use figures were calculated. These figures were calculated on a per 1kg of the food
189 item basis; this was done by using a weighted average based on GHGE and land use figures related
190 to the production of the basic commodities and the proportions of these commodities needed for
191 production of each food code. In addition to the emissions arising from the basic commodities,
192 additional GHGE were added to the final figures for each product to account for: 1) additional
193 processing not included in the GHGE figures for the raw commodities; 2) canning or freezing of
194 products, and; 3) cooking of products either by the consumer or by the retailer (for products bought
195 ready-to-eat from out of the home, i.e. a takeaway or restaurant). In this study, we did not try to
196 quantify the exact emissions related to processing and cooking for each product separately (although
197 the framework would allow this option if such data are available). Instead, for each product, we

198 specified whether or not it is likely to be processed and/or cooked, and then used typical GHGE
 199 values for processing, canning, freezing, drying and cooking as found in the literature[39, 40].

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

- 202 • Primary production of the raw materials
- 203 • Processing
- 204 • Transport (including the raw materials and final products)
- 205 • Cooking

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

207

$$208 \quad GHGE_i = GHGE_{c_i} + \sum_{j=1}^n p_j GHGE_j$$

209 Where $GHGE_i$ is the total GHG emission associated with food item i , (kg CO_{2e}/kg) $GHGE_{c_i}$ the
 210 GHG emission associated with further processing and cooking of food item i (kg CO_{2e}/kg), $GHGE_j$
 211 the GHG emission associated with production, processing and transport of raw commodity j (kg
 212 CO_{2e}/kg, weighted average of different origins), p_j the proportion of raw commodity j in food item i ,
 213 and n the total number of raw commodities included in the analysis.

214

215 2.4. Diet Quality Index

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

221 The scoring system is described in Supplementary Table S1, which provides details of the foods
 222 and nutrients that are included in the DQI, and the scoring methodology and rationale for each
 223 component. The definitive index comprises three food scores and six nutrient scores with a total score
 224 out of 85. Coding frames, for each of the food groupings described in Supplementary Table A2,
 225 indicate which foods and drinks are included in each of the food groupings and list adjustment
 226 factors. Estimated waste figures [42] were applied to adjust purchases for waste prior to calculating
 227 the DQI as the DQI represents the quality of the diet as eaten not purchased.

228 To calculate the scores linked to food consumption, food purchase data (minus waste) from the
 229 LCFS 2012, 2013 and 2014 data were linked to the DQI coding frame; each food code was multiplied
 230 by the appropriate adjustment factor and summed by food grouping. **Summed household data was
 231 then adjusted to an average adult consumption figure for the household as g/2000 kcal (8368 kJ) to
 232 standardise the data. This figure was used as it is the Reference Intake used on food labels across the
 233 EU for the average adult (<https://referenceintakes.eu/reference-values.html>).**

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

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

243

244 2.5. Cost

245 Using the total food-related expenditure derived from the LCFS **raw unadjusted data** for each
 246 household the average cost of food per person within each household was calculated. We thus
 247 obtained the actual cost of food at the time of purchase regardless of where it was purchased or the
 248 time of purchase. **Controlling for inflation was not necessary for our study as we based our results**

249 on the actual median expenditure specified separately for each year included in the dataset (see
250 section 2.6. below). We did not average over the population [26, 43] as we wanted to record the actual
251 price paid by individual consumers.
252

253 2.6. Database Variables and Integration

254 There are four groupings of variables (shown in Supplementary Table S3): LCFS-related
255 variables (including weight of food purchased and expenditure); DQI variables; LCA variables; and
256 Household Basal Metabolic Rate estimate [44]. The latter was developed in order to exclude
257 households who purchased an amount food that would be unable to sustain energy requirements
258 (see Supplementary material 2 for calculation). In summary, food purchase data for 2012, 2013 and
259 2014 combined, from the UK LCFS, detailing food weights and costs, were mapped to the LCA
260 variables of Greenhouse Gas Emissions (GHGE) (estimated for primary production, processing,
261 transport and cooking of the individual food commodities and composite foods) and Land Use to
262 produce estimates of the total GHGE and land use for any specific food product purchased by the
263 consumer, calculated in a systematic and transparent method based on disaggregated food items. A
264 DQI was assigned to each household in the survey [41].
265

266 2.6 Analysis

267 Using the framework described the median GHGE (kgCO₂), expenditure on food per person (£),
268 land use (m²) (all standardised per person and per week) and DQI were calculated for three years of
269 data (2012, 2013 and 2014) from the LCFS. Households whose purchase patterns were unlikely to
270 sustain estimated Basal Metabolic Rate of its members for the 2 weeks of data collection were
271 removed (see method in supplementary material 2) to avoid underestimation of actual diet and
272 environmental cost. Households were classified as having a more sustainable diet based on GHGE,
273 expenditure and land use being less than the median and DQI being higher than the median; similar
274 to the procedure used by Masset and co-workers in France [29]. As median expenditure rose each
275 year the median cut off for expenditure was done on a yearly basis. There was no significant change
276 in DQI, GHGE, or land use over the three years. The percentage of households exhibiting the more
277 sustainable diet were compared by equivalised income quintile (calculated per year), and also
278 household composition (for the 4 most common types of household, **single man; single woman; one
279 man and one woman; families with man, woman and one or two children**) using the Chi-square
280 statistic.

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

286 SPSS V24.0 (SPSS Statistics, IBM, New York) was used for all statistical analyses.
287

288 3. Results

289 3.1. Characteristics of final sample.

291 The number of households, after removal of those who purchased a lower than feasible amount
292 of food to maintain the Basal Metabolic Rate of the members of the household, was 12434. All had
293 data on equivalised income and could be categorised into quintiles. The majority (72.2%; n 8982)
294 could be categorised into 4 household types, **single man (14.5%); single woman (21.7%); one man and
295 one woman (48.4%); families of a man, woman and 1 or 2 children (15.5%)**. **This was** a pattern broadly
296 similar to the UK population in 2011[45].
297

298 3.2. General findings

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

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

313 Applying similar criteria for the more sustainable category but with a DQI >80% only 100
314 households were selected, representing 0.8% of the sample (Table 3). The characteristics of this group
315 (More sustainable, DQI >80%) are given in the following section. When the stricter criteria of DQI
316 >90% only 16 households were selected, that is 0.13% of the sample.

317
318

319 Table 1. Median and Inter quartile Range (IQR) of GHGE, Land Use, Expenditure (per person per
 320 week) and DQI
 321

	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 ₂ e)	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)		

322 Table 2. Percentage (number) of households exhibiting more or less sustainable food purchase
 323 patterns within equivalised income quintiles and household type
 324

	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)

325 *P<0.001 using chi-square for group differences in proportions in more or less sustainable

326

327 3.2. *Food purchase pattern for households with high diet quality (More sustainable DQI >80)*

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

337

338 About 1.5 litres of milk (with semi skimmed being the most popular choice) and 2-4 portions of cheese
339 were purchased each week. Red meat and processed meat were purchased but means and medians
340 showed that intake was likely to be no more than four portions a week, 23% of households purchased
341 no red meat at all but 18% purchased enough red and processed meat to consume a portion every
342 day. A smaller amount of poultry was purchased equivalent to up to 2 portions per week (48% non-
343 purchasers) with fish up to 3 portions per week (19% non-purchasers) including tinned, fresh and
344 frozen varieties of white fish and salmon. All households that purchased some animal protein, but
345 3% purchased no animal flesh in the form of poultry, fish or red and processed meat.

346

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

351

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

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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%,

366

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 x40g portions per day
Pasta, rice and noodles	408	575	218	0-500	1-3 portions per week
Flour	470	1014	0	0-500	Around 250g per week
Pizza	133	256	0	0-249	No more than 1 x 200g 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 x 150ml 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 30g portions per week
Unprocessed red meat	258	430	0	0-371	Up to 1-2 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 25g packets per week
Cake, pastries, puddings, biscuits	758	573	636	306-1080	1-4 20g 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
Sugar containing	431	918	0	0	330ml cans per week
Sugar free	788	2293	0	0	mixed or 1-2 per fortnight sugared.

367

368 4. Discussion

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

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

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

385 A practical advantage of the framework developed here is related to the detailed disaggregation
 386 of the purchased food items. In earlier studies [15, 18-23], the environmental impacts of foods (mainly
 387 GHGE only) are usually based on "food groups", not on individual products. Relying on such
 388 relatively coarse categories can in the worst case lead to insufficient or even misleading conclusions.

389 In reality, the composition of a single food group can be highly variable. Just as a simplified example,
390 foods classified as “meat products” can include items such as whole meat, meat pies (containing
391 mainly cereals) and meat soups (containing mainly water). Therefore, shifting dietary habits between
392 such products can have a high impact on the GHGE associated with the diet, yet it can be observed
393 only with detailed disaggregation of the food items. In general, the disaggregation approach allows
394 for identification of the effects of much smaller scale changes in diets than major dietary shifts e.g.
395 from meat-based diet to vegetarian diet [8, 11, 13, 47]. However, it should be noted that the LCFS
396 dataset applied in this study included some food categories that did not allow a detailed
397 disaggregation (for example “complete meat-based ready meals”). However, a further advantage of
398 our method is that such categories can be handled in systematic way, based on the weighted average
399 of the actually consumed items belonging to that category (see Supplementary Material 1 and Table
400 S2). Therefore, we believe that our framework can handle both very detailed and less accurately
401 specified food categories without bringing any bias to the results. Furthermore, the tool can handle
402 unlimited combinations of raw materials in food items. Therefore, any number of new foods can be
403 included in detailed calculations, as far as their “recipes” are known.

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

415 The study used purchase data from a large representative sample of the UK population. It has
416 been suggested that purchase data is less subject to bias than individual food diaries [31, 48] but as it
417 combines data from purchase diaries within households it is not possible to see the individual diets
418 of household members or adjust for household composition or ages within the household. In addition
419 it is not possible to determine how much, if any, food and drink may have been purchased for friends
420 and family outside the household, or whether the purchases were consumed within the 2 week
421 recording period. However a method for checking that the food purchased was an adequate amount
422 for the household was provided and excluded about 20% cases where it was unlikely. Wastage was
423 accounted for in calculation of the DQI using average figures from the Waste and Resource Action
424 Programme (WRAP) [42] , but not in the calculation of GHGE and Land use as these will be
425 appropriate for the actual food purchased.

426 The DQI used to determine the nutritional quality of the diet was constructed using widely
427 accepted dietary guideline cut-off points at the time of the surveys, (for example those from the World
428 Health Organization[49] and others detailed in Supplementary Table S2) and although there have
429 been recent changes to recommendations for added sugars and fibre (with changes to definitions and
430 cut-offs [50]), it was not possible or considered appropriate to compare with guidelines that were
431 constructed after the dates of the actual surveys.

432 There is no “recommendation” as yet for the ideal GHGE from food for individuals to limit
433 climate change but this is also hampered by the fact that reported GHGE figures are variable and not
434 standardised as pointed out by Clune and co-workers [51]. However within our study the figures are
435 comparable with each other as a result of the systematic methods used. Results for different food
436 items are fully consistent, traceable and transparent, and go beyond the “farm gate”. The method
437 used was flexible (for example could be used to compare different scenarios) and could be applied to
438 any food item (with known composition).

439 Our research confirms previous work that the average UK diet does not meet dietary guidelines
440 [52-54]. However contrary to previous research it would appear that it is possible to purchase a diet

441 that is healthy and sustainable at a relative low cost. This would appear to contradict work that shows
442 that the cost of a healthy sustainable diet is more expensive than conventional diet [26, 28, 29]. It
443 should be noted that a relatively low cost, high quality sustainable diet was purchased by a very
444 small proportion of survey participants but it does show that there is potential for a carefully chosen
445 diet to be both affordable, sustainable and healthy.

446

447 *Conclusion*

448 Using a systematic methodology that where purchased food items were disaggregated into their
449 components with traceable environmental impact data we found that there were households who
450 were purchasing a diet that was both low cost, and had a lower environmental impact, combined
451 with a higher quality in terms of nutrition. Using the higher criteria for DQI the diet of the 100 more
452 sustainable households was not unlike that recently proposed by EAT-Lancet Commission [2]. The
453 purchase patterns of the 100 households were not uniform and some purchased no red or processed
454 meat or other types of animal protein. There has been criticism of the EAT-Lancet proposal on the
455 grounds that it is not feasible or practical [55] or fits with the UK situation [56] but there seems to be
456 no appreciation of the flexibility within the plan and that it represents an average. There will be some
457 individuals and household who choose to eat more of their protein from animal sources and others
458 purely from plants. What is needed is a population shift towards lower meat and dairy consumption
459 and higher consumption of wholegrains and fruit and vegetables, the point that nutritionists in public
460 health have been making for over two decades.

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

474

475 **Supplementary Materials:** The following are available online at www.mdpi.com/xxx/s1, Supplementary
476 material 1. Disaggregation method. Supplementary material 2. BMR calculation. Table S1: Table S1: Components
477 of the Diet Quality Index and Scoring System Table S2 Coding frame for the Diet Quality Index Table S3 List of
478 variables in the final dataset

479 **Author Contributions** Conceptualization, W.W. and I.L.; methodology, W.W., I.L., K.B.; formal analysis, W.W.,
480 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.;
481 funding acquisition, W.W. and I.L.

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

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

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

491

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