Using household demographic data to estimate demand for sustainable diets

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Abstract

Sustainable diets incorporate consumer acceptability whilst being nutritious and having a low carbon footprint. This paper estimated Exact Affine Stone Index (EASI) incomplete demand systems for different households using the Scottish section of Kantar Worldpanel data from 2010 to 2015. The resulting price elasticities were used within the Green et al (2015) quadratic programming diet model to estimate the quantities of food products which would constitute a sustainable diet. Four demographic groups were modelled and the results suggested that three of the groups could experience carbon emission reductions of between 30 to 55 per cent relative to baseline emissions. The diets would also likely offer an improvement in terms of nutritional quality as measured by the Mean Excess Ratio (MER).

Keywords [Food Consumption, Preferences, Nutrition, Sustainability]

JEL code [D12, Q56, Q18]

1. **Introduction**

Drewnowski (2017) defines sustainable food and nutrition security as encompassing four principal domains whereby "Foods and food patterns need to be nutrient-dense, affordable, culturally acceptable, and sparing of the environment." These four domains are therefore relevant for identifying what constitutes a sustainable diet. Clearly a sustainable diet must incorporate these four domains, yet public health nutrition focusses on populations of demographic groups, whilst economics usually focusses on households. This shows the difficulties of incorporating nutrition and economics into estimating demand for sustainable diets. A further difficulty is how economic studies such as Green et al (2015) and Irz et al (2015) have estimated demand systems at household level without making a distinction to represent different demographic groups.

This paper will estimate demand systems at household level using the household demographic data within Kantar Worldpanel data thus extending the work of Chalmers and Revoredo-Giha (2018). The elasticities will then be used in a quadratic programming model (based on Green et al (2015) diet model) to estimate sustainable diets for the different household demographic groups with a selected number of nutritional constraints. The resulting diets will then be assessed in terms of diet quality i.e. how they conform to overall dietary reference values (DRVs) of nutrients which were not constrained within the diet model.

The structure of the paper is as follows: The background section focusses on the representation issues of estimating demand systems in addition to a brief section on what constitutes a sustainable diet. The data section presents a description of the data required for the estimation of the diet model. The methods section details how the demand systems and subsequent quadratic programme were estimated along with an explanation of diet quality. The results and discussions section details and discusses the estimates of the diet model.

2. Background

This section presents the main themes of modelling demand for a sustainable diet which are: Composition of sustainable diets, accounting for preferences and household demographic groups.

The recent findings of Willett et al (2019) state that "achieving healthy diets from sustainable food systems for everyone will require substantial shifts towards healthy dietary patterns, large reductions in food losses and waste". This diet does not eliminate meat or dairy but merely reduces the consumption of these two relatively high carbon footprint food groups with the focus of the diet being mainly plant based (Willett et al., 2019). The nutritional requirements of the "universal healthy reference diet" of Willett et al (2019) are based on different epidemiological and health studies. The dairy group encompasses many different products and cheese and milk are very different products in terms of carbon emissions, consumer preferences and nutritional quality. It does not seem sensible to consider the dairy group in this aggregated form.

Whilst Willett et al (2019) detail "preferences" they do not seem to account for how preferences could vary within countries and by different household demographic groups. Incorporating preferences in the form of elasticities is still largely ignored within the sustainable diet literature.

Estimating elasticities for different food products is an important input for modelling sustainable diets (i.e., diets which incorporate consumer acceptability, low in carbon emissions and meet nutritional requirements). Previous studies such as Green et al (2015) and Irz et al (2015) have estimated elasticities at household level and assumed that they are representative of all the different demographic groups (e.g. males 19 to 50 etc.). Chalmers and Revoredo-Giha, (2018) used cross sectional nutritional surveys to estimate the elasticities for different demographic groups which is an issue considering that demand systems are estimated at household level. Given that teenagers are unlikely to be heads of households it is not logical to estimate the demand systems at this level. Nor is it logical to assume that both males and females have the same preferences as in the case of Green et al (2015) and Irz et al (2015).

Green et al (2015) used a quadratic programming based diet model and their emission reductions were based on running the model through reducing the GHG emissions by 10 per cent relative to the baseline emissions. The 40 per cent reduction results for both males and females show similar reductions in beef to zero grams and relatively small reductions in processed beef which is likely a result of the same price elasticities being used (Green et al., 2015)[1]. The changes occurring for the other food groups were somewhat similar for the genders and where difference occurred, it is likely that it is a result of the different dietary reference values.

Demand systems need to be estimated at household level as the underlying preferences of the household members will be aggregated. Deaton and Muellbauer (1980) discussed the issue of aggregation over households and how the Almost Ideal Demand System (AIDS) allows for the rational representative household to be represented within the demand system. The household budget constraint is per household and extracting the food consumption of say children aged between 11 to 18 and estimating demand systems for this group would violate the budget constraints unless they belonged to the same household. The recent work of Hovhannisyan et al (2019) whilst modelling EASI demand systems at household level did state that "Future work would benefit significantly from the use of individual consumer/household level data as such data become available. This would make possible the estimation of individual-level fixed effects models of consumer behavior". However, this argument of using individual household level data within demand systems could only be justified if it were single person households.

Microeconomics usually estimates demand at household level and yet the area of nutrition usually provides DRVs for populations of demographic groups such as males aged 19 to 50. This highlights the difficulties of estimating the demand systems for modelling sustainable diets which this paper aims to solve by using demographic data to estimate demand for the purposes of dietary modelling.

3. Data

The food groups along with a detailed list of matching food products (column three) shown in Table 1 were matched to the years 2010 to 2015 Kantar purchase data for Scotland. These food groups are also succinctly summarised in Figure 1. The Scottish section of Kantar Worldpanel data provided information on the demographics of households and their respective purchased volumes and prices of food and drink products. The Kantar data are categorised as panel data.

[1] Supplementary text

The food groups shown in Table 1 were created from the Kantar data and matched to similar groups from the National Diet and Nutrition Survey (NDNS) in order to estimate their nutrient content (required for the diet models and more information provided in the methods section).

Table 1 Demand system groups

Group	Demand groups	Products within group
1	Grains and grain-based products	White Bread Brown Bread Wholemeal Other Bread Oat products Cereal Pasta Pizza Other cereal foods Rice Flour
2	Vegetables and vegetable products	Salad Vegetables Vegetable based meals Canned Vegetables Herbs
3	Starchy roots, tubers, nuts and oilseeds	Nuts and nut based products Potatoes Canned Potatoes Instant potato Chips
4	Fruit, fruit products and fruit and vegetable juices	Oranges Other citrus Bananas Apples Other fruit Frozen fruit Dried fruit Tinned fruit Pure fruit juices
5	Beef, veal and lamb	Beef joints Beef steak Minced beef

Group	Demand groups	Products within group
		Other beef and veal
		Lamb joints
		Lamb chops
		Other lamb
6	Pork	Bacon and ham
		Pork joints
		Pork chops
		Pork fillet
		Other Pork
7	Poultry, eggs, other fresh meat	Quiche
		Chicken and turkey
		Chicken
		Turkey
		Other Poultry
		Eggs
8	Processed and other cooked meats	Cooked sandwich meats
		Canned meat
		Meat pies
		Meat ready meals
		Other processed meats
		Sausages and Burgers
		Pate and paste
		Cooked sandwich meats
9	Fish and other seafood	White fish
		Salmon
		Blue fish
		Shellfish
		Tinned fish
		Fish ready meals
10	Milk, dairy products and milk product imitates	Whole milk
		Skimmed milk
		Semi-skimmed milk
		Condensed or evaporated milk
		Dried milk
		Cream
		Milk drinks
		Non-dairy milk
11	Cheese	Hard cheese

Group	Demand groups	Products within group
		Cottage cheese Soft cheese Processed cheese
12	Sugar and confectionary and prepared desserts	Puddings Custard Yoghurt Sugar Jam Jelly Honey Syrup Chewing gum Ice cream Confectionery
13	Soft drinks	Soft drinks low cal Soft drinks Soft drinks conc
14	Tea, coffee, cocoa, and drinking water	Coffee Instant coffee Other coffee Tea Fruit tea Water
15	Snacks and other foods	Buns Savoury biscuits Crispbread Biscuits Cakes Snacks
16	Residual category	Food and drink products which were not categorised into the previous groups

The NDNS data were used to estimate the mean daily baseline diet quantities (as shown in Table 2) for the purposes of diet models as the data includes all foods consumed unlike the Kantar data (e.g., Kantar data covers food purchased) which is considered to be a more accurate representation of baseline diets. There was also concern that for some demographic household groups, the NDNS baseline diets differed relative to the Kantar baseline. NDNS years 1 to 8 were used to form these baseline diets.

Table 2 Initial NDNS quantities

Initial	Food Groups														
Results	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Female 1950	170.99	154.47	91.68	153.56	48.86	27.72	70.84	43.52	42.87	153.37	21.86	66.60	370.70	1091.09	38.64
Male 1950	224.61	159.82	112.03	176.28	64.75	38.68	92.56	68.71	52.07	180.49	25.31	69.56	477.71	1112.29	47.40
Three Adults	523.60	486.87	309.76	515.23	167.83	96.30	215.98	156.65	146.86	543.23	67.46	225.02	1053.48	3450.26	130.37
One Adult Child	370.79	251.08	187.11	323.16	95.81	57.70	141.60	97.73	79.32	336.27	40.30	135.43	846.60	1612.99	87.74

Notes: Food group numbers correspond to the demand groups of the figure below.

Figure 1 Demand groups

Group 1 Grains

Group 2 Vegetables

Group 3 Nuts and Tubers

Group 4 Fruit

Group 5 Red meat

Group 6 Pork products

Group 7 Poultry and Egg dishes

Group 8 Processed meat products

Group 9 Fish

Group 10 Milk products

Group 11 Cheese

Group 12 High sugar foods

Group 13 Soft drinks

Group 14 Tea, coffee and water

Group 15 Cakes and Snacks

Group 16 Residual Group

Table 3 Median nutrition and carbon content of food groups (units per 1 gram of food)

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15
Energy (KJ)	12.4	3.395	7.96	2	6.27	8.32	7.25	10.005	7.08	2.96	12.4	8.4	1.125	0.63	16.93
Sodium (mg)	2.9	0.39	0.18	0.03	0.97	4.85	2	3.74	2	0.49	6.9	0.63	0.05	0.14	2.7
Free Sugars (g)	0	0	0	0.0575	0	0	0	0	0	0	0	0.157	0.0655	0	0.212
Fat (g)	0.034	0.018	0.094	0.001	0.073	0.104	0.09	0.137	0.091	0.036	0.235	0.046	0	0	0.166
Protein (g)	0.079	0.026	0.031	0.007	0.146	0.224	0.13	0.1375	0.166	0.033	0.186	0.037	0	0	0.057
Iron (mg)	0.018	0.008	0.006	0.004	0.014	0.008	0.009	0.016	0.007	0.003	0.003	0.004	0	0	0.014
Copper (mg)	0.0017	0.0007	0.0011	0.0006	0.0007	0.0008	0.0008	0.0011	0.0006	0.0003	0.0003	0.0004	0	0	0.0016
Zinc (mg)	0.01	0.004	0.004	0.001	0.027	0.021	0.009	0.019	0.006	0.005	0.021	0.004	0	0	0.007
Vitamin A (µg)	0	0.48	0	0.05	0.1	0	0.44	0.14	0.23	0.57	2.82	0.25	0	0	0.45
Vitamin C (mg)	0	0.07	0.073	0.11	0	0	0	0.0055	0	0.016	0	0.003	0.07	0	0
Calcium (mg)	0.6	0.35	0.13	0.14	0.16	0.09	0.31	0.36	0.36	1.1	5	0.9	0.06	0.095	0.68
Carbon (g)	0.003167	0.0017	0.0026	0.0012	0.0127	0.0046	0.00491	0.0046	0.0046	0.001232	0.0111	0.0024	0.000432	0.000212	0.0012

Notes: The food group number corresponds to the food group description shown above.

The population representation of the associated households is an important feature as future work may wish to consider the impact of dietary change on food supply chains. The household demographic groups were selected based on 2015 projections by National Records of Scotland (2017). The household demographics are shown in Table 4.

Table 4 National Records of Scotland type of household

Household size	Household type
One person households	1 adult male
	1 adult female
Two person households	2 adults
	1 adult, 1 child
3+ person households	1 adult, 2+ children
	2+ adult 1+ children
	3+ person all adult

Source: National Records of Scotland (2017)

Dietary reference values (DRVs) were sourced from Chalmers and Revoredo-Giha (2018) for individual demographic groups and adjusted to match the household demographics of Table 5. Therefore, household DRVs were formed and are shown in Table 11 of the appendix.

Household age demographic (household level using the "age" of the attributes Kantar file) data allows the years 2014 and 2015 to be estimated for two of the household demographic groups though most are full 2010 - 2015[2]. These household demographic groups were categorized into the following as shown in Table 5. Previous work by the authors found that modelling diets of those aged less than 11 were problematic thus the children in Table 5 are from 11 years of age. With regards to the initial NDNS values, this was harder to estimate given the household situation and approximately 4 days of diary data provided (the values were adjusted to be for daily data). To estimate the initial baseline daily values for three adults, the mean of those aged 19 and over were estimated. To estimate the initial values for one adult and one child, the mean of females aged 19 to 50 were added to the mean of children aged 11 to 18. It was not possible to form the initial baseline diets for these two groups as shown in Table 5.

[2] The households which covered on the years 2014 to 2015 were: Males aged 19 to 50 and Females aged 19 to 50

Table 5 Household demographic groups

Household group names	Composition
Two Adults1950	Two adults aged within the 19 to 50 age range
M1950	Single male households aged between 19 to 50
F1950	Single female households aged between 19 to 50
Two Adults 50 Plus	Two adults (either gender) aged 50 plus
One Adult Two Child	One adult aged 19 to 50 and two children aged between 11 and 19 years old.
One Adult Child	One adult aged 19 to 50 and one children aged between 11 and 19 years old
Two Adult One Child	One adult aged 19 to 50 and one children aged between 11 and 19 years old
Three Adults	F50Plus + M50Plus + (F1950 + M1950/2)

4. Methods

This section presents an explanation of the three methods: Demand systems, diet models and diet quality.

4.1 Demand systems and price elasticities

The Exact Affine Stone Index (EASI) developed by (Lewbel and Pendakur, 2009), was used for estimating Marshallian price elasticities in this paper. The EASI incomplete demand systems were estimated for the different household demographic groups in order to estimate price elasticities for the 16 aggregated food groups[3]. Whilst Lewbel and Pendakur (2009) estimated their system based on cross sectional data, this paper used panel data.

Incomplete demand systems were estimated based on the food and drink groups shown in Table 1. Equation 1 shows the "approximate" model of the linear EASI demand system with the following parameters: w = budget shares, b = represents the Engel curve, $\tilde{y}$ = the stone price index, A = compensated price effects, p = log prices and the error term ε represented random utility parameter, z = the demographic characteristics which include a time trend (year), social class and geographical location. The parameters of C and D allow the demographics to be reflected through intercept and slope terms of the budget shares (Lewbel and Pendakur, 2009). Given that a three stage least squares system is estimated, instrumental variables are estimated from using the exogenous variables of expenditure, price and demographic variables.

[3] Only 15 of these groups is used for thee diet modelling

$$w = \sum_{r=0}^{r} b_r \tilde{y}_r + Cz + Dz\tilde{y} + \sum_{l=0}^{L} z_l A_l p + Bp\tilde{y} + \tilde{\varepsilon}$$

1

Eight demand systems were estimated for the respective household demographic group using R package Easi (Hoareau et al., 2013) with no interactions between price, implicit utility and demographic variables. The own price elasticities were also estimated using package Easi. The EASI demand systems were initially estimated on cubic income systems and then tested against those systems of squared and linear income systems. Most of the demand systems were found to be cubic based income systems.

Conditional demand systems for meats were also estimated to provide an indication of what meat products were complements or substitutes to one another. This was considered necessary as the meat groups in the diet model are relatively aggregated and are based on nutritional groups rather than pure meat groups.

The Marshallian own price elasticities were also estimated using package Easi.

4.2 Diet models

Green et al (2015) quadratic programming diet model used the estimated elasticities. The model incorporated 11 nutritional constraints[4] (i.e. the dietary reference values). The models were run based on reducing the baseline emissions by five per cent for each run until the highest emission reduction could be achieved (i.e. until no solution could be found for the quadratic diet model).

The quadratic programming diet model used by Green et al (2015) and Milner et al (2015) takes the form of equation 2 which represents the objective function. The ratio of s_i/ε_i is the proxy for acceptability of diet weighting for the quadratic programme (Milner et al., 2015). This ratio is multiplied by the current and the ideal consumption for food group i (Δx_i) squared (Green et al., 2015) .

[4] These were: Energy, Sodium, Non-Milk Extrinsic Sugars, Fat, Protein, Iron, Copper, Zinc, Vitamin A, Vitamin C and Calcium

The purpose of the objective function is to minimise the weighted normalised deviations from the baseline diets for each demographic group of the 15 food groups. This was done through the use of nonlinear optimization with constraints i.e. Langrangian multiplier.

$$\underset{\{\Delta X_i;\, i\, =\, 1..15\}}{min} \left[\sum_{i=1}^{15} \frac{s_i}{\varepsilon_i} \left(\frac{\Delta X_i}{X_i}\right)^2\right]$$

2

The nutritional constraints ($\mathbf{r_j}$) are shown by equation 3 represents the nutrient coefficients (a_i) of seven beneficial nutrients (Protein, Iron, Copper, Zinc, Vitamin A, Vitamin C and Calcium), in addition to quantity of the food groups (x_i).

$$\sum_{\boldsymbol{i=1}}^{\boldsymbol{7}} \boldsymbol{a_i x_i} \, > \, \boldsymbol{r_j}$$

3

Equation 4 represents the overconsumed four nutrients: Energy, Sodium, Non-milk extrinsic sugars (i.e. free sugars) and fat.

$$\sum_{\boldsymbol{i=1}}^{\boldsymbol{4}} \boldsymbol{a_i x_i} \, < \, \boldsymbol{r_j}$$

4

The quadratic diet models were estimated in Excel using VBA.

4.3 Diet quality

The diet quality is estimated by creating a single metric of beneficial nutrients called the Mean Adequacy Ratio (MAR) and nutrients which are considered harmful which is called the Mean Excess Ratio (MER) (Vieux et al., 2013). The MAR has been used to estimate the 17 beneficial nutrients whilst the MER is used 3 harmful nutrients as based on the work by Chalmers and Revoredo-Giha (2018). Equation 5 represents the estimation of the MAR whereby the intake of beneficial nutrients (bn) is weighted by the Dietary Reference Values (DRV) and is scaled by the number of nutrients used (in this case 17) with overconsumption capped.

$$MAR = \frac{1}{17} * \sum_{bn=1}^{17} \frac{intake_{bn}}{DRV_{bn}} * 100$$

5

The MER estimated the mean daily maximum recommended intake of three nutrients (Sugars, Saturated fats and Sodium) and shown in equation 6 (harmful nutrients- hn). A value greater than 100 suggests excess consumption of these nutrients and the value cannot be lower than 100 (Vieux et al., 2013). Whilst this is common practice not to allow the value to be lower 100, it could cause issues whereby an estimated diet has very little of the three harmful nutrients thus leading to potential dietary problems. For the purposes of this study, the lowest MER will be set to 100.

$$MER = \left[\frac{1}{3} * \left(\sum_{hn=1}^{3} \frac{intake_{hn}}{DRV_{hn}} * 100\right)\right] - 100$$

6

5. Results and discussion

This section details and discusses the results of the demand systems with regards to price elasticities, diet models and diet quality.

5.1 Estimation of price elasticities based on household demographics

The Demand systems for the household demographic groups shown in Table 5 were estimated using the Kantar panel data, however, the results indicated that only four of these groups (single male aged 19 to 50, single female aged 19 to 50, three adult households and one adult with children households) provided credible results based on concavity and the resulting price negativity (of resulting elasticities). The price elasticity results for these four groups are shown in Table 12 to Table 15 of the appendix.

The price elasticities of the following demographic groups were used for the diet model: single male aged 19 to 50, single female aged 19 to 50, three adult households and one adult with children households.

The estimation of the conditional demand system Marshallian price elasticities revealed how low carbon chicken was not a statistically significant substitute of high carbon beef (for all the four estimated household demographic groups). As there is no substitution between these low carbon and high carbon meat products then the aggregated meat groups within the diet models are considered sufficient. The resulting conditional price elasticities are shown in Table 16 to Table 19 of the appendix.

5.2 Estimation of diet models and subsequent diets

The resulting diets for the different household demographic groups are shown in Table 6 whilst the associated baseline quantities are shown in Table 2. This section details the results of the diet models and how they compare to the third quartile and the maximum quantities of observed food consumption[5] shown in Table 9 and Table 10 appendix. The results for all the household demographic groups as shown in Table 6 show less variety in terms of the resulting food groups. Table 1 provides a detailed list of the food products associated with each food group and will serve as a useful reference for this section. This sub section will describe and discuss the results with a focus on potential preferences as a reason for the results.

The Females aged 19 to 50 household demographic diet model could not be estimated when decreasing the GHG emissions. Therefore, this household demographic group diet will not be discussed.

The resulting diet for males aged 19 to 50 household demographic group shows a similar quantity of grains i.e. group 1 (225[6] grams) as the baseline (203 grams). There is an increase in vegetables i.e. group 2 (531 grams) and this group does comprise of complete vegetarian meals. There is an increase in milk products (group 10) and an increase in cakes and snacks (group 15). The non-milk extrinsic sugars constraint is satisfied and given that zero grams are returned for high sugar group (group 12) and soft drinks (group 13) then this helps to explain why cakes and snacks appears within the sustainable diet.

With regards to the three adult household demographic groups, the resulting food groups have reduced to three: vegetables (group 2), milk products (group 10) and cakes and snacks (group 15). The 2,142 grams of vegetables does not exceed the maximum observed quantity of this demographic group (which is 3,078 grams). The increased quantity of milk products within the sustainable diet at 1,240 grams does not exceed the maximum of 5,661 grams. The sustainable diet returns 283 grams of the cake group which does not exceed the maximum intake of 779 grams.

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[5] Based on NDNS data

[6] Rounded values

With regards to the one adult and one child household group, the same food groups are appearing as for males aged 19 to 50. The grains group would result in 467 grams consumed which is within the third quartile quantity. The vegetables group would require 958 grams consumed which does not surpass the maximum quantity. The milk group would require 1,444 grams of milk products and this does not exceed the maximum quantities. Finally, the cakes and snacks group is the same quantity as for three adults and does not exceed the maximum intake of 7,954 grams.

As all the demographic household groups consume the vegetable-based food group then it is worth explaining the likely causes behind this result. This group contains many important nutrients and is relatively low carbon emissions based. The group also contains complete meals which is important when considering the potential for these results to be used in the "real" world. With regards to the own price elasticities, all the groups except One Adult Child have relatively inelastic price elasticities. Whilst the budget share varies little, the own price elasticities do, and these relatively price inelastic elasticities help provide a greater consumer preference within the diet models.

The lack of fruit within the estimated sustainable diet can be explained: firstly, 11 nutrients were used for creating the nutritional constraint. Secondly, out of these nutrients the vegetable groups contained higher quantities of the micronutrients. Finally, the own price elasticities for fruit were relatively more price elastic relative to those of vegetables (except One Adult Child) thus a larger preference weighting for vegetables within the diet model.

High carbon food groups such as meats and cheese were not present in the diet, which is likely to be attributed to their high carbon and nutritional content (particularly high for fats). However, the milk group show large quantities for all the household demographic groups. This is likely because milk products have a relatively smaller carbon content compared to cheese and despite Calcium also present in large quantities in cheese (as shown in Table 3), cheese contains a relatively higher quantity of saturated fat (thus contributing towards overall fat) and sodium. Saturated fats were constrained within the diet model. The own price elasticities for the cheese group were non-statistically significant (except the One child adult group) compared to the statistically significant milk own price elasticities. Thus, the milk own price elasticities create a larger preference weight in the quadratic programme when compared with cheese.

Table 6 Green et al Diet model results

Green								Food Groups							
Results	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Male 1950	202.52	530.57	0.67	0.00	0.00	0.00	0.00	0.00	0.00	874.77	0.00	0.00	0.00	0.00	139.64
Three Adults	0.00	2141.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1240.38	0.00	0.00	0.00	0.00	283.02
One Adult Child	467.08	958.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1444.27	0.00	0.00	0.00	0.00	283.02

Group 1 Grains

Group 2 Vegetables

Group 3 Nuts and Tubers

Group 4 Fruit

Group 5 Red meat

Group 6 Pork products

Group 7 Poultry and Egg dishes

Group 8 Processed meat products

Group 9 Fish

Group 10 Milk products

Group 11 Cheese

Group 12 High sugar foods

Group 13 Soft drinks

Group 14 Tea, coffee and water

Group 15 Cakes and Snacks

Group 16 Residual Group

The diet model estimated that three out of the four household demographic groups could potentially adhere to a more sustainable diet as shown in Table 7. The emissions associated with females aged 19 to 50 diet could not be reduced based on the baseline diet. The diet models found that for the male aged 19 to 50 group, emissions could be reduced by 40 per cent. Whilst three adult households could experience a 55 per cent reduction and one adult with children households could experience a 55 per cent reduction. These relative reduction figures are broadly in line with the findings from Green et al (2015). The main reason for the reduction is the elimination of meat, cheese and fish groups. However, the increase in dairy products does suggest that animal-based farming systems would still be required to satisfy sustainable diets. Willett et al (2019) described increases in dairy consumption as making sustainable diets difficult but this paper has been clear that liquid milk products should be separated from cheese and a single group is not realistic in the modelling of sustainable diets.

Table 7 Reductions in emissions associated with diets

Demographic Group	Baseline ($Kg\ CO_2e$)	New emissions ($Kg\ CO_2e$)	Emissions reduction Scenario (%)
Male1950	4.67	2.80	40
Three Adults	12.25	5.51	55
One Adult Child	7.50	5.23	30

Notes: Females aged 19 to 50 excluded because an emissions constraint could not be estimated
Sources: Own elaborations

5.3 Estimation of diet quality

The results for the MAR and MER are shown in Table 8. The MAR increased for females aged 19 to 50, males aged 19 to 50 and one adult children households yet decreased by 9 per cent for three adult households. There is some concern with regards to this decrease in MAR of the latter group.

The most interesting result is the decrease in the MER which reduced to 100 for all demographic households, except for females aged 19 to 50. The females group is an area of concern but given the issue of reducing its carbon emissions then a sustainable diet is not currently possible for this group. Males aged 19 to 50 households saw the largest percentage reduction in MER (32 per cent) which improved the quality of their diet. Three adults whilst experiencing a decline in MAR as a result of the sustainable diet, do experience a reduction in the MER which is considered beneficial. This does raise the issue of which diet quality indicator is of more importance to policymakers: MAR or MER.

Table 8 MAR and MER results

	MAR Baseline	MAR Sustainable Diet	MER Baseline	MER Sustainable Diet	% Change MAR	% Change MER
Female 1950	88	99	130	197	12	52
Male 1950	93	96	147	100	3	-32
Three Adults	92	83	133	100	-9	-25
One Adult Child	88	96	132	103	9	-22

6. Conclusion

This paper has contributed to sustainable diet modelling by demonstrating that estimating household demand systems based on household demographic data offers a more representative basis for estimating preferences within diet models compared to previous diet modelling. The resulting sustainable diets indicated that for three household demographic groups; four food groups would be required in order to satisfy nutritional constraints, carbon emission constraints and consumer preferences thus encompassing the four principal domains which are "Foods and food patterns need to be nutrient-dense, affordable, culturally acceptable, and sparing of the environment" (Drewnowski, 2017).

The diets for males aged 19 to 50, three adult households and one adult with children households indicated that emissions can be reduced whilst partially incorporating consumer preferences. Despite sustainable diets being modelled with only 11 nutritional constraints, the overall resulting diet quality as measured by the MAR (incorporates 17 nutrients) and MER (3 nutrients) suggests that sustainable diets would likely improve diet quality, yet in the case of three adult demographic households, an improvement for the MER would result in a worsening MAR which does demonstrate the trade-offs in dietary quality. Females aged 19 to 50, experienced an increase in MAR but it was not possible to reduce the GHG emissions within the quadratic model hence why a sustainable diet could not be estimated for this group.

This paper has contributed to the area of sustainable diets and the importance of milk products for meeting the requirements of such diets which does contradict the recent Willett et al (2019) report. Future work should adopt a whole dietary modelling approach in order to incorporate both substitution and complement effects.

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Appendix

Table 9 Observed NDNS quantities (grams) consumed (third quartile)

Initial	Food Groups														
Results	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Female 1950	217	209.2	124.1	214.2	63.11	36.41	97.34	59.38	55	207.5	30	92.63	497.7	1413	52.96
Male 1950	288.9	215	153.3	235.1	84.64	54.52	122.2	93.62	67.5	241.2	34.68	96.21	640.4	1442	65.78
Three Adults	673.2	651.6	412.8	708.6	225	129	287.94	210.75	188.25	731.4	90	315	1375.8	4401	178.29
One Adult Child[7]	469.3	340.9	251.6	448	124.16	75.91	191.97	133.16	100	454.6	54.1	187.62	1152	2115.2	118.49

Notes: Based on own elaborations of NDNS data

Table 10 Observed NDNS maximum quantities (grams) consumed

Initial	Food Groups														
Results	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Female 1950	716.1	743.3	565.2	1970	304.2	197.5	321.4	198	235	1740	160	612.9	3500	5055	181.1
Male 1950	738.1	1026	474	1541	461.2	300	1872	337.5	275.5	1772	161.2	527.8	3038	6385	259.5
Three Adults	2214.3	3078	2958.6	5910	1383.6	900	5616	1012.5	1203.3	5661	495	2310	19377	19155	778.5
One Adult Child	1563.9	1437.8	1091.7	3332	623	405.7	867.6	539.5	572	3840	327.7	1015.5	6236	9362	598.5

Notes: Based on own elaborations of NDNS data

[7] Quartile three and the maximum quantities were estimated by taking Female adults aged 19 to 50 and adding the associated values to children aged 11 to 18. Estimating representative samples is difficult

Group 1 Grains	Group 2 Vegetables	Group 3 Nuts and Tubers	Group 4 Fruit	Group 5 Red meat	Group 6 Pork products	Group 7 Poultry and Egg dishes	Group 8 Processed meat products	Group 9 Fish
Group 10 Milk products	Group 11 Cheese	Group 12 High sugar foods	Group 13 Soft drinks	Group 14 Tea, coffee and water	Group 15 Cakes and Snacks	Group 16 Residual Group		

Table 11 Dietary Reference Values (DRVs)

Nutrients	F1950	M1950	FM1950	FM50Plus	Three Adults	One Adult One Child	Two Adult Two Child	One Adult Two Child
Energy (Kj)	8950.00	11225.00	20175.00	18550.00	28637.50	20400.00	40800.00	40800.00
Protein (g)	45.00	55.50	100.50	99.80	150.05	97.58	195.17	195.17
Sodium (mg)	1600.00	1600.00	3200.00	3200.00	4800.00	3200.00	6400.00	6400.00
Calcium (mg)	700.00	700.00	1400.00	1400.00	2100.00	1533.33	3066.67	3066.67
Magnesium (mg)	270.00	300.00	570.00	570.00	855.00	573.33	1146.67	1146.67
Iron (mg)	14.80	8.70	23.50	17.40	29.15	24.37	48.73	48.73
Copper (mg)	1.20	1.20	2.40	2.40	3.60	2.20	4.40	4.40
Zinc (mg)	7.00	9.50	16.50	16.50	24.75	16.75	33.50	33.50
Vitamin A (µg)	600.00	700.00	1300.00	1300.00	1950.00	1300.00	2600.00	2600.00
Thiamin (mg)	0.80	1.00	1.80	1.70	2.60	1.82	3.63	3.63
Riboflavin (mg)	1.10	1.30	2.40	2.40	3.60	2.33	4.67	4.67
Niacin (mg)	13.00	17.00	30.00	28.00	43.00	29.83	59.67	59.67
Vitamin B6 (mg)	1.20	1.40	2.60	2.60	3.90	2.60	5.20	5.20
Vitamin B12 (µg)	1.50	1.50	3.00	3.00	4.50	2.90	5.80	5.80
Folate (µg)	200.00	200.00	400.00	400.00	600.00	400.00	800.00	800.00
Vitamin C (mg)	40.00	40.00	80.00	80.00	120.00	78.33	156.67	156.67
Iodine (µg)	140.00	140.00	280.00	280.00	420.00	276.67	553.33	553.33
Selenium (µg)	60.00	75.00	135.00	135.00	202.50	126.67	253.33	253.33
Sugar (g)	30.00	30.00	60.00	60.00	90.00	60.00	120.00	120.00
Fat (g)*	59.13	87.92	147.05	135.72	209.25	146.75	293.50	293.50
Saturated Fat (g)*	18.58	27.63	46.21	42.66	65.77	45.92	91.84	91.84
Fibre (g)	18.50	18.50	37.00	37.00	55.50	36.07	72.13	72.13

Notes: Based on the DRVs of Chalmers and Revoredo-Giha (2018)

Incomplete demand system Marshallian price elasticities

Table 12 Females aged 19 to 50 price elasticities

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16
Group 1	-1.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.15	0.00	0.00	0.00	0.00	0.73	0.00	0.00
Group 2	0.00	-0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 3	0.00	0.00	-0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 4	0.00	0.00	0.00	-1.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.40	0.00	0.00	0.00	0.00
Group 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 7	0.00	0.00	0.00	0.00	0.00	0.00	-1.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 9	-0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.96	0.00	0.00	0.00	0.00	0.00	0.00
Group 11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 12	0.00	0.00	0.00	-0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.01	0.00	0.00	0.00	0.00
Group 13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.11	0.00	0.00	0.00
Group 14	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.26	0.00	0.00
Group 15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.45	0.00
Group 16	0.28	-0.02	-0.20	-0.18	-0.69	-0.53	0.27	0.29	-0.46	-0.17	0.31	0.67	0.50	-0.43	0.53	-1.04

Notes: “0” indicates non-statistically significant price elasticity

Table 13 Males aged 19 to 50 price elasticities

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16
Group 1	-1.40	0.00	0.62	0.44	0.00	0.00	0.00	0.00	-1.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 2	0.00	-0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 3	0.22	0.00	-0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 4	0.53	0.00	0.00	-1.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.53	0.00	0.00	0.00	0.00
Group 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 6	0.00	0.00	0.00	0.00	0.00	-0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 7	0.00	0.00	0.00	0.00	0.00	0.00	-1.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 9	-0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.31	0.00	0.00	0.00	0.00	0.00	0.00
Group 11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 12	0.00	0.00	0.00	-0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.83	0.00	0.00	0.00	0.00
Group 13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.04	0.00	0.00	0.00
Group 14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.25	0.00	0.00
Group 15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.45	0.00
Group 16	-0.05	0.02	-0.29	-0.12	0.51	-0.96	0.21	0.28	-0.69	-0.65	0.65	0.87	0.49	-0.41	0.59	-1.03

Notes: "0" indicates non-statistically significant price elasticity

Table 14 Three adult household price elasticities

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16
Group 1	-0.73	-1.37	0.00	0.00	0.00	-1.49	0.00	-1.24	-2.52	0.00	0.00	0.00	0.00	0.00	0.55	0.00
Group 2	-0.38	-0.70	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	-0.09	0.00	0.00	0.00
Group 3	0.00	0.00	-1.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 4	0.00	0.00	0.00	-0.79	0.00	0.00	0.00	0.72	0.00	0.00	0.00	0.00	-0.15	0.00	0.00	0.00
Group 5	0.00	0.00	0.00	0.00	-1.08	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 6	-0.31	0.00	0.00	0.00	0.00	-1.29	0.16	0.00	0.00	-0.31	0.00	0.00	0.00	0.00	0.00	0.00
Group 7	0.00	0.77	0.00	0.00	1.12	1.30	-0.68	0.79	1.69	0.00	-2.22	0.00	-0.28	0.00	0.00	-0.01
Group 8	-0.53	0.00	0.00	0.53	0.00	0.00	0.21	-1.55	0.00	0.00	2.82	0.41	0.00	0.00	0.00	0.00
Group 9	-0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 10	0.00	0.00	0.00	0.00	0.00	-0.80	0.00	0.00	0.00	-1.07	0.00	-0.26	0.00	0.00	0.00	0.00
Group 11	0.00	0.00	0.00	0.00	0.00	0.00	-0.16	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.00	-0.41	0.00	-1.44	0.00	0.00	0.00	0.00
Group 13	0.54	-0.72	0.00	0.00	0.00	0.00	-0.44	0.00	0.00	0.00	0.00	0.00	-0.69	0.00	0.00	0.00
Group 14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.33	0.00	0.00
Group 15	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.34	0.00
Group 16	1.30	0.92	-0.46	0.26	0.30	1.23	0.02	0.50	1.88	0.38	-0.74	-0.19	0.28	1.06	-0.30	-1.03

Notes: “0” indicates non-statistically significant price elasticity

Table 15 One Adult Child price elasticities

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16
Group 1	-2.12	0.00	-0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.89	0.00	0.00
Group 2	0.00	-1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	-0.20	0.00
Group 3	0.00	0.00	-0.71	-0.42	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00
Group 4	0.00	0.00	-0.47	-1.11	0.00	0.00	0.00	0.00	-0.94	0.00	0.00	0.24	0.00	0.00	0.34	0.00
Group 5	0.00	0.00	0.00	0.00	-1.04	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 6	0.00	0.00	0.00	0.00	0.00	-1.83	0.00	0.00	0.00	0.00	0.00	-0.17	0.00	0.00	0.00	0.00
Group 7	0.00	0.00	0.00	0.00	0.00	0.00	-1.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.04	0.00	0.00	0.99	0.00	0.00	0.00	0.00	0.00
Group 9	0.00	0.00	0.00	-0.20	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00
Group 10	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	1.03	-0.77	0.00	0.00	0.00	0.00	0.00	0.00
Group 11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.48	0.12	0.00	0.00	0.26	0.00
Group 12	0.56	0.49	0.00	0.72	0.00	-1.31	0.00	0.00	0.00	0.00	1.20	-1.41	0.28	0.00	0.00	0.00
Group 13	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.24	-1.15	0.00	0.00	0.00
Group 14	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.11	0.00	0.00
Group 15	0.00	-0.41	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	-1.42	0.00
Group 16	1.27	0.92	0.81	1.42	0.01	2.32	1.94	0.37	0.54	0.31	1.36	0.62	0.28	-0.08	0.45	-1.06

Conditional Marshallian price elasticities

Demand Groups

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Beef	Lamb	Pork	Egg based products	Chicken	Turkey and Other poultry	Processed meat

Table 16 Conditional Marshallian Price Elasticities Female 19 to 50

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Group 1	0.00	0.00	0.00	-0.07	0.00	0.00	0.00
Group 2	0.00	0.00	0.00	-0.03	0.00	0.00	0.00
Group 3	0.00	0.00	-0.84	-0.06	0.00	0.00	0.00
Group 4	0.00	0.00	0.00	-0.65	0.00	0.00	-0.44
Group 5	0.00	0.00	0.00	-0.09	-0.53	-0.96	0.00
Group 6	0.00	0.00	0.00	0.00	-0.25	0.00	0.00
Group 7	0.00	0.54	0.00	-0.39	0.00	0.63	0.00

Notes: “0” indicates non-statistically significant price elasticity

Table 17 Conditional Marshallian Price Elasticities Male 19 to 50

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Group 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 2	0.00	-3.66	0.00	-0.02	0.00	0.00	0.00
Group 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 4	0.00	0.00	0.00	-0.59	0.00	0.00	-0.46
Group 5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Group 7	0.00	0.00	0.00	-0.37	-0.26	0.42	0.00

Notes: “0” indicates non-statistically significant price elasticity

Table 18 Conditional Marshallian Price Elasticities One Adult Child

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Group 1	-0.51	0.00	0.00	-0.09	0.00	0.00	0.00
Group 2	0.00	0.00	0.00	-0.05	0.00	0.00	0.00
Group 3	0.00	0.00	0.00	-0.08	-0.19	0.00	0.00
Group 4	-0.34	0.00	-0.22	-0.36	-0.24	0.00	-0.36
Group 5	0.00	0.00	-0.34	-0.16	0.00	0.00	-0.30
Group 6	0.00	0.00	0.00	-0.03	0.00	0.00	0.00
Group 7	-0.30	0.59	-0.21	-0.36	-0.51	0.15	0.00

Notes: "0" indicates non-statistically significant price elasticity

Table 19 Conditional Marshallian Price Elasticities Three Adults

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Group 1	-0.862	1.530	0.000	-0.130	0.000	-0.382	0.000
Group 2	0.157	0.000	0.000	0.000	0.000	-0.269	0.000
Group 3	0.000	0.000	0.000	-0.177	-0.189	0.000	0.000
Group 4	-0.505	0.000	-0.346	-0.474	-0.354	0.000	0.000
Group 5	0.000	0.000	-0.246	-0.227	-0.352	0.000	0.000
Group 6	-0.224	-1.942	0.000	0.000	0.000	0.000	0.000
Group 7	0.312	0.195	-0.260	0.000	0.000	0.000	0.000

Notes: "0" indicates non-statistically significant price elasticity

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