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Assessing the Affordability of Nutrient-Adequate Diets

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Abstract

The affordability of nutritious diets is increasingly used as a metric of how well a food system provides access to nutritious diets for all. Recent work on least-cost diets has focused on individuals, while most food and anti-poverty programs and policies target the household level. Members within households have differing nutritional needs, presenting the methodological question: how should the cost of nutritious diets be estimated at the household level? This study develops bounds on the cost, affordability, and seasonal variation of least-cost diets for whole households, illustrated with the example of Malawi. When intrahousehold sharing is not possible to observe, the bounded approach provides insights into the range of the cost and affordability, and the extent to which the cost may vary seasonally. The results reveal that when meals are shared, ignoring demographic diversity within households greatly underestimates the affordability of adequate diets.

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1. Introduction

An important criterion in assessing the performance of national and global food systems is the extent to which markets can provide access to nutritious diets for all. Several recent studies have analyzed the cost and affordability of least-cost diets meeting nutrient adequacy using retail market prices. In doing so, they typically calculate the diet cost for a single individual, most often a woman of reproductive age at a particular place and point in time. Different individual nutrient intake criteria have been used, including minimum scientific nutrient requirements for optimal growth and long-term health (Bai et al. 2021; Masters et al. 2018; Institute of Medicine of the National Academies 2006; Herforth et al. 2020); food-based dietary guidelines (Raghunathan, Headey and Herforth 2021; Mahrt et al. 2019; Dizon, Herforth and Wang 2019; Herforth et al. 2020); or the sustainable diet recommendations of the EAT-Lancet commission (Hirvonen et al. 2019; Willett et al. 2019).

However, the least-cost basket of foods that would meet a woman's needs does not contain the same items or proportions that would meet the needs of growing children, the elderly, teenage boys, adult men, or breastfeeding mothers. Evaluating access to nutritious diets at the household level, to which most food and agricultural policies are targeted, requires considering the biological nutrient needs of all sub-population groups, as well as household compositions and meal sharing norms. Further, many of the nutrient-dense foods required for adequate diets are only seasonally available and perishable. Since all foods contain many different nutrients, a nutritionally adequate diet can be comprised of multiple combinations of items. Foods in the same food group are especially close nutritional substitutes with similar nutrient compositions (Arimond et al. 2010; Fiedler and Lividini 2017). Substitution among foods could potentially moderate seasonal fluctuation in the availability and cost of an adequate diet relative to the seasonal fluctuations in the availability and costs of individual foods and help establish a lower bound on seasonality. It is an open empirical question, however, whether such substitution is possible or even sufficient to ensure households' access to nutritious diets throughout the year.

Linking micro-level household demographic and food consumption data from nationally representative household surveys with sub-national monthly food prices and local food composition data, this study asks whether markets across Malawi's rural districts can supply diets meeting scientifically established nutrient requirements for all household members at an affordable cost throughout the year. Two possible ways to estimate the minimum cost for the whole household are considered, which could essentially be seen as establishing a lower and upper cost bound. It could be done by 1) summation of the cost of individually optimized diets across all household members (henceforth "individualized diets"); or 2) optimization for the combined nutrient needs of everyone in the household, accounting for the nutrient needs of the neediest member given the total energy intake needed by each member (henceforth "shared diets" or "household sharing"). While the former approach essentially assumes perfect intrahousehold targeting of individual foods according to individual nutrient needs, the latter assumes that meals are fully shared with individual quantities proportional to energy needs (Schneider et al. 2021).

If the only consideration were market prices for each food item, the lowest-cost method for a family to secure a nutritionally adequate diet would be for each person to eat a tailored diet meeting their own minimum needs and without exceeding the upper limits for the subset of essential nutrients where excess consumption causes illness (toxicity). Costing individual diets for each person in a household and adding them up over all members therefore provides a lower bound on the cost of an adequate diet for the entire family. Preparing separate meals for each individual, however, is impractical, time consuming, and cumbersome, which may help explain why households share meals in practice. When sharing, diets would need to be sufficiently nutrient-dense to meet all nutrient needs of all individuals; they would need to be equally or more nutrient-dense than individualized diets and have lower upper limits on certain nutrients (e.g., copper, zinc) to ensure that the most sensitive member would not exceed their limit (Schneider et al. 2021).

At the extreme, perfect sharing requires a food basket dense enough in each nutrient to provide a sufficient amount such that every member will have their nutrient requirements satisfied from the total quantity of the family meal meeting their energy need (Schneider et al. 2021). Costing this shared diet provides an upper bound on the cost of adequate diets for the family. It must include more nutrient dense foods (i.e., have higher total nutrient density) to meet that shared set of needs than the summation of individuals procuring a diet meeting only their individual requirements, hence being higher in cost. But it also must optimize the combination of foods to meet nutrient density constraints with smaller ranges between the minimum requirement and upper limit, hence potentially becoming less feasible.

The central contributions of this paper are twofold. The first is methodological. It extends the least-cost diets framework from individuals to households and demonstrates that widely available nationally representative household survey data on household composition and food consumption can be linked with frequently collected sub-national monthly food prices and local food composition data to estimate a bounded range of the cost of nutrient adequate diets that meet the needs of all household members. This enables policy makers to assess the extent to which markets can supply their population with an adequate diet at an affordable cost. The range between the bounds offers a more useful policy indicator than either bound on its own, as both individually optimized as well as fully shared meals (the assumptions underpinning the calculations of the lower and upper bound respectively) are unlikely to fully capture household eating habits. Practice most likely lies somewhere in between. A fair degree of proportional sharing of all meal ingredients across all household members according to caloric needs has been observed in many places (Berti 2012). But some targeting of individual foods also undoubtedly occurs for reasons of their nutrient content considering (perceived) differential nutrient requirements across members as well as reasons of individual preferences and/or biases.

To be sure, in actual food choice other factors beyond cost are likely at play as well. Time or fuel use, difficulty of meal preparation, tastes and preferences for each individual, as well as intra-household allocation all can influence food choices, household resource allocation, and dietary intakes. These are abstracted from in this analysis, and as such the normative least-cost diets are themselves a lower bound on actual costs, computed as a metric of food system performance. Affordability thereof is thus a necessary but not sufficient condition for individuals and households to achieve nutrient adequacy.

Second, by drawing on monthly price data, the paper provides a practical way to assess the extent to which seasonality in individual food availability and prices affects the affordability of nutrient adequate diets. Seasonality in food availability and prices in rural agricultural settings is well known and much evidence has shown it to be particularly pronounced in Malawi (Gilbert, Kaminski and Christiaensen 2017; Devereux, Sabates-Wheeler and Longhurst 2011; Chirwa and Chinsinga 2015; Sassi 2012; Ellis and Manda 2012). Two related studies have examined the seasonality in total diet cost for adult women in Malawi and India (Bai, Naumova and Masters 2020; Raghunathan et al. 2021), while another used seasonal data to develop recommended diets for low-income consumers in several places (Chastre et al. 2009). We add to this growing literature with analysis at the household level.

We investigate and compare the two methods for estimating nutrient adequate diets using the case of rural Malawi and discuss the policy implications of methodological choice and empirical results. The case of Malawi is of particular interest. Although Malawi has made substantial progress reducing stunting in the last decade, diets remain of poor quality largely dominated by maize and other staples, and with insufficient variety and nutrient-dense foods, micronutrient deficiencies persist (Pauw, Verduzco-Gallo and Ecker 2018; National Statistical Office (NSO) Community Health Sciences Unit (CHSU) [Malawi], Centers for Disease Control and Prevention (CDC) and Emory University 2017; Gilbert, Benson and Ecker 2019; Schneider 2021a). Malawi further presents an interesting example because of the social norm of shared plate eating, a pronounced form of meal sharing. But a methodology for establishing a range of least-cost diets at the household level is relevant throughout the world, given how many food and anti-poverty programs target households and the widespread practice of eating common meals (i.e., "family style") across cultures (Hjertholm et al. 2019; Gelli et al. 2020; Hjertholm et al. 2018).

The remainder of this paper proceeds as follows. Section 2 presents the conceptual framework describing the two approaches to estimating household diet costs. Section 3 presents the data sources as well as key background features of Malawi's food system. Section 4 explains the methods used to define the nutrient requirements and calculate diet costs; it reviews how the extent of seasonality in diet costs and food group prices will be evaluated and introduces the criteria to assess affordability. Section 5 discusses the findings, followed by section 6 which concludes.

2. Conceptual Framework

To identify the cost of purchasing a nutrient-adequate diet for all members of a family, one must consider who the members are in terms of demographic characteristics, their individual nutrient needs, and how the family shares food among its members. To motivate the bounds we develop, consider a family of five members (the median household size in rural Malawi). This family has a mother (26 years old), a father (30 years old), and three children: a daughter of 29 months, and two sons, 5 and 7 years old. Consider the simplified case with only two nutrients: energy and iron. Iron is important for red blood cells to transport oxygen around the body. This is needed for energy metabolism and plays a role in immune function as well; menstruating women's need for iron also incorporates the amount lost each month. The mother requires 2,043 kcal per day and a minimum of 8.1 mg of iron per day, not to exceed 45 mg per day (Schneider and Herforth 2020; Institute of Medicine of the National Academies 2006). When she satisfies her own nutrient requirements alone, she would find the combination of foods that meets her energy need and contains between 8.1 and 45 mg of iron at the lowest total cost.

To develop the nutrient requirement for a shared family diet, consider the mother's needs in terms of nutrient density, the quantity of iron per unit of energy. Her iron density need is 4 mg per 1,000 kcal. But the rest of her family members need only between 2.1 and 2.7 mg per 1,000 kcal. Her iron density need then defines the nutrient density of iron in the shared family diet because she has the greatest need for iron relative to her need for energy, and more iron rich foods will need to be part of the diet. Those with lower iron density needs eating the shared meal will consume more than their minimum need, so we also ensure no member would exceed their upper tolerance by similarly defining the upper limit in terms of nutrient density and setting the shared limit at the most restrictive tolerance. The defining member for each nutrient can differ.

The lower bound on the household diet cost ("individualized diets") corresponds to the case where the combination of foods eaten by each member meets their own minimum requirements and does not exceed their individual upper limits at the lowest aggregate cost. The upper bound ("sharing") corresponds to the case where the shared family diet can meet total energy needs for the whole family and is dense enough in each nutrient so that whichever member has the greatest requirement for that nutrient per unit of energy will get enough when eating sufficient energy from the family meal to meet their calorie needs. The household upper limit is defined such that the most sensitive member will not consume more than their upper limit when eating sufficient energy from the family meal to meet their calorie needs. The total household energy budget is identical under both scenarios so total nutrient quantities are calculated as the level of nutrient density required by the neediest person times the total household energy. For further detail and comparison of the average individual and shared nutrient requirements for the Malawian population, see Schneider et al. (2021).

The method of defining shared nutrient requirements for a group of people who have different individual needs based on the nutrient density of the present individuals has its origins in the scientific nutrient requirements literature (Beaton 1995; Institute of Medicine 2000). Ethically, it follows Rawls' *maximin* principle, i.e., to maximize the welfare of the worst-off group in society, or extending to our case, to define the household diet that preferences the welfare of the nutritionally neediest member of the family (Ravallion 2016; Rawls 1971). Finally, the shared diet is most often the diet that meets *her* needs, so it is also a more gender equitable metric that can be used where intrahousehold allocation is not observed (Schneider et al. 2021).

The diet cost offers two evaluative functions: first, to identify those for whom the market does not provide access to an adequate diet, and second, to estimate the cost level in a given food system which can be monitored and compared across time and space and used for policy making. Both the shared and individual diet cost indicators could serve this purpose, establishing an upper and lower bound respectively. The analogy with the poverty literature is illustrative. Early on, poverty lines were set at the level of expenditures needed to meet minimal caloric needs given a culturally acceptable diet, augmented with a small mark up to allow for covering other basic needs such as clothing and housing (Ravallion 1996). The lines were set at the absolute minimum needed so that no one would dispute to consider someone earning less than this amount as poor, establishing a lower or extreme poverty line, and avoiding error of inclusion. Similarly, "individualized" least cost household diets, which maximize nutrient allocative efficiency within the household could be seen as establishing a lower bound on the affordability of an adequate diet. Households who cannot afford the lower bound ("individualized") diet cost cannot purchase a diet complete in all required nutrients for all members of the family, a form of definitive unaffordability.

Later on, when poverty started to decline globally, Pritchett (2006) turned the reasoning on its head by asking "what would be the amount of income below which societies might start considering people as poor," establishing an upper poverty line and avoiding error of exclusion (he set this upper poverty line at US$10/day, corresponding to the US poverty line). The "shared" least-cost diet could thus be seen as establishing an upper bound on affordability, ensuring that every household member meets their nutrient needs if some food sharing is practiced. It offers a metric above which nobody would reasonably dispute that the household's income is sufficient to meet every member's nutrient needs.

The intent with these scenarios is not to describe behavior, but to demonstrate how policy decisions can be made at the household level when intrahousehold resource allocation is unobserved yet a combination of members with different needs are present and some degree of sharing common meals is likely. In the Malawi context, shared plate eating is the dominant social norm, so it provides a particularly interesting case to ask the question about how the cost of the diet should be measured at the household level.

3. Data

Food availability and food prices in Malawi are typically described as having two seasons, lean (Sept-Feb) and post-harvest (Mar-Aug), with January typically identified as the height of the lean season, when food prices are highest (Chikhungu and Madise 2014; Chirwa, Dorward and Vigner 2012). These seasons correspond to the maize harvest, the crop that plays an outsized role in Malawi's food policy as well as in consumers' diets, and whose prices have been most extensively studied (Sibande, Bailey and Davidova 2017; Gilbert et al. 2017; Schneider et al. 2021; Pauw et al. 2018). Seasonality in food item availability and price may inhibit consumers' physical and economic access to nutritious diets year-round. However, several nutrient-dense foods are also harvested during the rains of the lean season (Chikhungu and Madise 2014; Gelli et al. 2020; Gilbert et al. 2017). Since nutritionally adequate whole diets require a combination of foods whose seasonality patterns may differ in periodicity, and where maize will play a smaller role in the adequate diet than it does in current (largely inadequate) diets, it is not clear *a priori* whether the cost of whole diets will follow similar seasonal trends identified in studies of single food items or groups.

Combining the 2013 and 2016/17 nationally representative Integrated Household Panel Surveys (IHPS) from Malawi with newly compiled local food composition data for Malawi, human nutrient requirements, and monthly market food prices across 25 markets, we are able to calculate monthly lower and upper bound least-cost nutrient-adequate diets for all households from January 2013 to July 2017. The household data provide the necessary information to identify individual nutrient needs (age and sex for all household members, occupational data), geographic identifiers to match households to markets, and all requisite expenditure information to calculate annualized household food spending and total expenditure following the methods used for poverty calculation in Malawi (National Statistical Office (NSO) [Malawi] and World Bank Poverty and Equity Global Practice 2018; National Statistical Office (NSO) [Malawi] 2017).

We use the sample of rural households from the IHPS since the food price data set to which we have been given access only covers markets in the rural districts of Malawi. The National Statistical Office (NSO) does collect prices in Malawi's four urban centers with locations stratified by the general income level of the clientele served but does not share these data. Further, although there is an earlier round of the IHPS data, the price data only contain more nutrient dense food items beginning in January 2013. Since the surveys are representative of both urban and rural strata nationwide, our results can be considered representative of the rural population.

We use monthly prices for 51 food items collected between January 2013 and July 2017 by the NSO in 29 markets across Malawi. We identified households in 25 of the 29 markets for which price data are collected (Supplementary Table A). The markets were purposively selected and are in the main district or trading towns in the rural districts outside of Malawi's four largest urban areas. These are nonetheless still relatively small. For context, Malawi's urbanization status is well below the Sub-Saharan African (SSA) overall level. In 2020, less than 6% of the population lived in cities with more than one million people, compared to 15% in SSA overall, and only 17% of Malawians lived in urban areas at all, compared to 41% in all of SSA (World Bank 2021). The consumer food price index computed with these price data is considered representative of rural Malawi. Food items selected for price monitoring were revised at the end of 2012 based on nationally representative household survey data collected in 2010 to include any item accounting for more than 0.02% of total household expenditure (Kaiyatsa, Schneider and Masters 2021). The list of food items whose prices are monitored includes foods from all food groups.

We match households to the market corresponding to their district of residence (or in a few cases of multiple markets per district, their sub-district market) (National Statistical Office (NSO) [Malawi] 2011; National Statistical Office (NSO) [Malawi] 2012; National Statistical Office (NSO) [Malawi] 2018). Our emphasis is on the market and its ability to provide access to nutritious diets, as a metric of food system performance. The prices observed in the market are for standardized items of a particular quality, so they are not directly comparable to unit costs reported by households. Unit costs reflect both quality and price, and therefore differences are not necessarily attributable to different price environments (Gibson 2016; Gibson and Kim 2018; Gibson 2013). The food price environment faced by households and their preferences are reflected in the numerator of the affordability analysis, namely the food and total expenditure calculated using reported unit costs and standard methodology to value own produced goods.[2]

[2] For the purpose of context, Supplementary Tables G-1 (by size of difference) and G-2 (by food group) show the comparisons for items that could be compared at the district level in the same month and year, showing differences of varying magnitude (some small in practical terms) and where the market prices are more often higher but not always.

Analysis at the market level provides a policy-relevant metric to assess food system performance, and our analysis offers the added value of ensuring that the assessment is relevant for all types of individuals, and in realistic household settings.

Table 1 presents the characteristics of the households, household expenditure, markets, foods, and nutrients included in our sample. To establish the context for our affordability results, the median household already spends three-quarters of its resources on food and lives just above the international poverty line threshold of $1.90 per person per day in 2011 purchasing power parity (PPP) dollars (World Bank 2021).

Table 1. Rural households and food markets in Malawi

	2013		2016/17		Overall	
	Mean	(SE)	Mean	(SE)	Mean	(SE)
Household size	4.76	(0.12)	4.98	(0.15)	4.90	(0.11)
Number of adults (>18)	2.32	(0.05)	2.52	(0.05)	2.44	(0.05)
Number of children (≤18)	3.51	(0.10)	3.52	(0.10)	3.51	(0.09)
Food items available per month per market†	39.83	(4.94)	39.47	(4.59)	39.71	(4.82)
Household Expenditure (2011 US$ PPP)	Median	(SE)	Median	(SE)	Median	(SE)
Annual Food Expenditure	2,588.47	(113.63)	2,292.84	(94.08)	2,429.85	(91.74)
Per day (household)	7.09	(0.31)	6.28	(0.26)	6.66	(0.25)
Per day per capita	1.60	(0.10)	1.42	(0.06)	1.47	(0.05)
Annual Total Expenditure	3,460.88	(155.13)	3,319.20	(149.13)	3,354.48	(139.83)
Per day (household)	9.48	(0.43)	9.09	(0.41)	9.19	(0.38)
Per day per capita	2.29	(0.14)	1.98	(0.09)	2.10	(0.09)
Food Spending Share of Total Expenditures	0.76	(0.01)	0.73	(0.01)	0.74	(0.00)
Observations †		N		N		N
Households*		1,424		1,693		3,117
Individuals‡		6,995		7,907		14,902
Markets⸸		25		25		25
Food items		51		51		51
Nutrients		22		22		22

Population statistics corrected using sampling weights.
†Standard deviation in parentheses.
† Excluded: 260 infants under 6 months who are assumed to be exclusively breastfeeding, 4 rural households unable to be matched to a market.
* 1,081 are unique households observed at both time points, however the composition of those households changes in January 2016, so these are best thought of as two consecutive, but separate panels of households and individuals.
‡ Excludes individuals who reported eating no meals in the household in the prior week, allowing diet cost to be compared to reported food consumption expenditure.
⸸ List of markets and districts provided in Supplementary Table A.

We calculate the food composition for all the foods available in the markets using the recently compiled Malawi Food Composition Table (MAFOODS 2019) supplemented by the USDA National Nutrient Database for Standard Reference where necessary (USDA 2018). Specific information regarding food item composition matching records available in the replication data files and we also point readers to the MAFOODS data tables (MAFOODS 2019). USDA records were used for edible portions. Where the item is not contained in the Malawi tables, USDA data used minimally and only where the item-nutrient was deemed unlikely to be affected by location-specific factors. All items are converted to kilograms using conversion factors provided by the NSO.[3] To perform seasonality analysis at the food group level, we also classify foods by food groups using a combination of food groups used for household, child, and women's dietary diversity indicators (WHO 2008; FAO and FHI 360 2016; Kennedy, Ballard and Dop 2010; Ministry of Health (MOH) [Malawi] 2017).

Supplementary Tables B and C present the food item sources of each nutrient and the food items within each food group. As these tables illustrate, there are multiple food sources for all essential nutrients, and all food items contain multiple nutrients. This means that there are many food combinations that could meet all the minimum requirements. However, there might not be any solution to the linear optimization if there is no combination of foods that could meet the minimum requirements while also staying under all the upper limits and including the exact amount of energy required. This is the intuition behind the lack of solution to the least-cost diet problem. How the nutrient requirements drive the results is especially evident when the foods available in one market and month can meet the individual requirements (where the ranges

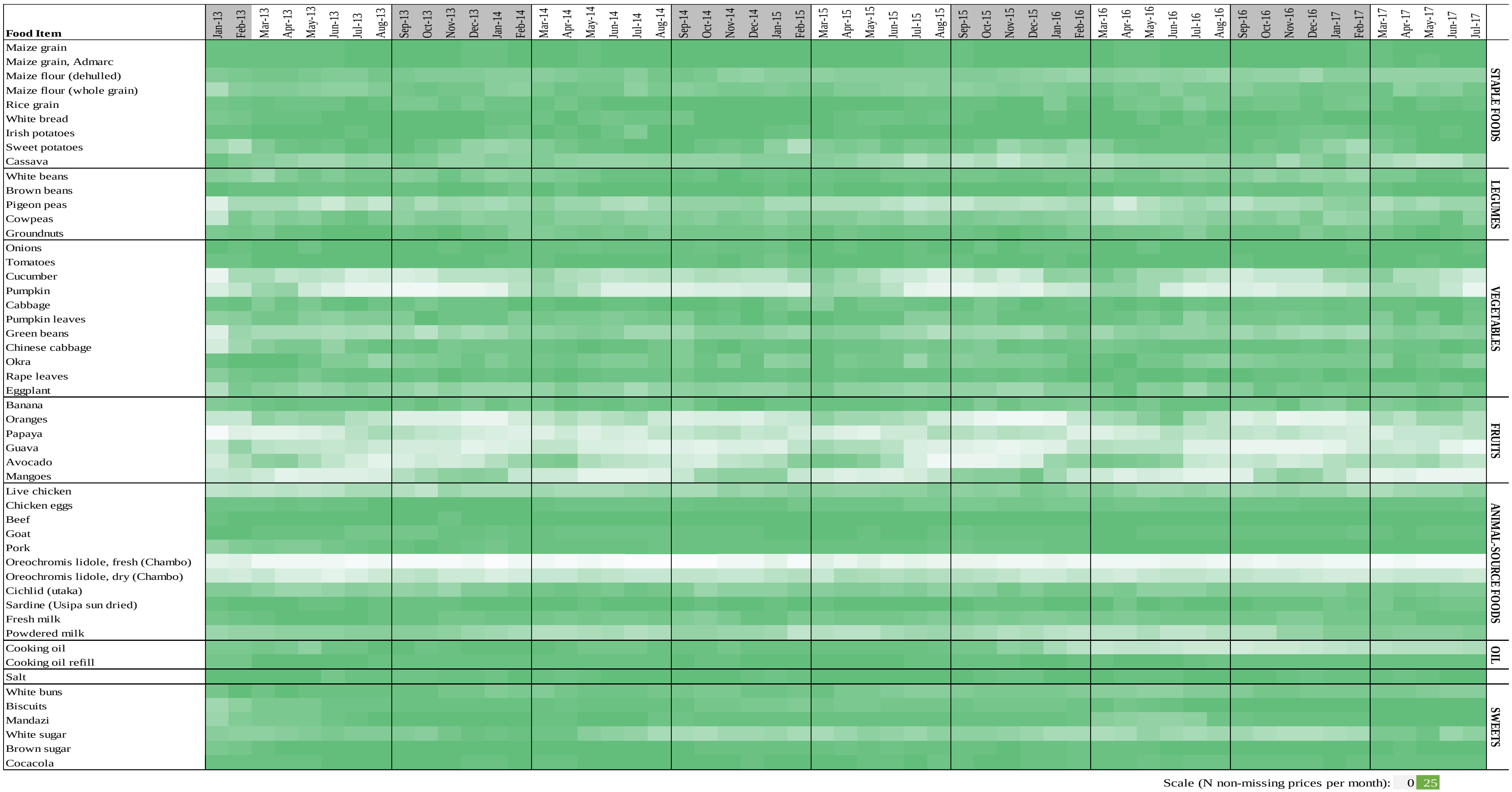
[3] Provided to the research team directly, available upon request.

between minimum needs and upper limits are larger), but no combination of foods can satisfy the nutrient requirements when the ranges narrow to allow for household sharing (Schneider et al. 2021).

We note that the least cost diets can only select from the menu of 51 items included in the price data set and where there is a price observation. To address potential concerns that missing data in the food prices (a common feature of consumer price index data sets) could bias the results, we present Figure 1 showing the pattern of price records. The darkest green cells indicate a price was observed for that item in all markets. The figure clearly shows that the most common items with missing prices are items where seasonal lack of availability makes sense, namely fruits and vegetables. It shows that maize is available in all markets in all months in at least one form, and that in all months there are some foods available in every food group.

Several items often missing have another clear substitute and no food group has all items missing at the same time. For example, there are two types of cooking oil whose price is monitored. From late-2015 onwards, some markets appear to have only a refilled bottle option, but cooking oil is nonetheless present. Other items may never be present by location, such as the fresh *chambo* fish (tilapia), but other types of fish (cichlid, sardines, sometimes dried *chambo*) that are nutritional substitutes do have price observations in most markets and months.

Figure 1. Frequency of observed prices by item, month, season, and food group



Gray dates indicate identified lean season.

Notes: The darker the cell color the more markets in which the item is available; lighter cells indicate more markets where the item is unavailable (missing).

Chambo is a white fish, also known as tilapia. Admarc maize grain indicates maize available from the parastatal Agricultural Development and Marketing Corporation.

In related research, key informants in each of these same markets were surveyed to test the hypothesis that missing prices are related to seasonal availability, and to estimate the bias measurement error in missing prices would have on a least-cost diet estimate. The nutrient-adequate diet was estimated in that study for the case of a woman of reproductive age (Kaiyatsa et al. 2021). Comparing the 2013 – 2017 price data to the survey results, the authors found that 79.1% of the price records were concordant with the reported availability (of which only 6.2% were missing and the missingness was explained by seasonality and the rest had a price record for the markets and months where they were reported to be usually available). Seventeen percent of the price observations were missing when reported available ("discordant missing") and the remainder (3.9%) had a price observation when reported usually unavailable. The discordant missing prices were not meaningfully explained by food item, time, market, or their interactions. While statistically significant, food item and month only explained a fraction of a percent of the discordant missing prices, and therefore measurement error is a likely explanation. In markets with higher-than-average discordant missing prices (pooling all items and months), the authors estimated the least-cost diet was likely biased upwards by approximately 6.4% (Kaiyatsa et al. 2021). These results lend confidence that even where missing prices are due to measurement error, the magnitude of bias introduced into the cost estimate is reasonably small.

We also remind the reader that as a data envelopment technique, missing or erroneous data would only affect the linear optimization results if that item *would have otherwise been selected into the diet* were the true data value known. Additionally, where we find solutions to the least-cost diets under the individualized scenario but not under the shared scenario, the difference is due to the nutrient requirement constraints since the input data (prices and nutrient composition) are the same used to solve both scenarios' least-cost diets. Further, no single item is so optimal in nutrient density for all individuals and households that its missing price would likely be binding in all cases.

4. Methodological considerations

Individual Nutrient Requirements

Biological nutrient requirements for individuals by age, sex, maternity status, and physical activity level have been defined by the Institute of Medicine in the US and are known as the *Dietary Reference Intakes* (DRIs) (Institute of Medicine of the National Academies 2006). These requirements dictate lower and upper bounds for all the essential macronutrients, vitamins, and minerals. Essential nutrients are those that must be consumed through food because the body cannot make them at all or cannot do so in large enough amounts for all the functions they are needed to perform (e.g., metabolism, growth, immunity, etc.). The nutrients we include are energy, macronutrients (carbohydrates, protein, fat), and all the micronutrients (vitamins and minerals) where there is sufficient scientific evidence to set an average minimum requirement at the population level (vitamins A, C, E, B6, and B12, thiamin, riboflavin, niacin, folate, calcium, copper, iron, magnesium, phosphorus, selenium, zinc and sodium). Twelve nutrients have an upper and lower bound, seven have only a lower bound and no upper limit, and retinol has only an upper bound (National Academies of Sciences Engineering and Medicine 2019; Institute of Medicine of the National Academies 2006; Institute of Medicine of the National Academies 2011).

We calculate energy needs using equations specified in the DRIs taking median weights and heights from the WHO growth charts, and assuming an active level of physical activity for most individuals and very active for men 14-59 if reporting a physically demanding occupation (WHO Multicentre Growth Reference Study Group 2006; Schneider and Herforth 2020). We assume breastfeeding practices in line with WHO guidelines and consistent with observed median breastfeeding of 23 months in Malawi, assuming exclusive breastfeeding to six months, and continued breastfeeding to two years. During continued breastfeeding, only some nutrient requirements need to be met with food sources, and all mothers of children under two are assumed to be breastfeeding (Dewey 2005; WHO 2008; National Statistical Office (NSO) Community Health Sciences Unit (CHSU) [Malawi] et al. 2017). We refer to these scientifically defined nutrient requirements as the "individual" requirements, and they are the requirements for which the lower bound (individualized diets) least-cost diet problem is solved.

Household Nutrient Requirements

To define the shared household nutrient requirement, we consider the nutrient density needs and upper limits for all members aged four and above. To define the minimum amount for each nutrient in the shared diet, we identify the largest nutrient density required by any member. Similarly, for the upper limits we use the most restrictive (minimum) upper tolerance in terms of nutrient density to ensure that the shared diet would not exceed any member's limits for any nutrient. We compute the total quantity of each nutrient in the household diet as the sum of all members' energy needs times the defining nutrient density, to get the total quantity of each nutrient.

We then add in the needs of children ages six months through three years on top, such that their needs are included in the total household need, but that they do not define the nutrient density of the shared diet (i.e., do not define the nutrient density of the diet consumed by other household members). Children under two are likely to, and should, be fed a separate diet. Three-year-old children are a unique case where they often eat from the family meal but require much higher nutrient density for several nutrients such that a solution to the household shared diet becomes infeasible in most cases where they are present. Thus, we do not allow this age group to define the household level of nutrient density in the shared diets.

Formally, we define the shared nutrient requirements for each household (h) in terms of every individual (i) household member's requirement for each nutrient (j) given their energy needs (E), using the most restrictive of their nutrient density requirements for each upper and lower bound:

$$Lower_{hj} = \sum_i E_i * max_i \{MinimumNeed_{j,i}/E_i\},\ j = 1, \dots, 19 \quad (1)$$

$$Upper_{hj} = \sum_i E_i * min_i \{MaximumTolerance_{j,i}/E_i\},\ j = 1, \dots, 13 \quad (2)$$

$$HHE_h = \sum_i E_i \quad (3)$$

Equations (1-3) are used for shared meals among all household members aged four and above. To this we then add individual meals for children six months through three years of age, meeting their individual requirements for energy and each nutrient, to arrive at the household total for which the least cost diet problem is solved. More information on the nutrient requirements, requirement tables, and comparison of the individual and shared nutrient requirements can be found in (Schneider et al. 2021) and Schneider (2021).

Cost of Nutrient Adequacy (CoNA) Index Construction

Using linear programming, we attempt to identify a diet that meets all the specified nutrient requirements at the lowest total cost. For the individual indicators, upper and lower nutrient constraints correspond to the individual nutrient requirement as scientifically defined, and the household indicators correspond to the shared requirement defined per above. Formally, the linear optimization model (solved using the R package "lpSolve" by Buttrey (2005) minimizes total cost over all foods (f) within upper and lower bounds for all nutrients (j) and meets the specified energy budget (E). Adding data on price (p_f) for each food item (f) and its nutrient contents (a_{fj}) yields:

$$CoNA: minimize\ C = \sum_f p_f * q_f \quad (4)$$

Subject to:

$$\sum_i a_{fj} * q_f \geq Lower_j\ ,\ \ j = 1, \ldots, 19$$

$$\sum_i a_{fj} * q_f \leq Upper_j,\ \ j = 1, \ldots, 13$$

$$\sum_i a_{fe} * q_f = E$$

$$q_1 \geq 0, q_2 \geq 0, \ldots\ q_i \geq 0, \text{for all foods } i = 1, \ldots 51$$

Equation (4) is solved for each individual (with individualized requirements) and household (with shared requirements, i.e., replacing $Lower_j$, $Upper_j$ and E by equations (1), (2) and (3) respectively) every month, using the foods and prices in the market of the household's district of residence. We compute least-cost diets at the monthly level based on the household composition observed at the two points in time the household was surveyed. Nutrient requirements corresponding to the observed demographics in 2013 are used to solve the diet cost problem from 2013 through 2015, and then the household composition and corresponding nutrient requirements observed in 2016/17 are used to solve the diet cost problem from January 2016 forward. We scale the nutrient requirements for any partial meal-taking in order to accurately draw comparisons with observed food spending which was collected for the previous seven days and therefore reflects the consumption of those who ate in the household in the last seven days (Fiedler and Mwangi 2016). For every household, 55 CoNA indices (36 observations from 2013-2015 and 19 observations from January 2016 to July 2017) are thus obtained, at both upper and lower bounds (based on shared and individualized diets, respectively).

We focus on two primary results from the linear modeling: feasibility of a solution and cost. We use the binary outcome of a solution or no solution to summarize the extent to which there is a feasible diet given the items for which prices are recorded and their known nutrient composition. Under the individualized diets scenario, we consider the household to have a least-cost diet solution only if there is a solution for all members. Where the market price list does not have an observation, it might reflect seasonal unavailability or an item that is never present in that market, or it could be measurement error as missing prices are common in agricultural price data even where items are known to be available (Kaiyatsa et al. 2021; Pauw et al. 2018).

Confidence that no solution to the least-cost diet problem mostly reflects realistic infeasibility to compile a diet that meets the specified nutrient requirements in that market and month rests on three observations. First, patterns observable in Figure 1 show the majority of unobserved prices in the data are for items that are perishable and thus reasonably understood to be only available during their production season. Further, they show that even when an item has no price observation, other items in the same food group (closest nutritional substitutes) do have observations. Second, where the price for a market food item is missing while the item was reported as usually available in the market (17% of all observed market/food item combinations in the detailed follow up study by Kaiyatsa et al. (2021)), and that the pattern of missing prices was not explained by the food item, time, or market. Third, the fact that individual diets are feasible in most markets and months provides further confidence. While each of these observations does not exclude the possibility of erroneously missing prices leading to an erroneous non-solution of the least cost diet problem, together they suggest that no-solutions of the least cost diet problem mostly correspond to realistic infeasibility in that market/month.

If the model can converge on a solution, we calculate the total cost of the diet multiplying the quantities of each food obtained through the linear programming results with the prevailing prices in that market and month. To compute the total household diet cost at the lower bound, we solve the linear programming for each individual and then add their diet costs together to get the household total. The cost under household sharing is solved as a single problem per household and month where the diet solution must meet the shared household nutrient requirements and total energy budget.

We convert all costs into 2011 US$ PPP, smoothing the annual conversion factors provided by the World Bank's International Comparison Project over our monthly time series using the Denton method (World Bank 2015; Denton 1971; International Monetary Fund 2018). We calculate monthly food and total expenditure based on one month of annualized expenditure calculated following Deaton and Zaidi (2002) and the method of poverty calculation in Malawi (National Statistical Office (NSO) [Malawi] and World Bank Poverty and Equity Global Practice

2018). We then proceed to study two aspects of these two least-cost indicators: their fluctuations within the year and their affordability.

Seasonality

Food availability and prices vary across and within years. However, since the linear programming model will substitute among foods given availability and prices, this does not necessarily carry over to the same extent to CoNA indices. Intra-annual fluctuations can be regular and stochastic. Here the focus is on regular intra-annual fluctuations, or seasonality, of the CoNA index. A standard indicator to measure seasonality is the seasonal gap, the ratio between the seasonal peak and trough. For food prices in low-income country settings characterized by one growing season per year, these are most commonly observed just before and just after the harvest respectively (Gilbert et al. 2017).

Linear detrended seasonal dummy and moving average deviation models are often used to estimate seasonality. They also have some limitations. The linear detrended seasonal dummy model suffers from the challenge of specifying the trend component; the assumption of trend stationarity (reversion to deterministic trend over time) is required by a linear model but not grounded in any theoretical basis. The moving average deviation method offers one way to address this challenge allowing for a variable trend, however it sacrifices a full year of data (six months at each end of the series) and is further complicated by the requirement that data are interpolated over any gaps. Furthermore, the calculation of the moving average introduces systematic variation in the error term that invalidates inference, though inference is not our pursuit in this particular application.

Trigonometric (also known as harmonic) regression models have been shown to address some of the limitations of the seasonal dummy and moving average deviation methods. They are parsimonious in the number of parameters to estimate and less prone to biased gap estimation, especially when the number of years from which to identify seasonal patterns is limited as is the case here (Ray et al. 2001; Kaminski, Christiaensen and Gilbert 2016; Bai et al. 2020; Kotu et al. 2019; Wassie, Kusakari and Sumimoto 2019). Gilbert et al. (2017) find the more parsimonious trigonometric method to be preferable for food price data. When applied to our least cost diet indicators, this translates into:

$$\Delta C_{hym} = \gamma + \alpha \Delta \cos\left(\frac{m\pi}{6}\right) + \beta \Delta \sin\left(\frac{m\pi}{6}\right) + \mu_{hym} \quad (5)$$

where *C* is the log diet cost observed, in nominal terms, for household (h) in year (y) and month (m). The cost in nominal terms is used since food expenditure comprises a large proportion of budget shares. Therefore, deflation factors (to domestic real or international PPP dollars) are sensitive to food prices and their use in seasonality analysis may understate the extent of seasonality (Gilbert et al. 2017). The seasonal factors can be computed as follows:

$$S_m = \lambda \cos\left(\frac{m\pi}{6} - \omega\right) \quad (6)$$

where $\lambda = \sqrt{\alpha^2 + \beta^2}$ and $\omega = \tan^{-1}(\frac{\alpha}{\beta})$

The disadvantage of the trigonometric specification is that it imposes vertical and horizontal symmetry to the seasonality pattern. It will perform poorly if the time series is not well represented by that functional form. It is possible that the diet cost may not follow a symmetrical pattern if the timing of price fluctuations for nutritionally comparable food items are spread over longer periods or throughout the whole year; there could then be multiple local maxima and minima. A stochastic trend seasonal dummy model allows for multiple fluctuations within the year (see Gilbert et al. (2017) for further discussion). The estimating equation is specified allowing for gaps of (k) months prior to the observation (a) in time *(*y,m) as follows:

$$\Delta_k C_{hym} = C_{hym} - C_{hy,m-k-1} = k\gamma + \sum_{a=1}^{k-1} \delta_{m-a}(s_{m-a}) + w_{hym} \tag{7}$$

Where *C* is again specified as the log cost in nominal terms. The seasonal differenced dummies are then defined as:

$$s_{m-a} = \begin{cases} 1 & a = m \\ -1 & k = 0 \\ -1-k & k > 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

And the seasonal factors are calculated by demeaning the coefficients. We run both models (5) – (6) and (7) – (8) and present model fit statistics.

Both models can allow for gaps in the data. In typical seasonality analysis of food prices, gaps are due to missing prices. In our case, gaps are the household-months with no solution to the linear programming problem given the foods and prices observed in the market. Where there are gaps the differences are calculated as the difference between a diet cost observation and the most recent preceding observation. An alternative way to think about no solution to the least-cost diet problem is that the diet has infinite cost.[4] We estimate the seasonality model first with these months recorded as missing, and then with costs for those months imputed as the highest cost observed over all markets and households in that same month and year. Repeating the seasonality analysis using these imputed data allows us to estimate a lower bound on the magnitude of the true seasonality in the diet cost.

[4] This assumes that a no-solution represents infeasibility of a solution in the market (and not because of erroneously missing market prices), which we have shown above to be realistic in the context of our data.

To explore the role of least cost diet availability in our least cost diet seasonality estimates further, we compare the seasonality in cost with the prevalence of a feasible diet, conditional on the month and by scenario (individualized and shared least cost diets), modeled with a linear probability model as follows:

$$A_{hym} = \gamma + month_m + market_l + \mu_{hym} \quad (9)$$

Where (A) is a binary indicator of diet feasibility for household (h) in time (y,m), and the probability of feasibility is estimated for each scenario with indicator variables for each calendar month (m) and market location (l). The seasonal factors on feasibility are calculated following equation (8) by demeaning the coefficients.

Lastly, we model the seasonality in underlying food prices to see to what extent substitution mitigates seasonality in prices. We repeat equations (5) and (7) replacing *C* with *P*, the logged price per kilogram edible portion. We calculate the difference in logged price for each food item (in nominal terms), allowing gaps where no price was observed. We then regress the difference in price on the monthly indicator variables, pooling items in each food group. Food groups classify items into nutritionally relevant categories, those that might be substitutes in the linear programming. Greater seasonality would be expected with short harvest periods, perishability, and groups with few items. Since much research has been done on the seasonality in maize prices (in Malawi) and the importance of maize in Malawian diets, we present the same seasonality analysis for maize prices, separating maize grain in regular retail markets and maize grain sold by the parastatal Agricultural Development and Marketing Corporation (Admarc).

Affordability

To assess affordability, we examine the ratio of the individual and shared least diet cost to food and total spending in the month the household was surveyed. This limits the affordability analysis to households with a solution to the least-cost diet in their month of survey. This avoids the need for deflating household expenditures (accurate deflators are often hard to come by in practice) and avoids the introduction of measurement error due to changes in household consumption and composition over time, and relatedly nutrient requirements (recall that the household composition is only observed at the point of survey, but not in the months in between or beyond the two survey points). Given that the surveys were rolled out across the year, this still gives a representative picture of affordability per month at the national level. Relative expenditure ratios compare the daily cost for the whole household, per scenario, to daily food or total expenditure, in nominal terms. Expenditure accounts for the contribution of own produced goods in household consumption. The premium for the shared diet is expressed through the ratio of shared to individualized diets daily cost, in nominal terms.

5. Results

Feasibility & Cost

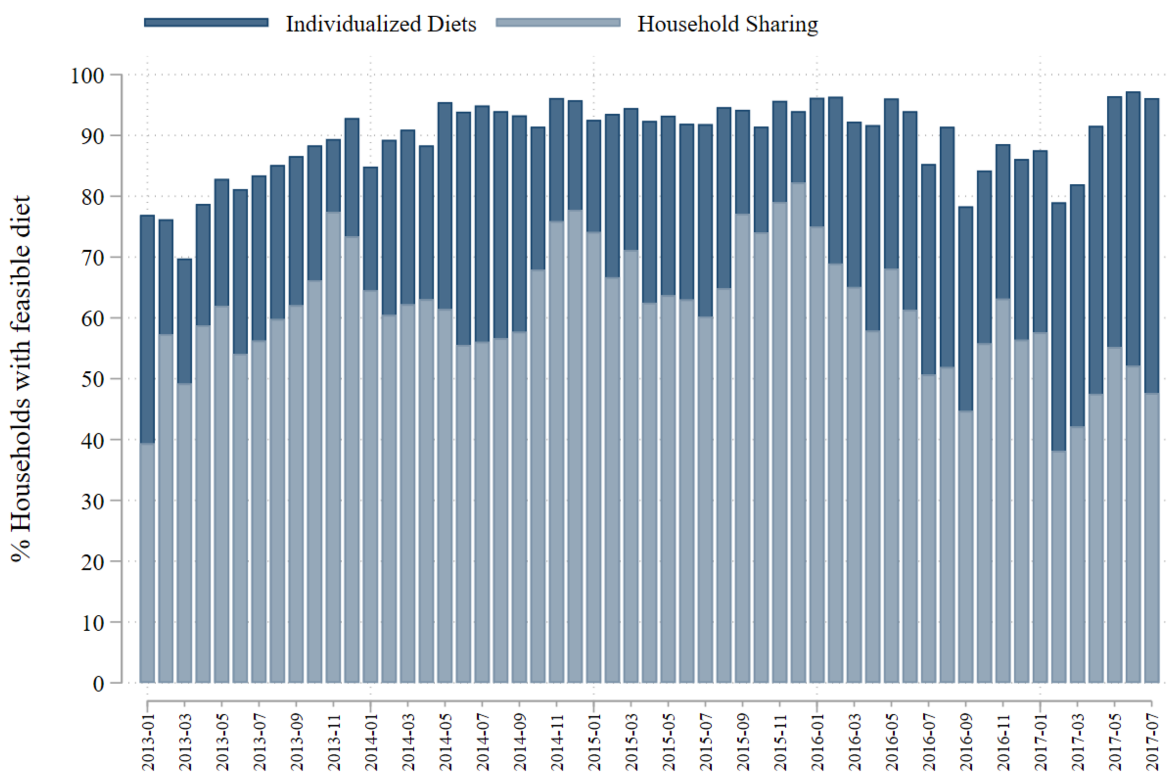
Figure 2 depicts the percent of households in each month for whom the linear programming identifies a solution given foods and prices in the market and their known composition, i.e., the extent to which a nutrient-adequate diet is feasible within Malawi's current food system. Figure 3 presents diet cost per capita per day, by sharing scenario. As expected, individualized diets are consistently more feasible and lower cost than the shared diet. Considering all months between

January 2013 and July 2017, the individualized diets are feasible 90% of all household-months, on average, while the shared diets are feasible only 60% of the time. When the diet is feasible for all members of the household as individuals but is not feasible for the shared diet, it means that there is a combination of foods dense enough in nutrients to meet all the minimum requirements but not too dense in those nutrients with upper limits. This means the foods are there, and their price and nutrient composition are observed and can satisfy individuals' nutrition needs. When the requirements are tightened to account for sharing (higher nutrient density needed at the lower bound while tolerance for certain nutrient's density lowers at the upper bound), minimum requirements cannot be met without exceeding upper limits. This underscores that the difference in feasibility between the individual and shared diets is driven by the different nutrient requirements. Since all foods contain a combination of nutrients, it is unlikely that missing prices for one type of food would drive the results in the majority of cases where there is a feasible diet for individuals but not under household sharing. In related research, Schneider (2021b) finds that the feasibility of a shared diet is systematically related to both household composition and household size, and confirms that the infeasibility is most often driven by an inability to meet selenium requirements without exceeding upper limits on copper.

We estimate the median daily cost per capita to be $1.79 at the lower bound and $2.26 at the upper bound, at least for the household-months where the diet is feasible (Table 2). Examining the feasibility of the lower bound diet for a generic individual of each age and sex group in every market and month (Supplementary Table D, also showing the population distribution and median cost per day for all age and sex groups) shows that if an adequate diet is not feasible, it mainly concerns children six months through three years, breastfeeding women, and older adults (70+

years). Since the equation is estimated with the same items and prices for all members of a household, the difference in individual feasibility derives from variation in biological nutrient requirements over the life course. In other words, these age-sex groups have a greater need for nutrient density, and for young children they are also more sensitive to toxicity and therefore have a lower tolerance at the upper limit for certain nutrients, tightening the constraints on the optimization problem relative to other age and sex groups. Households with these types of members are therefore more likely to have an infeasible diet.[5]

Figure 2. Feasibility of Household Nutritious Diet, by scenario



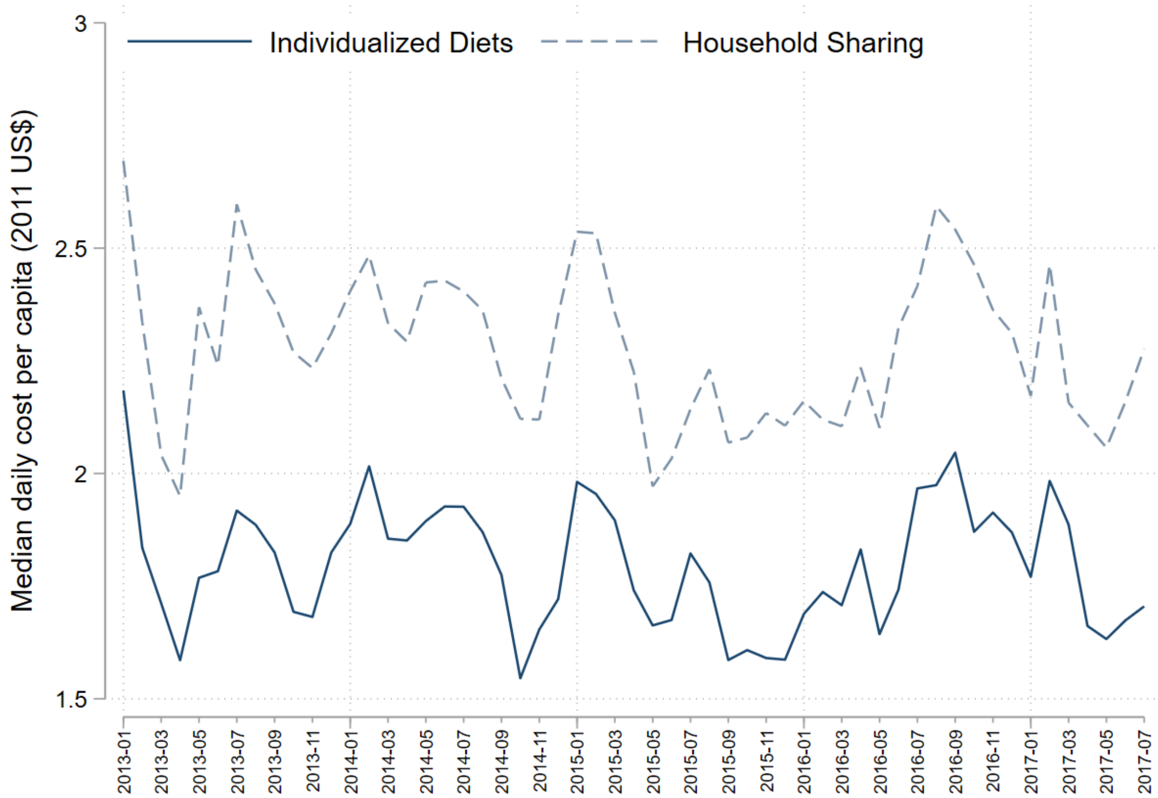
Population statistics corrected using sampling weights. Percent of households with a feasible diet in the market under the individualized diets scenario is defined as households with a solution for all members.

[5] Though the children three and below do not set the household level of nutrient density, a feasible diet must be available for them as individuals for the household to be categorized as having a feasible diet.

The individualized diet was most feasible in the period between the 2014 and 2016 harvests, while the shared diet demonstrates clearer seasonal fluctuation in the ability for the model to identify a solution given items, prices, and known nutrient composition. The shared diet is most feasible September–January, even though the latter months in this range are typically considered the lean season, with the diet most likely to be feasible in December. One potential explanation for this is the greater availability of animal-source foods (ASFs) (which are very nutrient-dense) in the market during those months for cultural reasons. Many Malawians consume meat during the holidays (particularly Christmas), which for some is the only meat in the year. More fish is also available in the market in preparation for the spawning season fisheries ban (FAO 2005; Gelli et al. 2020; Gilbert et al. 2017). A poor harvest in 2015 and complete failure in 2016 likely explain the lower availability between the 2016 and 2017 harvests (Gelli et al. 2020). The cost dynamics over time show the two scenarios largely track one another and appear to have a general seasonal pattern of peaks and troughs.[6] We also see indications that the years surveyed (2013, 2016/17) were slightly different than the intervening years.

[6] Note, however, that these results are presented in real terms (international 2011 US$ PPP) but that deflation likely blunts the appearance of seasonal effects since food prices comprise a large share of the consumption basket on which deflation factors are based. We formally estimate seasonality using nominal prices using the regression framework presented above that controls for the price trend and therefore can isolate the seasonal gap estimate.

Figure 3. Cost of Household Nutritious Diet, by scenario



Population statistics corrected using sampling weights.

Seasonality

Figures 2 and 3 present visual evidence of a seasonal pattern in the cost of the diet. We now estimate more rigorously the extent of that seasonal fluctuation, and how this relates to the extent of seasonality in the availability of the diet and in the underlying food prices. Table 2, column 1 presents the percent of households with a feasible diet, conditional on month (equation (9)). Column 2 shows the monthly seasonal factors on diet cost (equation (8)) when the diet is feasible. Table 2 also presents the average availability and median cost/person/day. For the diet cost, model fit statistics (Supplementary Table E) prefer the stochastic trend seasonal dummy variable model, so we estimate equation (7) using ordinary least squares. We calculate seasonal factors as in equation (8) – interpreted as the percent difference between the monthly conditional mean cost/availability and the grand mean – and the seasonal gap is the difference between the highest and lowest seasonal factor.

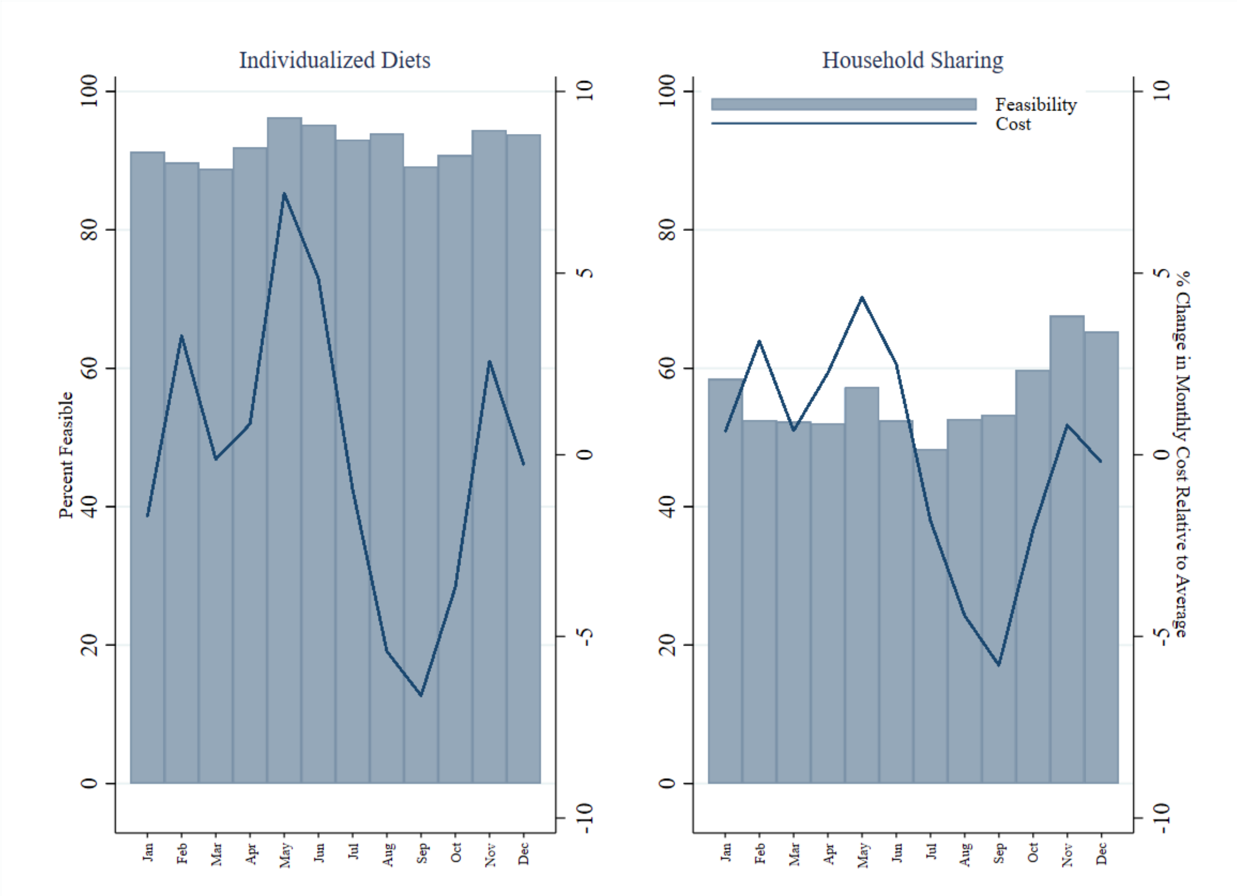
Table 2. Seasonal Variation in Diet Feasibility and Cost, 2013–2017

	(1) **Household-Months With Feasible Diet**		(2) **Seasonal Variation in Diet Cost *if feasible***		(3) **Seasonal Variation in Diet Cost *imputing infeasible***	
	Estimated Percent Feasible[‡]		*Seasonal Factors*[*]		*Seasonal Factors*[*]	
	Individualized Diets	Household Sharing	Individualized Diets	Household Sharing	Individualized Diets	Household Sharing
January	91.23	58.41	-1.70	0.63	4.19	42.24
February	89.69	52.51	3.28	3.13	-3.61	31.30
March	88.80	52.25	-0.13	0.66	-10.89	-7.99
April	91.89	52.03	0.85	2.25	-13.42	-9.50
May	96.24	57.29	7.20	4.33	-0.38	-11.70
June	95.19	52.42	4.85	2.49	18.47	21.83
July	93.05	48.31	-0.96	-1.81	8.30	-18.43
August	93.91	52.64	-5.41	-4.43	-4.94	-51.53
September	89.15	53.26	-6.63	-5.79	5.10	-38.56
October	90.73	59.73	-3.65	-2.08	-11.71	-33.40
November	94.44	67.53	2.58	0.82	-1.61	11.61
December	93.82	65.26	-0.28	-0.21	10.49	64.14
Seasonal Gap	7.44	19.22	13.83	10.12	31.89	115.67
Mean Availability[†]	89.72	60.18				
(% Household-Months)	(0.91)	(1.56)				
Median Cost, per capita per day[†]			1.79	2.26		
(2011 US$ PPP)			(0.03)	(0.04)		

[‡] Calculated as in equation (9), interpreted as the percent of households with a feasible diet on average each month. The seasonal gap in feasibility is the percentage point difference between the most feasible and the least feasible month.
[*] Seasonal factors of diet cost calculated as in equation (8) interpreted as the percentage point difference in average cost in that month relative to the average over all months of the year.
[†] Standard error in parentheses.

Looking first at feasibility, as noted above the individualized diet is more often possible to identify as least-cost solution than the shared diet, nearly 90% of the time on average, compared to only 60% of the time under household sharing. The seasonal gap in feasibility – defined here as the percentage point difference in feasibility between the most and least feasible months – is only 7% for individualized diets while it is 19% for shared diets, showing that the shared nutrient requirements are more sensitive to seasonality in item availability (as the same menu of items have a price observation in a given market-month, the difference in feasibility by scenario is driven by the ability of those foods to meet the different nutrient requirement constraints). Even in the most feasible months, the share diet is only feasible for about two-thirds of all households. We observe a large difference in the average cost by scenario ($1.79/person/day for individualized diets and $2.26 under household sharing), when the diets are feasible. We find that cost and feasibility appear to track one another, where cost is greater when availability is also greater. This suggests that households for whom the diet is sometimes infeasible face higher costs on average when that diet is feasible. This also suggests that our estimate of the shared diet cost and seasonal gap are both likely biased downward by the absence of households for whom the shared diet is only sometimes possible.

Figure 4. Monthly Variation in Feasibity and Cost of Nutrient Adequate Diet when the diet is feasible, 2013–2017



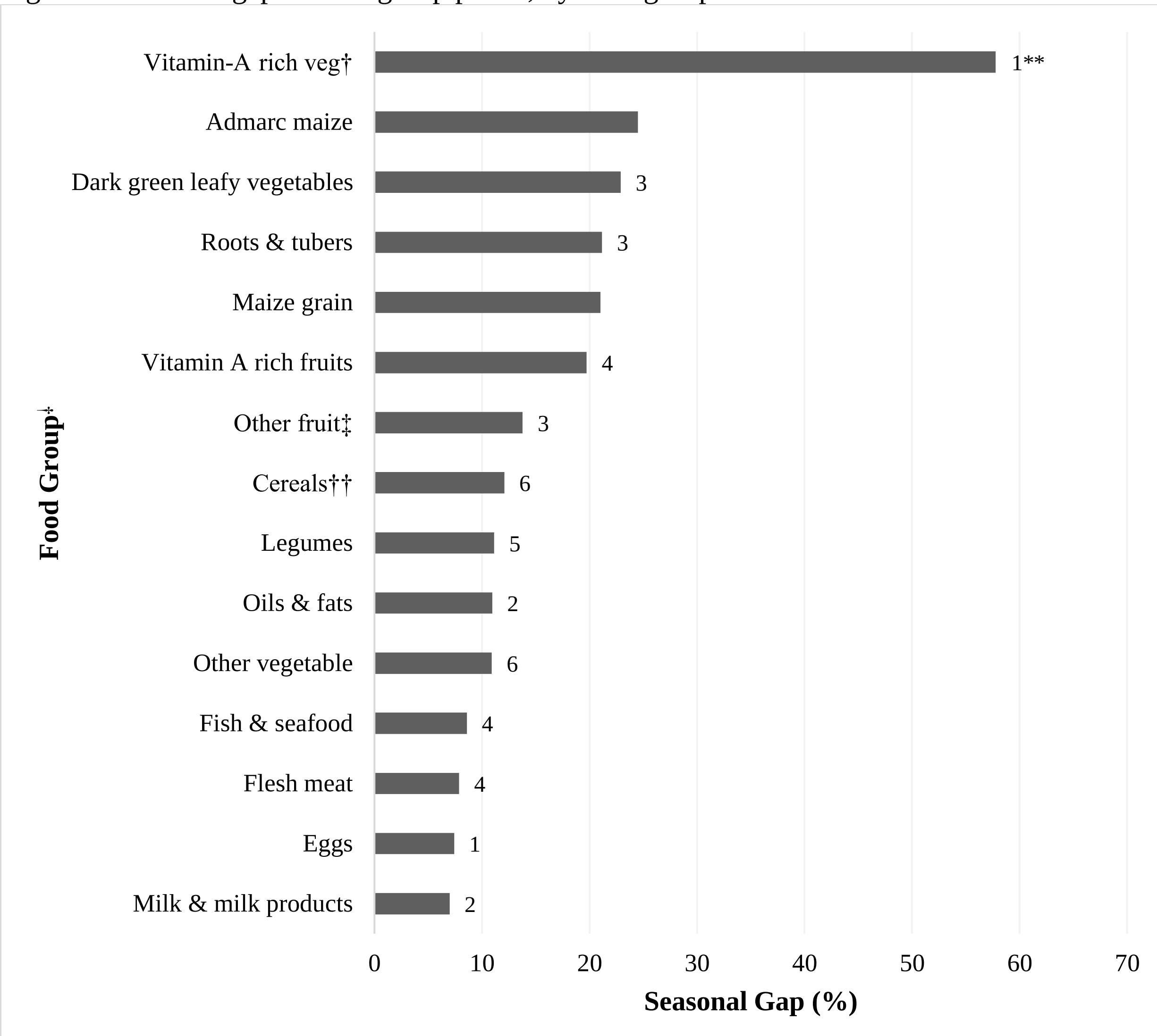
Population statistics corrected using sampling weights. Seasonal factors estimated as in equation (7). Predicted feasibility of the diet estimated as in equation (9).

Treating an infeasible diet as having infinite cost, we test the magnitude of the bias introduced by the elimination of infeasible household-months. We repeat the seasonality analysis imputing the diet cost where infeasible as the highest cost observed by month and year (per scenario). Table 2, column 3 presents the seasonal variation in diet cost by scenario using the imputed data, putting a lower bound on seasonality, as the highest observed cost is still lower than the theoretical infinite cost. We find that there is much greater seasonal fluctuation in the cost of the shared diet than observed only in the household-months where the diet is feasible, with a seasonal gap over 11 times greater at nearly 116%. The seasonal variation in the individualized diets also slightly more than doubles, suggesting that seasonality contributes to lack of a feasible diet for certain household members (see Supplementary Table D for individual results). Table 2, column 3 (visualized in Supplementary Figure A) shows that, the highest cost month for the shared diet is December and the lowest is August. For the individualized diet, the highest cost month is June and the lowest is April. Once infeasible diets are imputed as having infinite cost the individualized diets have much more limited seasonal fluctuation while the shared diet varies greatly from month-to-month (see Supplementary Figure A). This suggests that given available foods in rural markets in Malawi, guiding consumers to pursue more individualized diet strategies could help to smooth access to nutritious diets throughout the year. Additional measures are also necessary to meet the needs of the most nutritionally vulnerable individuals including children through three years old, breastfeeding mothers, and adults over 70 years.

To further understand the policy implications of these findings, we compare the extent of seasonality in the diet cost to seasonality in food item prices by food group. Figure 5 shows the estimated seasonal gap in food group prices. We estimate the seasonal variation in food group prices (price per kg edible portion per food item, estimated in a pooled regression by food group) based on the trigonometric model as in equations (5) and (6), which was preferred by model fit statistics. For all food groups where AIC and BIC model fit statistics agree, both favor the trigonometric model. Where they disagreed, BIC favored the trigonometric model in all cases (both maize grains, legumes, milk, other fruit, roots and tubers, and vitamin A-rich vegetables). Our results show that the food groups with the greatest seasonal gaps are vitamin A-rich vegetables and tubers (pumpkin), dark green leafy vegetables, and fruits (vitamin A-rich and others). We find seasonality to be lowest for milk, eggs, fish, and meat, as to be expected for items that can be produced year-round, and consistent with other findings in Malawi and neighboring countries (Bai et al. 2020).

Importantly for maize-focused policy in Malawi, the cereals food group has much lower seasonality (12.1%) than maize alone (21.0% for retail market, 24.5% for Admarc maize grain). These findings are consistent with Manda (2010) and Christiaensen, Gilbert and Kaminski (2017), who found that seasonality was much greater in maize prices than in other foods studied, and among other staples, much greater than rice. This suggests that consumers could smooth consumption by switching away from maize in high price times to other staples. The high seasonality in vitamin A-rich vegetables is likely driven by having price data for only one item (pumpkin) in this food group so the food group follows its harvest pattern.

Figure 5. Seasonal gap in food group prices, by food group



Notes: Heteroskedasticity robust standard errors clustered at the market level. Pooled trigonometric regression estimated by food group.
[**] **Numbers indicate the number of items per food group.**
[††] Cereals includes maize grain, Admarc maize grain, maize flour dehulled, maize flour whole grain, rice, white bread.
[†] The single item in this food group is pumpkin. Although orange-fleshed sweet potato has become widely disseminated in Malawi in recent years (Low et al. 2017; Low and Thiele 2020), the NSO collects prices only for white sweet potatoes and Irish potatoes.
[⸸] Sweets and condiments excluded from seasonality analysis. The seven items not included in this figure are: Coca-cola, biscuits, scones/buns, *mandazi* (fried dough), white sugar, brown sugar, salt.
[‡] BIC equivalent for fixed effects dummy and trigonometric specifications.

The degree of seasonality in the lower bound diet cost is comparable to the range of seasonal gaps in food group prices, which range for most food groups from 7.7% for eggs to 23.1% for green leafy vegetables. This suggests that the degree of seasonal fluctuation in the individualized diets could provide a benchmark of the amount of seasonality to be expected given current seasonal price dynamics in Malawi due to natural agricultural calendars and lack of the storage, preservation, and transport year-round item availability would require (Bai et al. 2020; Shively and Thapa 2017; Brenton, Portugal-Perez and Regolo 2014). In other words, it is the amount of seasonality in the cost of nutritious diets that would be unavoidable under current conditions (not withstanding potential measurement error) reflecting the best achievable smoothing over the year by using food item substitutions to meet nutrient needs.

Affordability

Table 3 presents the feasibility, cost, and affordability relative to food and total expenditure for households who have a solution *in their month of survey*. Over both survey rounds, the individualized diet is feasible for almost 87% of households in the month the household was surveyed at a median cost of $1.83/person/day. Note that Table 3 reflects the data for each household in the survey month, where the median is $1.83/person/day. This differs from Table 2 which includes all data for all households and all months and finds the median to be $1.79/person/day. This is just above current food expenditure (1.11 times) and is equivalent to 78% of total expenditure. At the upper bound, over both survey rounds, only 56% of households had a feasible diet in the month of survey, which cost $2.31/person/day for the median household, equivalent to 1.35 times more than current food spending and 92% of total expenditure. Comparing the shared to the individualized diet costs, shows the premium for household sharing is 33%. This is only if the shared diet is feasible at all, which is a lower bound on the premium when considering infeasible diets to have infinite cost.

Table 3. Nutritionally Adequate Diet Feasibility, Cost, and Affordability in Month of Survey

	2013 – 2015		2016 – 2017		Overall	
	Median	(SE)	Median	(SE)	Median	(SE)
Lower Bound: Individualized Diets						
Households with a feasible diet *in month of survey* (%)	83.71	(3.02)	88.45	(2.39)	86.73	(2.12)
Cost per day (household)	7.51	(0.26)	8.31	(0.37)	7.96	(0.29)
Per capita	1.85	(0.07)	1.82	(0.08)	1.83	(0.05)
Per 1,000 kcal	0.95	(0.04)	0.94	(0.04)	0.94	(0.03)
Cost/Food Expenditure	1.01	(0.05)	1.19	(0.07)	1.11	(0.06)
Cost/Total Expenditure	0.72	(0.04)	0.81	(0.05)	0.78	(0.04)
N households with a solution in month of survey	1,125		1,451		2,576	
N households with no solution any month in year of survey	37		52		89	
Upper Bound: Shared Diet						
Households with feasible diet in month of survey (%)	58.98	(3.71)	54.50	(3.25)	56.13	(2.58)
Cost per day (household)	9.49	(0.47)	9.13	(0.43)	9.24	(0.36)
Per capita	2.39	(0.10)	2.25	(0.08)	2.31	(0.06)
Per 1,000 kcal	1.26	(0.05)	1.20	(0.04)	1.21	(0.03)
Cost/Food Expenditure	1.24	(0.09)	1.40	(0.09)	1.35	(0.06)
Cost/Total Expenditure	0.88	(0.06)	0.95	(0.07)	0.92	(0.04)
N households with a solution in month of survey	792		956		1,748	
N households with no solution any month in year of survey	187		223		410	
Scenario Comparison (annualized)						
Shared Cost/Individualized Diets Cost	1.34	(0.02)	1.31	(0.02)	1.33	(0.02)
N Households with solution under both scenarios in month of survey	727		897		1,624	
Households (total N)	1,424		1,693		3,117	

Population statistics corrected using sampling weights, standard errors clustered at the enumeration area level.

If we consider that households for whom the diet is infeasible as also not being able to afford the diet, then we can estimate the share of the population for whom the adequate diet (in the market) is out of reach. Since the lower bound cost is the least costly way for a household to meet all members' nutrient needs, those for whom it is infeasible, or costs more than their total expenditure, do not have access to an adequate diet at all. Our results show 44% of rural Malawian households face this situation. For an additional 18%, the lower bound diet is feasible but unaffordable without increasing current food expenditure (though technically affordable within total expenditure). In total, 62% of rural Malawians cannot access any adequate diet in the market at all – not even the lower cost individualized diet – because it is infeasible, costs more than they choose to allocate to food, or costs more than they have to spend at all.

Even fewer households have access to the shared diet. For 69.5% of rural households, the diet is infeasible or costs more than all of their resources (total expenditure). For an additional 10.5%, the diet is feasible but costs more than current food spending, though less than total expenditure. There are only 20% of rural Malawian households for whom the shared diet is feasible and who could afford it within their current food budget. In between those who cannot afford the lower bound without increasing food spending and those who cannot afford the upper bound without increasing food spending, we identify 18% of the population who could afford to meet the family's nutrient needs if carefully allocating household resources to achieve that goal.

6. Discussion

In this paper, we developed two methodologies to estimate least-cost diets for whole households and used empirical analysis of Malawi's markets as demonstration. The two methods produce a lower and upper bound on the cost of a nutrient-adequate diet for a whole household in the market. The lower bound reflects the cost of each person's own tailored diet to meet their minimum scientific nutrient needs. This describes the least costly way a family could meet everyone's needs, but in practice it would be onerous to prepare individualized meals when members will eat together. The upper bound cost is the lowest cost diet that meets the energy and all other nutrient requirements for every family member when eating a shared diet. It is ethically grounded in Rawls' *maximin* principle (Rawls 1971; Ravallion 2016).

In the case of Malawi, we find the higher diet quality demanded for shared meals is less likely to be feasible in the market and costs more, on average, than if households were to pursue individualized diet strategies. The median cost per household-market in every month from January 2013 to July 2017 is $1.79/person/day (2011 US$ PPP) for the individualized diets but $2.26 for the shared diet.[7] Individualized diets are feasible 90% of the time compared to 60% of the time for shared diets. Further, when considering infeasible diets to have very high cost instead of being infeasible altogether (infinite cost), we estimate that the extent of seasonal fluctuation for the shared diet is at least 116%, constituting a lower bound on the extent of seasonality when optimizing for shared meals.

We have shown that the seasonal gap in the cost of the lower bound diet is similar to that of food groups when the diet is feasible, and lower than that of individual prices, suggesting that substituting items within food groups to meet nutrient requirements can stabilize diet cost throughout the year. We find that seasonality is a factor in the feasibility of a nutrient-adequate diet under both scenarios, driven in the lower bound case by certain nutritionally vulnerable household members for whom the diet is not always feasible (Supplementary Table D), specifically breastfeeding women, children three years and under, and elderly adults. The observed seasonal gap in the cost of the lower bound diet – which we estimate to be approximately 13% when the diet is feasible and at least 30% when considering infeasible diets to have infinite cost – can be considered the amount of seasonality in the cost of nutritious diets that would be unavoidable under current conditions or the best possible smoothing under current conditions. Clearly, seasonality in diet costs in Malawi's current food system remains substantial and cannot be ignored.

[7] These compare with an unweighted population average individual cost of a nutrient-adequate diet in Malawi calculated by (Herforth et al. 2020) of $1.29/person/day (2011 US$ PPP), which was calculated using different food price and nutrient composition data for global comparability. That paper used the food list and prices from the World Bank's International Comparison Project and used USDA food composition data (Herforth et al. 2020).

We estimate 44% of rural Malawians cannot afford the adequate diet in the market *even* at the lower bound and *if spending all their resources on food*. At current food spending, 62% of rural Malawian households cannot afford a nutrient-adequate diet, as the lower bound cost exceeds current food expenditure. Recalling that households already spend an average 74% of their resources on food, increasing food budgets without increasing incomes would be near-impossible for many. At the other extreme the shared diet is feasible and affordable to 20% of households within their current food budgets. That leaves 80% of households who cannot afford to completely share meals, either because it is infeasible or costs more than current food spending, and 69.5% for whom it is infeasible or costs more than all available resources.

As discussed above, there are some limitations to the food price and nutrient composition data and that may be consequential to our results. However, several factors lend confidence to the data quality and our ability to draw meaningful conclusions for Malawi from this demonstration case of the household least-cost diets methodology. First, the list of food items includes all items that accounted for at least 0.02% of household expenditure in 2010 (including own-produced goods), indicating prices are monitored for the vast majority of foods households choose to consume. For comparison, the household survey included 129 items that we could identify, convert to kilograms, and match to food composition data, reflecting a total of 93% of all reported item-source observations. We estimate approximately 90% of household expenditure is spent on items that are present in the food item list. At the nutrient level, 94% of all energy and macronutrients is consumed from items in the market price list and for micronutrients at most 22% of consumption comes from items *not* in the market price list (see Supplementary Table F).

Second, missing data are common in agricultural price series, and we cannot assume that lack of a price observation indicates the item was not available in that market-month, though often missing data do arise from seasonal lack of availability (Gilbert et al. 2017). In related work we collected a survey in all the markets for which we have price data and asked about the usual availability of each item every month. Comparing the missing data in the CPI price data set to the results of this survey from August 2016 – July 2017, we found concordant results 79% of the time where there was a price observation present (absent) when the item was reported to be available (unavailable) (Kaiyatsa et al. 2021). This study also confirmed that the potential impact of discordant missing prices (missing when reportedly available) on the CoNA estimate was likely small in practical terms.

Third, the food composition data are the best available for Malawi, however more of certain nutrients may be available than we estimate but would only affect the results if that item would have been selected into the diet. One way to examine where this might be the case is to model scenarios. Doing so in a related study for the shared diets scenario, we found selenium to be the limiting nutrient (the nutrient causing the diet to be infeasible) (Schneider 2021b). Selenium is the nutrient for which there are more foods with no data than for any other nutrient, however there is also strong evidence that selenium is lacking in Malawian soils and diets, and there is widespread deficiency in the population (Joy, Kumssa, et al. 2015; Joy, Broadley, et al. 2015; Phiri et al. 2019; Schneider 2021a; Schneider 2021b). So there is some evidence that little selenium is present and available to consumers in Malawi, but also note that our results show this does not hinder the individualized diets, so there is sufficient selenium present given the data to identify a solution to meet individual needs. What Schneider (2021b) demonstrates – to support the intuition behind these results – is that there is enough selenium present, but it comes from sources that also add copper to the diet, and when attempting to meet the shared nutrient requirements with lower upper tolerance for copper density of the diet relative to most individuals makes it impossible to satisfy the criteria of enough selenium without violating the copper limit (Schneider 2021b).

The least-cost diet metric at the household level could be useful for numerous policy purposes, but we also note that our methods are an initial attempt and further research is warranted. Food prices and item availability are already used in food security early warning systems, incorporating the cost of nutritionally adequate diets could be used to enhance such systems to become more nutrition sensitive. However, where the underlying food price data used for such analyses come from market prices, they may not reflect the prices households face in hyper-local markets nor the option to supplement market availability with own production. Future research should investigate how unit costs from household surveys could be used to estimate more precise least-cost diets, their composition, and the relative contribution of own production to what is available in markets in order to have access to a complete diet. Further, modeling tools such as stochastic optimization could be used to better capture the stochastic nature of the food environment and incorporate uncertainty in the underlying data.

Lowering the cost of nutrient-adequate diets could be achieved through myriad interventions throughout the food system, for example determining food items for investment to increase productivity and reduce cost, guiding safety net transfers to close the affordability gap, or using the food items that emerge in the least-cost diet food basket to guide dietary recommendations for low-income consumers. Although sharing meals is the cultural norm in Malawi, our study has shown that the food items available in rural markets cannot meet the needs of most rural families throughout the year for a diet that is sufficiently nutrient-dense to be shared by the family and meet the needs of all members. Least-cost diets have been used in other countries to determine the amount of public assistance provided to individuals and families to purchase food (Carlson et al. 2007), however if the markets do not have a sufficient mix of items, such cash transfers would not be sufficient to provide access to nutrient-adequate diets. Household least-cost diets could be used to identify nutritionally vulnerable households such as those for whom even the lower cost individualized diet is not feasible or affordable, calculate benefits, or assess benefit adequacy in the context of the social protection scheme and for other public programs such as Malawi's expanding Social Cash Transfer Program (Brugh et al. 2017). In the long-term, policy objectives could focus on making the shared diet feasible and to address the overall cost and its seasonal fluctuation.

The seasonality findings suggest that least-cost diet methods could be used to develop seasonally specific dietary recommendations for low-income consumers that could help smooth consumption and nutrient intakes throughout the year. Our model does not incorporate additional constraints that would be necessary to develop recommended diets such as palatability and diversity (Cost of Nutritious Diets Consortium 2018; Nykänen et al. 2018; Chastre et al. 2009; Frega et al. 2012; Baldi et al. 2013). That said, these findings suggest that doing so could be a useful approach to develop nutrition education to help consumers access high quality diets year-round.

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Supplementary Materials

Table A. Markets in CPI Price Monitoring Data Set Observed in IHPS Data Set

Region	District	Market
North	Chitipa	Chitipa Boma
	Karonga	Karonga Boma
	Nkhatabay	Nkhatabay Boma
	Rumphi	Rumphi Boma
	Mzimba	Ekwendeni
Central	Mzimba	Ekwendeni
	Kasungu	Kasungu Boma
	Nkotakota	Nkhotakota Boma
	Ntchisi	Mponera
	Dowa	Mponera
	Salima	Salima Boma
	Lilongwe Non-City	Mitundu
	Mchinji	Mchinji Boma
	Dedza	Dedza Boma
	Ntcheu	Ntcheu Boma
South	Mangochi	Mangochi Boma
	Machinga	Liwonde
	Zomba Non-City	Jali
	Chiradzulu	Mbulumbuzi
	Blantyre Non-City	Lunzu
	Mwanza	Mwanza Boma
	Thyolo	Thyolo
	Mulanje	Chitakale
	Phalombe	Phalombe Boma
	Chikwawa	Nchalo
	Nsanje	Nsanje Boma
	Balaka	Balaka Boma

Table B. Food Items by Food Group in Price Data Set

Food Group	Items
Cereals & Cereal Products	Maize flour (dehulled)
	Maize flour (whole grain)
	Maize grain
	Maize grain, Admarc
	Rice grain
	White bread
Dark Green Leafy Vegetables	Chinese cabbage
	Pumpkin leaves
	Rape leaves
Eggs	Chicken eggs
Fish & Seafood	Cichlid (Utaka, dried)
	Oreochromis lidole, dry†
	Oreochromis lidole, fresh†
	Sardine (Usipa, sun dried)
Flesh Meat	Beef
	Goat
	Live chicken
	Pork
Legumes	Brown beans
	Cowpeas
	Groundnuts
	Pigeon peas
	White beans
Milk & Milk Products	Fresh milk
	Powdered milk
Oils & Fats	Cooking oil
	Cooking oil refill

Food Group	Items
Vitamin-A rich fruits	Mangoes
	Oranges
	Papaya
	Tomatoes
Vit-A rich Vegetables	Pumpkin
Other Fruits	Avocado
	Banana
	Guava
Other Vegetables	Okra
	Onions
	Cabbage
	Cucumber
	Eggplant
	Green beans
Roots & Tubers	Cassava
	Irish potatoes
	Sweet potatoes
Salty & fried foods	Mandazi
Sweets & Confectionary	Biscuits
	Brown sugar
	White buns
	White sugar
Stimulants, Spices, & Condiments*	Salt
Caloric beverages*	Coca-cola
Total items (N)	51

† Tilapia, known locally as *chambo*.

* The food list also monitors the price of three types of tea and a fermented maize-based drink, *Maheu*. Tea is excluded because it confers no essential nutrients. *Maheu* has been excluded from the analysis for lack of food composition data.

Table C. Nutrient Composition and Density by Food Item and Nutrient

Nutrient	Items with highest nutrient quantity per 100g edible portion*	Items with highest nutrient density (quantity per unit energy)*
Energy	Cooking oil, Groundnuts, Powdered milk, Biscuits, Sugar, Maize flour, Pigeon peas, Dry *Usipa*, Cowpeas, Rice	Cooking oil, Groundnuts, Powdered milk, Biscuits, Sugar, Maize flour, Pigeon peas, Dried *Usipa*, Cowpeas, Rice grain
Carbohydrate	Sugar, Rice, Maize flour. Maize grain, Biscuits, Pigeon peas, Cowpeas, White beans, Brown beans, White bread	Coca-cola, Sugar, Cucumber, Cassava, Mango, Banana, Sweet potato, Oranges, Rice, Papaya
Protein	Dry *Chambo*, Dry *Usipa*, *Utaka*, Powdered milk, Brown beans, Groundnuts, Cowpeas, Pigeon peas, White beans, Chicken	Dry *Chambo*, Beef, Dry *Usipa*, Chicken, Fresh *Chambo*, *Utaka*, Goat, Eggs, Pumpkin leaves, Brown beans, Pork
Lipids	Cooking oil, Groundnuts, Powdered milk, Pork, Biscuits, *Utaka*, Avocado, Goat, Eggs, Dry *Usipa*	Cooking oil, Avocado, Pork, Groundnuts, Eggs, Goat, Fresh milk, Powdered milk, *Utaka*, Biscuits
Vitamin A†	Rape leaves, Powdered milk, Pumpkin, Biscuits, Pumpkin leaves, Mangoes	Rape leaves, Pumpkin leaves, Pumpkin, Chinese cabbage, Mangoes, Tomatoes
Retinol	Powdered milk, Chicken, Biscuits, Eggs, Fresh milk	Chicken, Eggs, Fresh milk, Powdered milk, Biscuits
Vitamin C	Guava, Papaya, Rape leaves, Oranges, Okra, Chinese cabbage, Cassava, Cabbage, Mangoes, Pumpkin leaves	Guava, Chinese cabbage, Papaya, Rape leaves, Oranges, Cabbage, Pumpkin leaves, Okra, Tomatoes
Vitamin E	Cooking oil, Groundnuts	Pumpkin leaves, Rape leaves, Cooking oil, Pumpkin, Tomatoes, Groundnuts, Papaya, Mangoes, Guava
Thiamin	Groundnuts, White beans, Pork, Cowpeas, Pigeon peas, Brown beans, White buns, Maize grain, Maize flour	Pork, Irish potatoes, White beans, Cowpeas, White buns, Rape leaves, Green beans, Cucumber, Pumpkin leaves
Riboflavin	Powdered milk, Dry *Usipa*, Eggs, Goat, Dry *Chambo*, Brown beans, Pork, White beans, Beef, Pigeon peas	Powdered milk, Eggs, Rape leaves, Pumpkin leaves, Fresh milk, Cucumber, Beef, Okra, Dried *Usipa*, Goat
Niacin	Dry Usipa, Groundnuts, Beef, Goat, Pork, Chicken, Dry *Chambo*, Cowpeas, Pigeon peas, Maize grain	Dried *Usipa*, Beef, Goat, Chicken, Groundnuts, Chinese cabbage, Tomatoes, Green beans, Irish potatoes, Pumpkin leaves

Nutrient	Items with highest nutrient quantity per 100g edible portion*	Items with highest nutrient density (quantity per unit energy)*
Vitamin B6	Dry *Usipa*	Guava, Dried *Usipa*, Rape leaves, Okra, Pumpkin leaves, Banana, Irish potatoes, Tomatoes, Onions, Cucumber
Folate	Cowpeas, Brown beans, White beans, Pigeon peas, Rape leaves, Okra, Groundnuts	Rape leaves, Okra, Cowpeas, Pumpkin leaves, Brown beans, White beans, Pigeon peas
Vitamin B12	Dry *Usipa*, Dry *Chambo*, Eggs, Powdered milk, Beef	Dried *Usipa*, Dry *Chambo*, Beef, Eggs, Goat, Fresh milk, Powdered milk, Pork, Chicken
Calcium	Rape leaves, Pumpkin leaves, *Utaka*, Dry *Chambo*, Dry *Usipa*, Cabbage, Papaya, Powdered milk	Pumpkin leaves, Rape leaves, Cabbage, Papaya, Tomatoes, Onions, *Utaka*, Dry *Chambo*, Chinese cabbage, Dried *Usipa*
Copper	Tomatoes, Cabbage, Papaya, Sweet potatoes, Pigeon peas, Onions, Pumpkin leaves, Groundnuts, Rape leaves, Cowpeas	Tomatoes, Cabbage, Pumpkin leaves, Papaya, Onions, Rape leaves, Sweet potatoes, Mangoes
Iron	Pumpkin leaves, Dry *Chambo*, Cabbage, Rape leaves, *Utaka*	Pumpkin leaves, Cabbage, Rape leaves, Tomatoes, Dry *Chambo*, Onions, Papaya, Beef, *Utaka*
Magnesium	Pumpkin leaves, *Utaka*, Papaya, Rape leaves, Cabbage	Pumpkin leaves, Cabbage, Rape leaves, Papaya, Onions
Phosphorus	Dry *Usipa*, Dry *Chambo*, Powdered milk, White beans, Brown beans, Cowpeas, Groundnuts, Pigeon peas, Rice, Maize grain	Dried *Usipa*, Dry *Chambo*, Pumpkin leaves, Beef, Cucumber, Okra, Powdered milk, Fresh milk, White beans, Eggs
Selenium	White beans, Pumpkin leaves, Papaya, Brown beans, Tomatoes, Rape leaves, Cabbage, Cowpeas	Pumpkin leaves, Tomatoes, Cabbage, Papaya, Rape leaves, Onions, Mangoes, White beans, Brown beans
Zinc	Dry *Usipa*, Rape leaves, Pumpkin leaves, Dry *Chambo*, Onions, Pork, Cabbage, Goat, Powdered milk, Brown beans	Rape leaves, Pumpkin leaves, Tomatoes, Cabbage, Onions, Dried *Usipa*, Chinese cabbage, Papaya, Goat, Beef
Sodium	Salt, White bread, White buns, Biscuits, Powdered milk, Dry *Chambo*, Dry *Usipa*	White bread, White buns

* Listed in descending order of quantity or density. Listing top sources where a natural divide in density or quantity occurs, otherwise top 10 items listed.

† Sugar and cooking oil are fortified with vitamin A in Malawi.

Table D. Individual Daily Cost of Nutrient Adequacy over 25 markets January 2013-July 2017, All individual types by nutrient requirement group

	Population Share	Months with Solution (%)		Cost/day (2011 US$)	
	%	Mean	(SD)	Median	(SD)
Infant (all) 6 months-1 y	1.35	**80.00**	(40.01)	0.08	(0.03)
Child (all) 1-2 y*	5.45	**62.36**	(48.46)	3.18	(11.15)
Child (M) 3 y	1.57	**86.61**	(34.06)	1.43	(3.74)
Child (F) 3 y	1.82	**86.46**	(34.22)	1.35	(4.62)
Child (M) 4-8 y	8.15	99.06	(9.68)	1.14	(0.40)
Child (F) 4-8 y	8.46	99.02	(9.83)	0.95	(0.38)
Adolescent (M) 9-13 y	7.92	97.76	(14.79)	1.78	(0.60)
Adolescent (M) 14-18 y	5.91	97.13	(16.69)	2.57	(2.44)
Adult (M) 19-30 y	8.14	97.15	(16.64)	2.57	(2.10)
Adult (M) 31-50 y	8.19	96.96	(17.17)	2.57	(2.09)
Adult (M) 51-70 y	3.04	**91.37**	(28.08)	2.47	(10.22)
Older Adult (M) 70+ y	0.99	**82.68**	(37.85)	2.29	(13.85)
Adolescent (F) 9-13 y	7.76	97.32	(16.14)	1.44	(0.68)
Adolescent (F) 14-18 y	5.53	96.85	(17.47)	1.94	(0.70)
Adult (F) 19-30 y	6.84	97.23	(16.42)	2.04	(0.96)
Adult (F) 31-50 y	7.31	96.98	(17.13)	2.00	(0.95)
Adult (F) 51-70 y	3.58	93.23	(25.13)	2.07	(4.33)
Older Adult (F) 70+ y	1.25	**87.65**	(32.90)	2.01	(7.07)
Lactation (F) 14-18 y	0.28	**56.79**	(49.54)	2.76	(1.63)
Lactation (F) 19-30 y	3.41	**57.04**	(49.51)	2.76	(1.87)
Lactation (F) 31-50 y	1.64	**56.94**	(49.52)	2.76	(2.03)
Population weighted Average		93.06		2.38	

Population shares calculated with survey weights from household data.
Age-sex groups based on *DRI* categories, disaggregating 3 year old children from the micronutrient group aged 1-3 years to accommodate separate estimated energy requirement equations.
* Upper bound of protein AMDR is relaxed (increased) by 50% for children 6-35 months.

Table E. Model Fit Statistics

	Stochastic Trend Dummy Model	**Trigonometric Model**
Individualized Diets		
(N=66,794)		
F-statistic	$F_{11,98}$=14.97***	$F_{2,98}$=5.252***
Adj. R-squared	0.0116	0.0009
AIC	0.8536	0.8642
BIC	0.8552	0.8646
Household Sharing		
(N=40,067)		
F-statistic	$F_{11,98}$=17.20***	$F_{2,98}$=15.36***
Adj. R-squared	0.0189	0.0026
AIC	0.9077	0.9240
BIC	0.9103	0.9246

Population statistics corrected using sampling weights. Preferred specification in bold.
AIC and BIC are reported on a per observation basis.
Heteroskedasticity robust standard errors clustered at the enumeration area level in all specifications.
*p < 0.05 **p < 0.01 ***p < 0.001

Table F. Percent of nutrients and expenditure supplied by food items included in the retail market food price list

% Consumption from items in food price list	**2013** Mean	**2013** (SE)	**2016/17** Mean	**2016/17** (SE)	**Overall** Mean	**Overall** (SE)
Energy	94.33	(0.553)	94.11	(0.454)	94.19	(0.389)
Carbohydrate	94.36	(0.580)	94.65	(0.453)	94.54	(0.401)
Protein	93.28	(0.635)	92.43	(0.622)	92.75	(0.507)
Lipids	95.20	(0.542)	94.36	(0.443)	94.67	(0.382)
Vitamin A	**78.52**	**(1.705)**	**84.27**	**(1.571)**	**82.13**	**(1.303)**
Vitamin C	**84.63**	**(1.072)**	**86.26**	**(1.038)**	**85.65**	**(0.935)**
Vitamin E	96.04	(0.341)	96.10	(0.313)	96.08	(0.265)
Thiamin	94.91	(0.574)	94.63	(0.513)	94.73	(0.433)
Riboflavin	91.47	(0.654)	92.91	(0.504)	92.38	(0.462)
Niacin	92.28	(0.670)	92.56	(0.541)	92.45	(0.493)
Vitamin B6	90.24	(0.772)	91.29	(0.585)	90.90	(0.515)
Folate	92.03	(0.646)	90.68	(0.798)	91.18	(0.625)
Vitamin B12	**83.17**	**(1.983)**	**94.45**	**(0.832)**	**90.06**	**(1.068)**
Calcium	**84.03**	**(1.161)**	**89.89**	**(0.607)**	**87.71**	**(0.673)**
Copper	95.35	(0.485)	94.55	(0.489)	94.85	(0.425)
Iron	**86.31**	**(0.992)**	**92.16**	**(0.527)**	**89.98**	**(0.555)**
Magnesium	90.67	(0.723)	92.53	(0.527)	91.84	(0.488)
Phosphorus	**89.56**	**(0.905)**	**89.28**	**(0.838)**	**89.38**	**(0.733)**
Selenium	90.49	(1.012)	89.90	(1.057)	90.12	(0.926)
Zinc	92.69	(0.578)	92.80	(0.518)	92.76	(0.442)
Sodium	96.79	(0.394)	97.74	(0.262)	97.38	(0.223)
Total Expenditure	90.01	(0.650)	89.86	(0.625)	89.91	(0.512)

Population statistics corrected using sampling weights. Heteroskedasticity robust standard errors clustered at the enumeration area level.

Table G-1. Difference between market unit prices and reported unit costs, by size of difference

Food item	Mean unit cost	Mean unit market price	Diff. (Market unit price - unit cost)	SE (Diff.)	p (Diff.)		Degrees of freedom
Sun Dried fish (Large Variety)	2,137	5,320	3,183.61	413.73	0.00000	***	43
Sun Dried fish (Medium Variety)	1,793	3,875	2,082.35	106.28	0.00000	***	177
Goat	1,103	3,063	1,960.49	628.87	0.00189	**	753
Beef	1,178	2,787	1,608.85	789.67	0.04232	*	374
Sun Dried fish (Small Variety)	2,015	3,150	1,134.60	44.62	0.00000	***	803
Pork	1,098	2,146	1,048.04	613.15	0.08837		319
Cooking oil	970	1,391	421.14	16.78	0.00000	***	2,282
Maize ufa mgaiwa (normal flour)	166	455	288.47	6.94	0.00000	***	1,092
Fresh milk	365	631	266.06	137.12	0.05321		326
Maize ufa madeya (bran flour)	156	393	237.69	30.91	0.00000	***	43
Buns, scones	572	747	175.23	29.98	0.00000	***	843
Chicken	1,326	1,490	164.43	35.63	0.00001	***	168
Onion	328	487	159.51	7.79	0.00000	***	2,125
Pigeonpeas	400	553	153.42	18.35	0.00000	***	257
Brown beans	491	610	118.84	6.10	0.00000	***	1,591
Guava	108	223	114.45	31.49	0.00071	***	45
Papaya	76	184	107.27	19.22	0.00001	***	24
Groundnut	275	378	103.10	8.53	0.00000	***	542
Cucumber	187	270	82.31	32.24	0.01458	*	40
Avocado	142	217	75.62	12.29	0.00000	***	69
White beans	424	493	69.40	10.75	0.00000	***	472
Tomato	217	284	66.91	2.89	0.00000	***	3,897
Citrus	122	189	66.22	8.71	0.00000	***	144
Cowpeas	360	423	63.00	13.40	0.00000	***	244
Cassava tubers	90	141	50.84	2.94	0.00000	***	688
Rice	416	458	42.92	3.95	0.00000	***	1,052
Pumpkin	52	87	34.73	7.57	0.00005	***	36
White sweet potato	92	113	21.35	2.02	0.00000	***	1,296
Mango	128	142	14.24	4.93	0.00435	**	190
Banana	152	164	11.97	2.83	0.00003	***	1,164
Irish potato	218	213	-4.74	5.60	0.39800		445
Cabbage	91	80	-10.37	1.50	0.00000	***	849
Maize grain	193	180	-13.48	22.95	0.55971		49
Chinese cabbage	230	190	-39.61	10.78	0.00028	***	348
Mandazi	708	665	-42.73	9.90	0.00002	***	1,193

Food item	Mean unit cost	Mean unit market price	Diff. (Market unit price - unit cost)	SE (Diff.)	p (Diff.)		Degrees of freedom
Eggs	1,071	1,026	-45.88	14.88	0.00209	**	1,205
Biscuits	675	617	-57.54	63.06	0.36230		277
Rape	185	127	-57.72	2.43	0.00000	***	2,844
Pumpkin leaves	263	204	-59.82	5.03	0.00000	***	1,228
Okra	364	256	-108.35	9.31	0.00000	***	726
Salt	373	232	-140.63	6.80	0.00000	***	4,109
Sugar	671	394	-277.03	20.34	0.00000	***	2,355
Powdered milk	7,187	1,675	-5,512.18	3,101.76	0.07746		159
Bread	151,944	355	-151,588.65	5,917.13	0.00000	***	843

Note: Unit costs and unit prices compared in the same month and year in nominal MWK. Extreme unit costs above the 99th percentile excluded. Red font indicates unit costs reported by households exceed market unit prices.
*** $p<0.001$ ** $p<0.01$ *$p<0.05$

Table G-2. Difference between market unit prices and reported unit costs, by food group

	Food item	Mean unit cost	Mean unit market price	Diff. (Market unit price - unit cost)	SE (Diff.)	p (Diff.)		Degrees of freedom
Staples	Bread	151,944	355	-151,588.65	5,917.13	0.00000	***	843
	Cassava tubers	90	141	50.84	2.94	0.00000	***	688
	Irish potato	218	213	-4.74	5.60	0.39800		445
	Maize grain	193	180	-13.48	22.95	0.55971		49
	Maize ufa madeya (bran flour)	156	393	237.69	30.91	0.00000	***	43
	Maize ufa mgaiwa (normal flour)	166	455	288.47	6.94	0.00000	***	1,092
	Rice	416	458	42.92	3.95	0.00000	***	1,052
	White sweet potato	92	113	21.35	2.02	0.00000	***	1,296
Legumes	Brown beans	491	610	118.84	6.10	0.00000	***	1,591
	Cowpeas	360	423	63.00	13.40	0.00000	***	244
	Groundnuts	275	378	103.10	8.53	0.00000	***	542
	Pigeonpea	400	553	153.42	18.35	0.00000	***	257
	White beans	424	493	69.40	10.75	0.00000	***	472
Vegetables	Cabbage	91	80	-10.37	1.50	0.00000	***	849
	Chinese cabbage	230	190	-39.61	10.78	0.00028	***	348
	Cucumber	187	270	82.31	32.24	0.01458	*	40
	Okra	364	256	-108.35	9.31	0.00000	***	726
	Onion	328	487	159.51	7.79	0.00000	***	2,125
	Pumpkin	52	87	34.73	7.57	0.00005	***	36
	Pumpkin leaves	263	204	-59.82	5.03	0.00000	***	1,228
	Rape	185	127	-57.72	2.43	0.00000	***	2,844
	Tomato	217	284	66.91	2.89	0.00000	***	3,897
Fruits	Avocado	142	217	75.62	12.29	0.00000	***	69
	Banana	152	164	11.97	2.83	0.00003	***	1,164
	Citrus	122	189	66.22	8.71	0.00000	***	144
	Guava	108	223	114.45	31.49	0.00071	***	45
	Mango	128	142	14.24	4.93	0.00435	**	190
	Papaya	76	184	107.27	19.22	0.00001	***	24
Animal-source foods	Beef	1,178	2,787	1,608.85	789.67	0.04232	*	374
	Chicken	1,326	1,490	164.43	35.63	0.00001	***	168
	Eggs	1,071	1,026	-45.88	14.88	0.00209	**	1,205
	Fresh milk	365	631	266.06	137.12	0.05321		326
	Goat	1,103	3,063	1,960.49	628.87	0.00189	**	753
	Pork	1,098	2,146	1,048.04	613.15	0.08837		319

	Food item	Mean unit cost	Mean unit market price	Diff. (Market unit price - unit cost)	SE (Diff.)	p (Diff.)		Degrees of freedom
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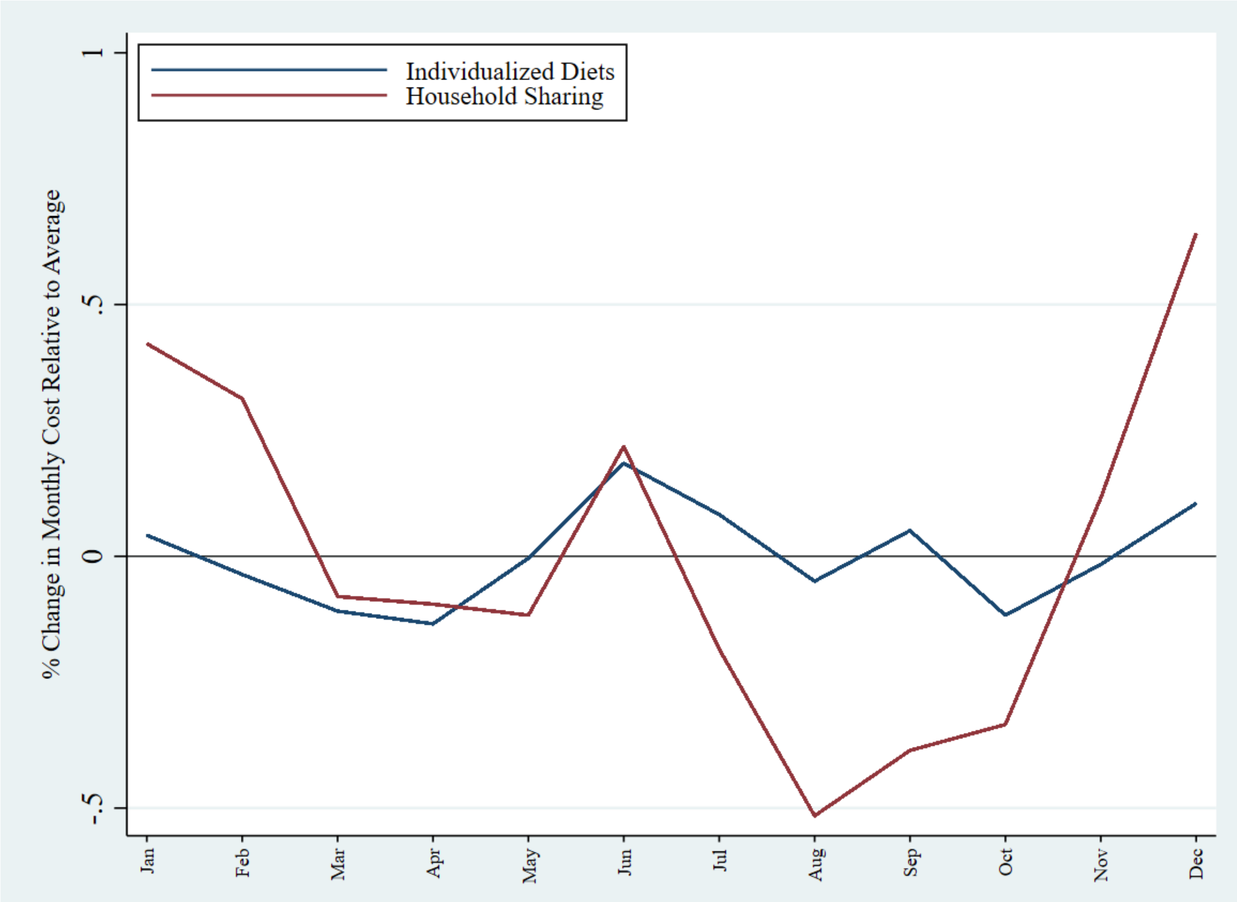
	Sun Dried fish (Large Variety)	2,137	5,320	3,183.61	413.73	0.00000	***	43
	Sun Dried fish (Medium Variety)	1,793	3,875	2,082.35	106.28	0.00000	***	177
	Sun Dried fish (Small Variety)	2,015	3,150	1,134.60	44.62	0.00000	***	803
	Cooking oil	970	1,391	421.14	16.78	0.00000	***	2,282
	Salt	373	232	-140.63	6.80	0.00000	***	4,109
Sweets	Biscuits	675	617	-57.54	63.06	0.36230		277
	Buns, scones	572	747	175.23	29.98	0.00000	***	843
	Mandazi	708	665	-42.73	9.90	0.00002	***	1,193
	Sugar	671	394	-277.03	20.34	0.00000	***	2,355

Figure A. Monthly Variation in Cost of Nutrient Adequate Diet when Imputing Infeasible Diets with Infinite Cost, 2013–2017



Population statistics corrected using sampling weights. Seasonal factors estimated as in equation (7).