Availability, Seasonality, and Affordability of Nutritious Diets for All - Evidence from Malawi

by Kate R. Schneider, Luc Christiaensen, Patrick Webō, and William A. Masters

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Kate R. Schneider*, PhD MPA, Johns Hopkins University

Luc Christiaensen, PhD, World Bank

Patrick Webb, PhD, Tufts University, Friedman School of Nutrition Science & Policy

William A. Masters, PhD, Tufts University, Friedman School of Nutrition Science & Policy

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* Corresponding author: Kate Schneider, kschne29@jhu.edu

Abstract

There is great interest in increasing the affordability of nutritious diets. This study contrasts with previous work which focuses on requirements for a representative person, often a woman of reproductive age. Instead, we assess the availability, seasonality, and cost of nutritiously adequate diets relative to household income, explicitly accounting for differing individual needs as well as the common practice of meal sharing within households. Applying linear programming techniques, we calculate the least cost diet meeting each person's needs using individualized diets, as well as the least cost diet which accounts for meal sharing following Rawls' maximin principle, constituting lower and upper bounds on diet cost, respectively. To do so, we use monthly market prices from 29 markets in rural Malawi during 2013-2017 and information on household composition from two nationally representative household surveys. Results reveal that when meals are shared, ignoring demographic diversity within households greatly underestimates the availability, seasonality, and affordability of adequate diets. Individualized diets are more often available and lower cost, but still exhibit substantial seasonality and are unavailable or unaffordable for 44% of households, even if spending all resources on food. Providing supplements with higher nutrient density to children, breastfeeding women, and older adults can help meet each group's needs at lower cost throughout the year, but individualized diets would imply a major change in household eating patterns. Policies should also aim to make nutrient dense foods more widely and more continuously available and affordable.

Keywords: food prices, seasonality, diet costs, nutrient adequacy, affordability, meal sharing

JEL codes: Q18, D63, I30, J18, C61, D16

1. Introduction

An important criterion in assessing the performance of national and global food systems is increasingly the extent to which they can provide access to nutritious diets for all. Against this background, several recent studies have recently analyzed the cost and affordability of least-cost diets meeting nutrient adequacy[1], with nutrient adequacy based on minimum scientific nutrient requirements for optimal growth and long-term health (Bai et al., 2020a; Institute of Medicine of the National Academies, 2006; Masters et al., 2018), food-based dietary guidelines (Dizon et al., 2019; Herforth et al., 2019; Mahrt et al., 2019; Raghunathan et al., 2020), or the recommendations of the EAT-Lancet commission (Hirvonen et al., 2019; Willett et al., 2019), and also used least-cost diets to construct poverty lines (Allen, 2017). Each of these studies have focused on the diet cost for a single individual; namely, a woman of reproductive age. However, the balance of foods that would meet her needs is not the same items or proportions that will 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 all sub-population groups, their biological nutrient needs and distribution in the population, as well as household compositions and meal sharing norms. Further, many of the nutrient-dense foods required for adequate diets are only

[1] Originally developed by Stigler (1945), least-cost diets that meet minimum nutrition requirements calculated using linear programming have been used for a variety of policy purposes in countries across the income spectrum. In the US, a least-cost diet meeting national dietary guidelines is the foundation of the food-based family assistance provided by government (van Dooren, 2018). In low-income countries, least-cost diets have also been used to guide public sector and donor food, development and nutrition assistance programs (Chastre et al., 2007; Deptford et al., 2017; Optifood, 2012). Recently, the cost and affordability of high quality whole diets were calculated for most countries in the world as of 2017 (FAO et al., 2020; Herforth et al., 2020). Since every aspect of the food system contributes to the availability and prices of foods, and that the food basket of an adequate diet can change in response to availability and prices if nutrient requirements are satisfied, least-cost diets can reveal how well the food system delivers continuous access to nutritious diets. They can be calculated at the spatial and temporal disaggregation of available data (Bai et al., 2020a; Dizon and Herforth, 2018; Herforth et al., 2020; Herforth and Ahmed, 2015; Masters et al., 2018).

seasonally available and perishable. Least-cost diets substitute foods in response to availability and price, to the extent there are other sources of required nutrients available. This could moderate seasonal fluctuation in availability and cost of the diet relative to that of individual foods and help establish a lower bound on seasonality. It is an open empirical question, however, whether such substitution is possible or sufficient to smooth households' access to nutritious diets in the face of high seasonal variation in specific food item availability and prices.

This study asks whether diets meeting scientifically established nutrient requirements are available and affordable for families in rural Malawi throughout the year. Since nutrient needs differ depending on age, sex, maternity, and physical activity level, 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 upper limits). Costing individual diets for each person in a household and adding them up over all members provides a lower bound on the cost of an adequate diet for the entire family.

However, families in Malawi and around the world typically eat shared meals together (Gelli et al., 2019; Hjertholm et al., 2019). For common meals to achieve nutrient adequacy for each family member, they have to be 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., 2020). Costing this shared diet provides an upper bound on the cost of adequate diets for the family. It must include more nutrient dense foods to meet that shared set of needs than the summation of individuals procuring a diet meeting only their individual requirements.

The central contributions of this paper are threefold. First, we extend the least-cost diets framework from individuals to households. Most research on the cost and affordability of nutritious whole diets focuses on individuals of representative sub-populations, typically adult men and women of reproductive age (Bai et al., 2020a; Herforth et al., 2020; Hirvonen et al., 2019; Masters et al., 2018; Omiat and Shively, 2017). We introduce two methods to cost the diet at the household level, using a conceptual framework describing two household sharing parameters that can be used to calculate a bounded estimate on the availability and cost of a nutrient-adequate diet for whole families. Either could be used to guide policymaking or evaluate interventions, and where both are feasible, the range between them may also provide a useful policy indicator.

Second, we estimate the degree of seasonality in diet cost and assess how it relates to the availability of the diet and to seasonality in the prices of individual foods and food groups. 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 (Chirwa and Chinsinga, 2015; Devereux et al., 2013; Ellis and Manda, 2012; Gilbert et al., 2017; Sassi, 2012). Yet, whether this also translates into seasonality in diet costs remains largely undocumented[2]. Third, we estimate the proportion of households who have access to and can afford the least-cost nutrient-adequate diet under each scenario in their nearest market in the month the household was surveyed, relative to current food and total expenditure. By linking micro-level individual and household data with sub-national monthly food prices and new local food composition data, we are able to provide a detailed depiction of the distribution in access to nutritious diets in rural Malawi and at a monthly time scale permitting analysis of seasonal fluctuations. Our approach is unique in that it incorporates variation in household demographics and location and social norms of family

[2] Only one related study has examined the seasonality in total diet cost for adult women including in Malawi (Bai et al., 2020b), while another used seasonal data to develop recommended diets for low-income consumers (Chastre et al., 2009).

meal sharing.

The remainder of this paper proceeds as follows. Section 2 presents the conceptual framework supporting 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). 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 her 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. Those with lower iron density needs eating the shared meal will consume more than his/her minimum need but we ensure no member would exceed their upper tolerance. And the defining member for each nutrient can differ.

The lower bound on the household diet cost (henceforth "individualized diets") corresponds to the case where the combination of foods eaten by each member meets their own minimum requirements at the lowest aggregate cost. The upper bound (henceforth "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 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.

This 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, we have shown in related work that 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., 2020).

The diet cost offers two evaluative functions: first, to identify those who are unable to access 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 policymaking. Both the shared and individual diet cost indicators could serve this purpose. Households who cannot afford the lower bound ("individualized") diet cost definitively could not purchase a diet complete in all required nutrients for all members of the family. Households who commonly share meals and who can afford the diet at the upper bound cost are able to access a culturally-appropriate nutrient-adequate diet (Pritchett, 2006).[3] Households in between face a tradeoff between the effort required to tailor food resources to individuals and a nutritionally incomplete diet that may require less effort to procure and prepare since it can be shared by all. The effort required for individualized meal preparation not only includes time, planning, and monitoring food stocks, but possible social consequences of practicing socially deviant[4] food sharing behavior in a culture where eating from a common plate is the dominant norm (Gelli et al., 2019; Hjertholm et al., 2019).

Some degree of individual targeting may be feasible, but foods with high nutrient density are more expensive and actual meals consist of mixed dishes, so social norms and actual practices strongly favor meal sharing. With more individualized diets it might be possible to meet each

[3] By culturally appropriate, we mean that the diet would be adequate when shared as is consistent for cultural food sharing practices. Other considerations like food combinations and preferences would also be needed to generate resulting diets that are culturally acceptable. Note the similarity with the upper poverty line promoted by Pritchett (2006), i.e. the amount of income below which societies might start to consider people poor, as opposed to the commonly used extreme poverty line below which no one would dispute that the person is poor.
[4] Social deviance refers to a behavior that is judged to violate normative practices in the given context, to behave in a way that is contrary to social norms and judged under those norms to be inappropriate behavior (Kaplan and Johnson, 2001).

person's need at lower total cost, but since household decision-makers cannot observe each person's requirements or the nutrient composition of foods, there is no behavioral mechanism for that to occur.[5] Therefore, as a target for the transformation of food systems towards becoming nutrition sensitive, the policy objective in a culture where food sharing is the common practice, such as Malawi, might focus on the shared diet scenario. However, if the food system is unable to provide shared diets reliably throughout the year, the policy objective could focus on the lower bound diet, which would also necessitate behavior change efforts to encourage families to target foods based on nutritional needs. Either cost benchmark could be used to guide policies focused on reducing the cost of the diet. This objective 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.

3. Households, diets, and food prices in Malawi

Not all foods are available in all markets and all months because of seasonality and supply variability. Food security 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 and when food prices are highest (Chikhungu and Madise, 2014; Chirwa et al., 2012). These seasons correspond to the maize harvest, the crop that plays an outsized role in Malawi's food policy and in consumers' diets and whose prices have been most extensively studied (Gilbert et al., 2017; Schneider et al., 2020; Sibande et al., 2017). Seasonality

[5] Importantly, an infinite variation of inequitably shared and/or nutrient inadequate diets are possible at any cost, so one cannot infer the equitability or the nutrient adequacy of an observed household diet simply by its cost.

in 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., 2019; 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 and availability 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 29 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], 2017; National Statistical Office (NSO) [Malawi] and World Bank Poverty and Equity Global Practice, 2018). We further limit the analysis to rural households since the food price dataset covers only markets outside the main urban centers.[6] Since the surveys are representative of both urban and rural strata nationwide, our results can be considered representative of the rural population.

[6] While there is an earlier round of the IHPS data, the price data only contain more nutrient dense food items beginning in January 2013.

We use monthly prices for 51 food items collected between January 2013 and July 2017 by the National Statistical Office (NSO) in 29[7] markets across Malawi. The markets were purposively selected and are in district capitals and large trading towns outside of Malawi's four largest cities. The consumer food price index they are used to compute 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 et al., 2019). The list includes foods from all food groups. We match households to the district or sub-district market of their residence (National Statistical Office (NSO) [Malawi], 2018, 2012, 2011).

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, 2020).

[7] We identified households in 25 of the 29 markets (Supplemental Materials, Table A).

Table 1. Summary Statistics

	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, 1,220 urban households, 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 Materials 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).[8] All items are converted to kilograms using conversion factors provided by the NSO.[9] 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

[8] Specific information regarding food item composition matching records available in the replication data files. USDA records 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.
[9] Provided to the research team directly, available upon request.

(FAO and FHI 360, 2016; Kennedy et al., 2010; Ministry of Health (MOH) [Malawi], 2017; WHO, 2008).

We note that the least cost diets can only select from the menu of 51 items included in the price dataset and not all foods have a price observation in every market and month. The list includes all items that accounted for at least 0.02% of household expenditure in 2010.[10] We also note the food composition data have some gaps, particularly no data for nutrients in items where it may be present. When there are no data, we assume the nutrient content to be zero., Therefore, more of certain nutrients may be available than we estimate biasing the diet cost upward and feasibility downward, but only if the item *would have been selected* into the least cost diet had that nutrient information been present. In a related study, we find selenium to be the limiting nutrient but also note that selenium is the nutrient for which there are more foods with no data than for any other nutrient (Schneider, 2020). Joy et al. (2015a; b) and Phiri et al. (2019) measured the presence of selenium in soils, foods, and deficiency in the population and their conclusions support that there is little selenium present and available to consumers, suggesting that lack of information of the selenium content for certain food items is not driving our results.

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

[10] 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 Materials Table D).

Dietary Reference Intakes (DRIs). 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.). Scientific evidence sufficient to set an average requirement at the population level exists for most but not all essential micronutrients (vitamins and minerals). Our study is thus limited to macronutrients (carbohydrates, protein, fat), the micronutrients with sufficient evidence of the distribution of biological need to be included (vitamins A, C, E, B6, and B12, thiamin, riboflavin, niacin, folate, calcium, copper, iron, magnesium, phosphorus, selenium, zinc and sodium), and energy (Institute of Medicine of the National Academies, 2011, 2006).

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 (de Onis et al., 2007; Schneider and Herforth, 2020; WHO Multicentre Growth Reference Study Group, 2006). 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; National Statistical Office (NSO) Community Health Sciences Unit (CHSU) [Malawi] et al., 2017; WHO, 2008). 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 age four and above. To define the minimum amount for each nutrient in the shared diet, we identify the maximum 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 density of the shared diet. 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 household (h) by the individual needs of each household's members (m) age four and above for density of each nutrient (j), meeting energy needs (E) using the most restrictive of their nutrient density requirements for each upper and lower bound:

$$HHLower_{hj} = \sum_m E_m * max_m \{MinimumNeed_{j,m}/E_m\},\ j = 1, \ldots, 19 \quad (1)$$

$$HHUpper_{hj} = \sum_m E_m * min_m \{MaximumTolerance_{j,m}/E_m\},\ j = 1, \ldots, 13 \quad (2)$$

$$HHE_h = \sum_m E_m \quad (3)$$

To this we then add the individual requirements for energy and each nutrient of children six months through three years to arrive at the household total for which the least cost diet problem is solved.

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 the 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[11] minimizes total cost over all foods (i) within upper and lower bounds for all nutrients (j) and meets the specified energy budget (E). Adding data on price (p_i) for each food item (i) and its nutrient contents (a_{ij}) yields:

$$CoNA: minimize\ C = \sum_i p_i * q_i \quad (4)$$

Subject to:

$$\sum_i a_{ij} * q_i \geq Lower_j,\ \ j = 1, \ldots, 19$$

$$\sum_i a_{ij} * q_i \leq Upper_j,\ j = 1, \ldots, 13$$

$$\sum_i a_{ie} * q_i = E$$

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

Equation (4) is solved for each individual (with individualized requirements) and household (with shared requirements)[12] every month, using the foods and prices in the market of the

[11] Solved using the R package "lpSolve" (Buttrey, 2005).
[12] Replacing $Lower_j$, $Upper_j$ and E by equations (1), (2) and (3) respectively.

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).

As the foods observed and their prices vary by market and month, the CoNA index for every household is comprised of 36 observations from 2013-2015 and 19 observations from January 2016 to July 2017 (55 months total), at both upper and lower bounds.

We focus on two primary results from the linear modeling: availability and cost. If the model cannot identify a solution, it indicates that the available foods – the 51 items in the price list, or the subset for which prices are present in any market and month – cannot satisfy all the nutrient requirements at any cost. Where the market price list does not have an observation, to the best of our knowledge it reflects seasonal unavailability or an item that is never present in that market (Kaiyatsa et al., 2019).[13] We use the binary outcome of a solution or no solution as an indicator of the availability of an adequate diet, given the available foods and the household's requirements. 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.

[13] Supplementary Materials Figure A shows the prevalence of missing prices by item and 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 (Denton, 1971; International Monetary Fund, 2018; World Bank, 2015). We calculate monthly food and total expenditure based on one month of annualized expenditure calculated following Deaton and Zaidi (2002). We then proceed to study two aspects of these two least cost indicators: their fluctuations within the year and their affordability.

Seasonality

The seasonal price gap is a standard indicator used to measure the extent of seasonality in food and agricultural commodity prices. It is defined as the difference between the peak and trough prices, most commonly observed just before and just after the harvest. Since the linear programming model will substitute among foods given availability and prices, it is an empirical question whether least-cost diets follow the same seasonal trends as individual foods' prices. This also necessitates careful consideration of the best model to estimate seasonality in the cost of whole diets.

We ruled out linear detrended seasonal dummy and moving average deviation models for their limitations detailed in Gilbert et al. (2017).[14] 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 (Bai et al., 2020b; Gilbert et al., 2017; Kaminski et al., 2016; Kotu et al., 2019; Ray et al., 2001; Wassie et al., 2019). Gilbert et al. find the more parsimonious trigonometric method to be preferable for food price data. When applied to our least cost diet indicators, this translates into:

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

Where *C* is the log diet cost observed, in nominal terms, for household (h) in year (y) and month (m). We use the cost in nominal terms since food expenditure comprises a large proportion of budget shares and 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:

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

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

However, the disadvantage of the trigonometric specification is that it imposes vertical and horizontal symmetry to the pattern and will perform poorly if the time series is not well

[14] 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.

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 be multiple local maxima and minima. A stochastic trend seasonal dummy model allows for multiple fluctuations within the year. The estimating equation is specified allowing for gaps of *k* months prior to the observation in time (y,m) as follows:

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

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

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

And the seasonal factors are calculated by demeaning the coefficients as:

$$s_m = \delta_m - \frac{1}{12}\sum_{i=1}^{12} \delta_i \;\; (m = 1, \ldots .12)$$

We run both models (5)-(6) and (7)-(8) and present model fit statistics. Both models can allow for gaps in the data, which typically are due to missing prices, where the differences are calculated as the difference between a price observation and the most recent preceding observation. But in our case, gaps are the household-months with no solution to the linear programming problem. In those settings, foods with sufficient nutrient density were not available in local markets to meet the specific needs of the household given its location and composition. An alternative way to think about it is that the cost of the least cost diet was very high. 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.

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 probability of an available diet, conditional on the month and by scenario (individualized and shared least cost diets), modeled with a linear probability model as follows:

$$A_{hym} = \gamma + S' + v_m + \mu_{hym} \tag{9}$$

Where *A*, is a binary indicator of diet availability for household (h) in time (y,m) and *S'* is a vector of dummy variables for the month. We estimate equation (9) for each scenario separately using a linear probability model controlling for market (v). The seasonal factors on availability 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 at the food item level (in nominal terms), allowing gaps where no price was observed, and then regress the difference in price on the seasonal dummies for each food group separately. 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

We develop relative ratios of the least diet cost to food and total spending in the month the household was surveyed and of the two diet scenarios to each other. We analyze affordability for all household-months with a solution to the least-cost diet in their month of survey for two reasons. First, the nutrient requirements are most accurately estimated in that month; our time series allow for a change in household requirements only at the second survey observation even though in reality individuals age in between those time points in ways that may change their nutrient needs. Second, annual household expenditure estimates are likely to vary systematically by survey month. Many expenditure categories are collected on short recall periods and will differ greatly between seasons due to the seasonal nature of incomes (Chikhungu and Madise, 2014; Kaminski et al., 2016; National Statistical Office (NSO) [Malawi] and World Bank Poverty and Equity Global Practice, 2018). Relative expenditure ratios compare the daily cost for the whole household, per scenario, to one day's worth of annual food or total expenditure, in nominal terms. The premium for the shared diet is the ratio of shared to individualized diets daily cost, in nominal terms.

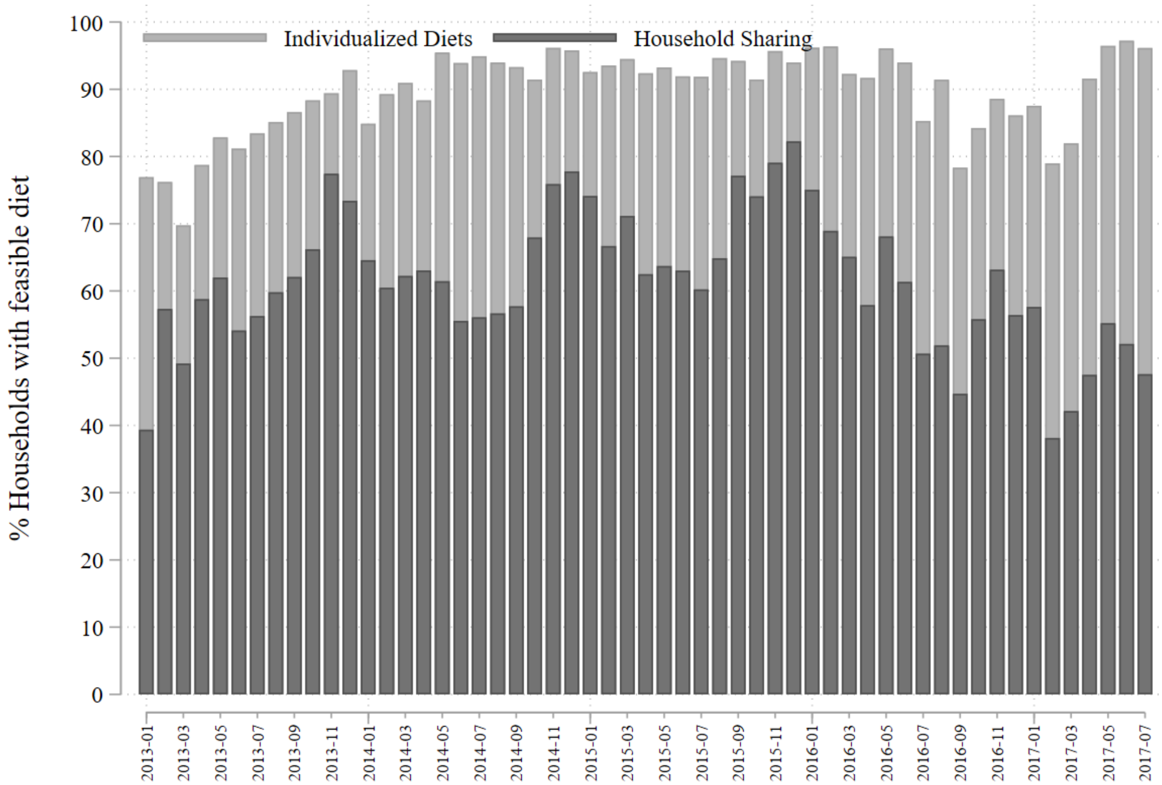
5. Results

Availability & Cost

Figures 1 and 2 summarize the availability and cost of the least-cost nutrient-adequate diet under each sharing scenario for every month from January 2013 to July 2017. Figure 1 depicts the availability – the percent of households in each month for whom a nutrient-adequate diet is feasible – and Figure 2 presents diet cost per capita per day, by sharing scenario. We find the individualized diets are consistently more feasible and (as expected) lower cost than the shared diet. Considering all months between January 2013 and July 2017, the individualized diets are available 90% of all household-months, on average, while the shared diets are available only 60% of the time. And 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 availability of the lower bound diet for a generic individual of each age and sex group in every market and month (Supplementary Materials Table B) shows that it is children six months through three years, breastfeeding women, and older adults (70+ years) for whom an adequate diet is not available in nearly all markets and months.

For each household-market-month, if the individualized diets are available but the shared diet is not, the latter must be due to the shared nutrient requirements determined by household composition. The shared nutrient requirements increase the lower bound density needs of the diet but also decrease the allowable upper limit, resulting in a tightened range between enough of the nutrient and too much. When the shared diet is infeasible it means that the foods available cannot meet the minimum lower bounds for some nutrients at all or cannot do so without exceeding the upper bounds for others (Schneider et al., 2020). The shared diet may be more sensitive to seasonality in item availability when attempting to find a diet solution meeting these narrower constraints. In a related study, we use scenario analysis to identify the limiting nutrients as selenium and copper, where the available sources cannot satisfy minimum selenium requirements without exceeding copper upper bounds (Schneider, 2020).

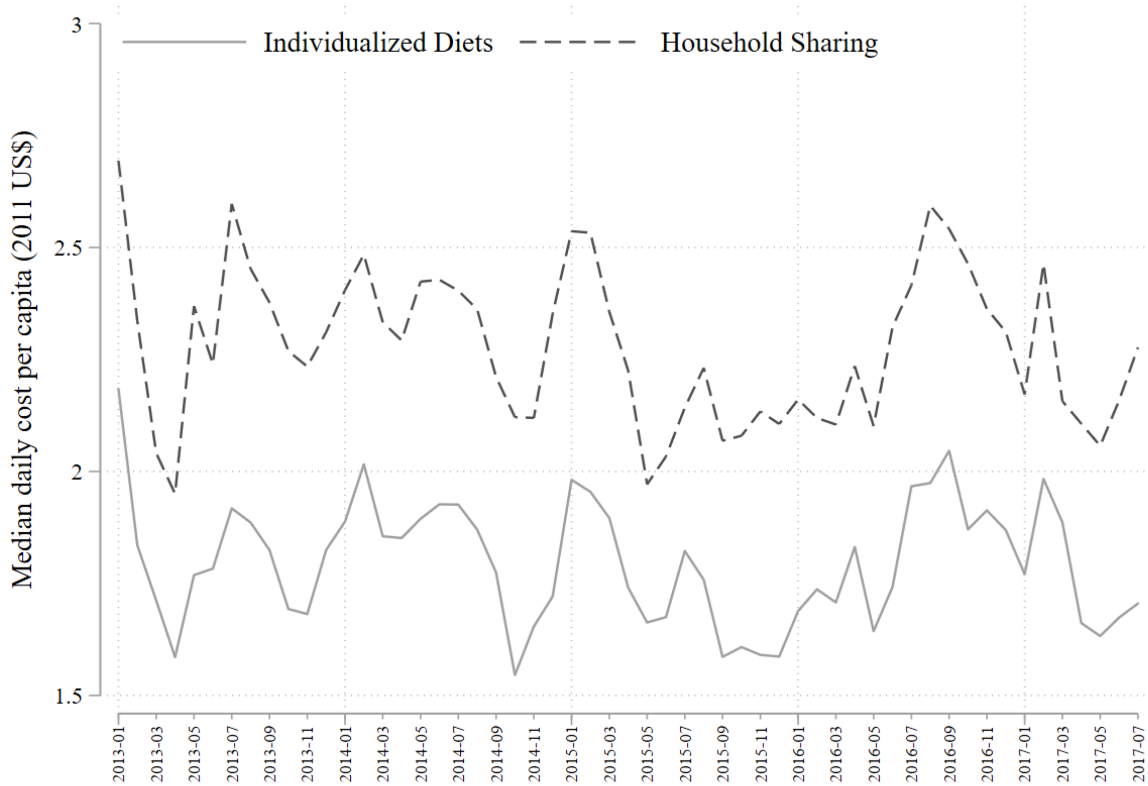
Figure 1. Availability of Household Nutritious Diet, by scenario



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

The individualized diet was most available in the period between the 2014 and 2016 harvests, while the shared diet demonstrates clearer seasonal fluctuation in availability. 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 available in December. One potential explanation for this is the greater availability of animal source foods (ASFs) during those months for cultural reasons, as many Malawians only consume meat during the holidays (particularly Christmas). More fish is also available in preparation for the spawning season fisheries ban (FAO, 2005; Gelli et al., 2019; 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., 2019). 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.[15] We also see indications that the years surveyed (2013, 2016/17) were slightly different than the intervening years.

Figure 2. Cost of Household Nutritious Diet, by scenario



Population statistics corrected using sampling weights.

Seasonality

Figures 1 and 2 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 presents the probability of an available diet, conditional on month (equation (9)), the monthly seasonal

[15] 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 and in the regression framework presented above that controls for the price trend and therefore can isolate the seasonal gap estimate.

factors on diet cost (equation (8)), and the average availability and median cost/person/day. For the diet cost, model fit statistics (Supplementary Materials Table C) 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. Figure 3 presents the results visually.

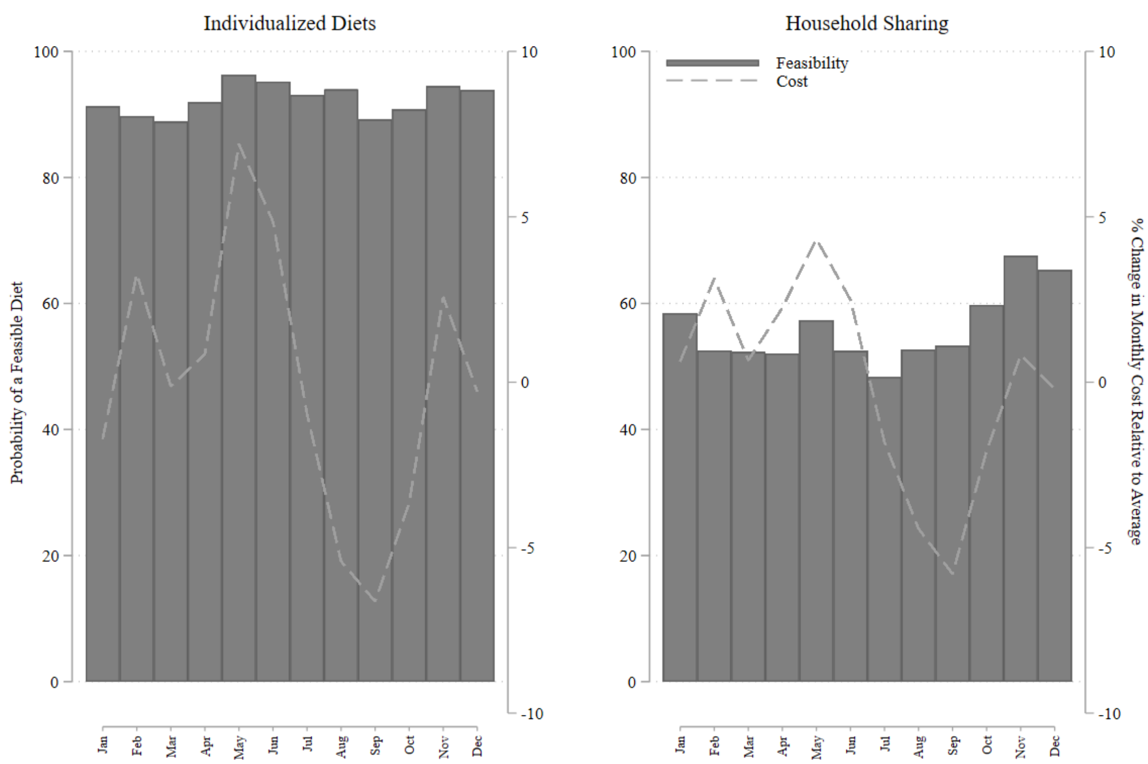
Table 2. Seasonal Variation in Diet Availability and Cost, 2013–2017

	Probability of Available Diet *Estimated Percent Available*‡		**Difference in Diet Cost Relative to Mean** *Seasonal Factors**	
	Individualized Diets	Household Sharing	Individualized Diets	Household Sharing
January	91.23	58.41	-1.70	0.63
February	89.69	52.51	3.28	3.13
March	88.80	52.25	-0.13	0.66
April	91.89	52.03	0.85	2.25
May	96.24	57.29	7.20	4.33
June	95.19	52.42	4.85	2.49
July	93.05	48.31	-0.96	-1.81
August	93.91	52.64	-5.41	-4.43
September	89.15	53.26	-6.63	-5.79
October	90.73	59.73	-3.65	-2.08
November	94.44	67.53	2.58	0.82
December	93.82	65.26	-0.28	-0.21
Seasonal Gap	7.44	19.22	13.82	10.12
Mean Availability† (% Household-Months)	89.72 (0.91)	60.18 (1.56)		
Median Cost, per capita per day† (2011 US$ PPP)			1.79 (0.03)	2.26 (0.04)

‡ Probability of an available diet calculated as in equation (9), interpreted as the percent of households with a feasible diet on average each month. The seasonal gap in availability is the percentage point difference between the most available and the least available 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 availability, as noted above the individualized diet is more often available 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 availability – defined here as the percentage point difference in availability between the most and least available 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. In the months where the shared diet is most available, it is still 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 availability 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 available. 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 available.

Figure 3. Monthly Variation in Feasibity and Cost of Nutrient Adequate Diet, 2013–2017



Population statistics corrected using sampling weights. Seasonal factors estimated using stochastic trend dummy variables regression of diet cost as in equation (7). Probability of available diet estimated by a linear probability model conditional on month 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 3 presents the seasonal variation in diet cost by scenario using the imputed data and Figure 4 illustrates this visually, putting a lower bound on seasonality, as the highest observed cost is still lower than the theoretical infinite cost.

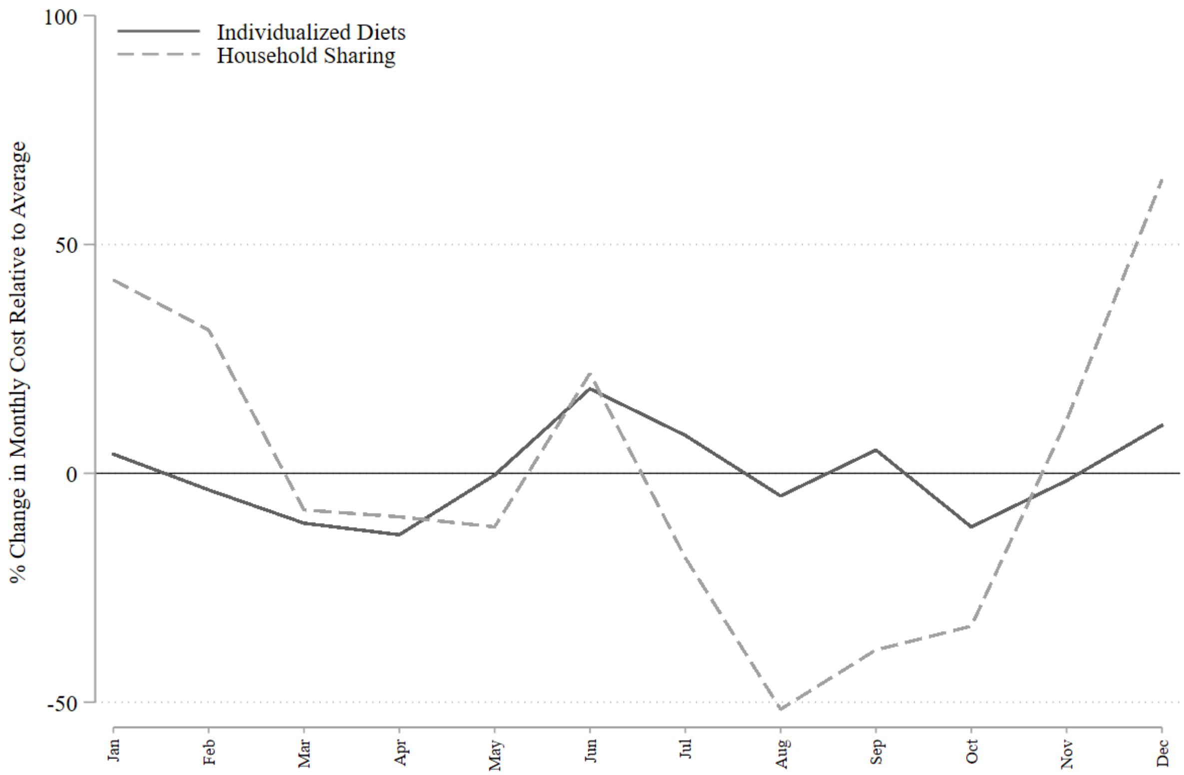
Table 3. Seasonal Variation in Diet Cost, Imputing Infeasible Diets at Highest Observed Cost, 2013–2017

	Diet Cost	
	Individualized Diets	Household Sharing
Seasonal Factors*		
January	4.19	42.24
February	-3.61	31.30
March	-10.89	-7.99
April	-13.42	-9.50
May	-0.38	-11.70
June	18.47	21.83
July	8.30	-18.43
August	-4.94	-51.53
September	5.10	-38.56
October	-11.71	-33.40
November	-1.61	11.61
December	10.49	64.14
Seasonal Gap	31.89	115.67

* Seasonal factors interpreted as the percentage point difference in average cost in that month relative to the average over all months of the year.

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 (Supplementary Materials Table B). We see 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. Figure 4 shows that the individualized diets have much more limited seasonal fluctuation while the shared diet varies greatly from month-to-month, suggesting 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.

Figure 4. Seasonal Variation in Diet Cost Imputing Infeasible Diets at Highest Observed Cost, 2013–2017



Population statistics corrected using sampling weights. Seasonal factors estimated using stochastic trend dummy variables regression of diet cost as in equation (7), imputing the cost of the diet to be the highest observed per month when unavailable.

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. Table 4 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 separately for each food group) based on the trigonometric model as in equations (5) and (6), which was preferred by model fit statistics.[16] 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., 2020b).

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 et al. (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.

[16] 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).

Table 4. Seasonal gap in food group median prices

Food Group	N items	Seasonal Gap (%)
Cereals††	6	12.1
Green leafy veg	3	22.9
Eggs	1	7.4
Fish	4	8.6
Meat	4	7.9
Legumes	5	11.1
Milk	2	7.0
Oils	2	10.9
Other fruit‡	3	13.8
Other vegetable	6	10.9
Roots & tubers	3	21.2
Vit A rich fruits	4	19.7
Vit A rich veg†	1	57.8
Maize grain	1	21.0
Admarc maize	1	24.5

Notes: Heteroskedasticity robust standard errors clustered at the market level. Trigonometric regression estimated over all items by food group.
†† Cereals includes maize grain, Admarc maize grain, maize flour dehulled, maize flour whole grain, rice, white bread.
‡ BIC equivalent for fixed effects dummy and trigonometric specifications.
† 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.

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., 2020b; Brenton et al., 2014; Shively and Thapa, 2017). In other words, it is the amount of seasonality in the cost of nutritious diets that would be unavoidable under current conditions reflecting the best achievable smoothing over the year by using food item substitutions to meet nutrient needs.

Affordability

Table 5 presents the availability, 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 available to almost 87% of households in the month the household was surveyed at a median cost of $1.83/person/day[17]. 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 an available 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 available at all, which is a lower bound on the premium when considering infeasible diets to have infinite cost.

[17] Note that Table 5 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.

Table 5. Nutritionally Adequate Diet Availability, Cost, and Affordability in Month of Survey

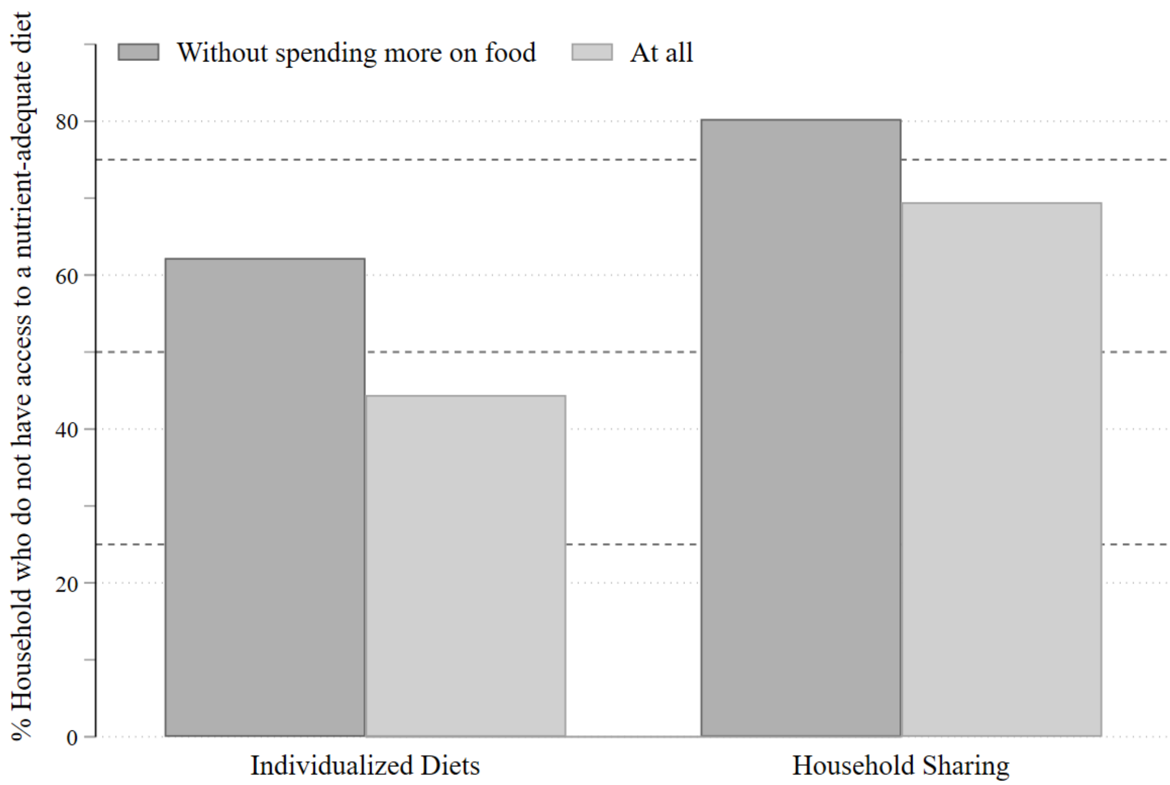
	2013 – 2015		2016 – 2017		Overall	
	Median	(SE)	Median	(SE)	Median	(SE)
Lower Bound: Individualized Diets						
Households with available diet in month of survey (%)	83.71	(3.02)	88.45	(2.39)	86.73	(2.12)
Cost per day (household)	7.51	(0.26)	8.31	(0.37)	7.96	(0.29)
Per capita	1.85	(0.07)	1.82	(0.08)	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 available 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. Heteroskedasticity robust standard errors clustered at the enumeration area level.

If we consider that households for whom the diet is unavailable as also not being able to afford the diet, then we can estimate the share of the population for whom the adequate diet is out of reach, depicted in Figure 5. Since the lower bound cost is the least costly way for a household to meet all members' nutrient needs, those for whom it is unavailable, 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 available but unaffordable without increasing current food expenditure (though technically affordable within total expenditure). In total, 62% of rural Malawians cannot access any adequate diet at all – not even the lower cost individualized diet – because it is unavailable, 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 unavailable or costs more than all of their resources (total expenditure). For an additional 10.5%, the diet is available 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 available 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 and without fully sharing meals in accordance with social norms.

Figure 5. Inaccessibility of Adequate Diet in Month of Survey



Population statistics corrected using sampling weights.

6. Discussion

In this paper, we asked whether a nutrient-adequate diet is available and affordable for rural Malawian households year-round. We developed two methods to calculate least-cost nutrient-adequate diets for whole households. 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; it also countervails social norms of family food sharing from a common plate. 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 (Ravallion, 2016; Rawls, 1971).

We find consistently that a combination of foods that can meet the higher diet quality demanded when families share common meals is less likely to be available and costs more, on average, than if families were to pursue individualized diet strategies. The cost for the median household – 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 and is more likely to be available (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.

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 available, (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 availability of a feasible diet for all members of the household under both scenarios, driven in the lower bound case by certain nutritionally vulnerable household members for whom the diet is not always feasible (Supplementary Materials Table B). The observed seasonal gap in the cost of the lower bound diet – which we estimate to be approximately 13% when the diet is available 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 remains substantial, and cannot be ignored.

We estimate 44% of rural Malawians cannot afford the adequate diet *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 available and affordable to 20% of households within their current food budgets. That leaves 80% of households who cannot afford the socially normative shared diet either because it is unavailable or costs more than current food spending, and 69.5% for whom it is unavailable or costs more than all available resources.

The least-cost diet metric at the household level could be useful for numerous policy purposes. 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. Additionally, 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). 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 available 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).

Although sharing meals is the common 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. Therefore, our findings suggest that for policy purposes where the cost of the diet is relevant, such as targeting vulnerable households and determining the size of transfers, the household-level least-cost diet computed using the lower bound method would likely be more appropriate in the short term. However, where food sharing is common accompanying nutrition education and social behavior change communication is needed to target nutrient-dense foods to the nutritionally neediest members, most often women and girls (Schneider et al., 2020). In the long-term, policy objectives could focus on making the shared diet available 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 (Chastre et al., 2009; Cost of Nutritious Diets Consortium, 2018; Frega et al., 2012; Nykänen et al., 2018; WFP, 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 Dataset Observed in IHPS Dataset

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. 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 C. 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

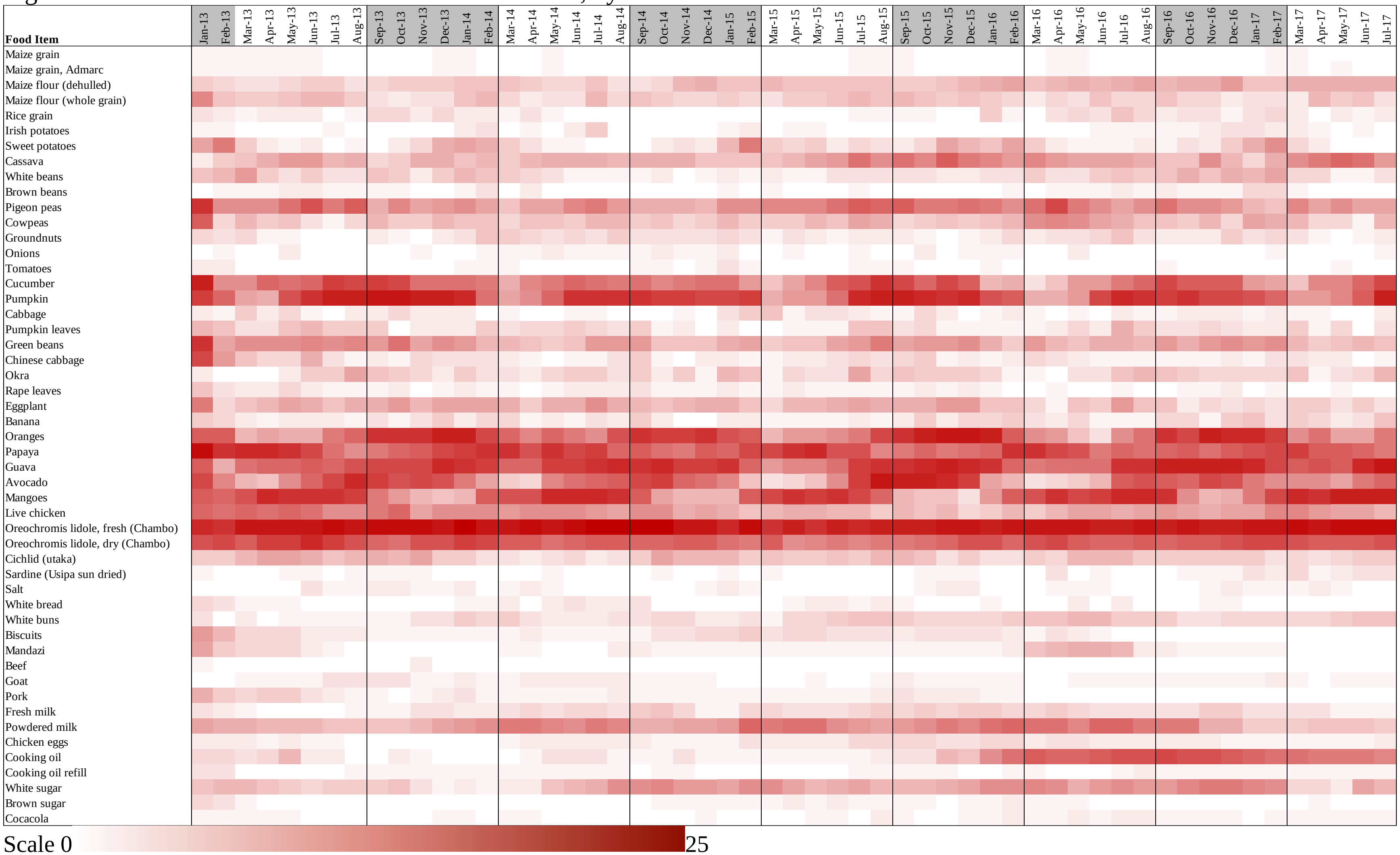
Population statistics corrected using sampling weights. Preferred specification in bold.
AIC and BIC are reported on a per observation basis.
Heteroskedasticity robust standard errors clustered at the enumeration area level in all specifications.
$^{*}p < 0.05$ $^{**}p < 0.01$ $^{***}p < 0.001$

Table D. 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	(SE)	**2016/17** Mean	(SE)	**Overall** Mean	(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.

Figure A. Number of markets where item is unavailable, by food item and month



Gray dates indicate identified lean season.

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

Admarc maize grain indicates maize available from the parastatal Agricultural Development and Marketing Corporation.