AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
<http://ageconsearch.umn.edu>
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

**Nationally representative estimates of the cost
of adequate diets, nutrient level drivers, and
policy options for households in rural Malawi**

by Kate R. Schneider

Copyright 2021 by Kate R. Schneider. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

**Nationally representative estimates of the cost of adequate diets,
nutrient level drivers, and policy options for households
in rural Malawi**

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

June 30, 2021

*Selected paper for the 31st International Conference of
Agricultural Economists, New Delhi, India, 20-25 August, 2021*

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

Abstract

A growing literature uses the cost of diets to evaluate how effectively a food system supports access to nutritious foods. We identify baseline levels, nutrient drivers, and potential policy-induced changes in the feasibility and cost of meeting nutrient requirements for whole households based on aggregate needs in rural Malawi from 2013 – 2017. We determine the availability and cost of a nutrient-adequate diet each month using the price and composition of foods available at the nearest market. We run more than 1 million models in total, one for every household in each month under baseline and eight policy simulation scenarios. We find diets containing adequate nutrients for whole families to be available 60% of the time from 2013–2017, and when available, costing an average \$2.32/person/day (2011 US\$ PPP). Further, we illustrate that as households grow in size and diversity of member types, the cost to acquire 1,000 calories of a sufficiently nutrient dense diet increases. Our policy simulations reveal that selenium is the nutrient hindering the availability of diets adequate and balanced in essential nutrients, but that riboflavin is the costliest nutrient to obtain in the market when a least-cost diet is available. We estimate selenium soil biofortification of maize would result in nearly universally available (94%) adequate diets at half the cost (\$1.22/person/day on average). This far exceeds the potential impact of price or availability changes of foods dense in the costliest nutrients including eggs, milk, groundnuts, and dried fish. No other scenario improves availability or exceeds 1% average cost reduction. Of direct relevance to agriculture and nutrition policy in Malawi, this study demonstrates how the availability and cost of whole diets and the shadow prices of individual nutrients in retail markets can be used to identify barriers to accessing an adequate diet and estimate the potential impacts of policy options.

Keywords: least-cost diets, nutrient requirements, shadow prices, policy modeling, linear programming, nutritious diets, biofortification

JEL Classification: C610, Q180

1 Introduction

Access to a nutritious diet for all individuals is necessary for optimal growth and long-term health yet many food systems are unable to facilitate such access. Least-cost diets are particularly amenable as a food system metric since they are flexible to changes in the availability and price of foods, considering all food items that could supply required nutrients while keeping total diet cost at a minimum (Allen 2017; Masters et al. 2018; FAO et al. 2020). Most research on nutritionally adequate least-cost diets has focused on a few representative types of persons, since nutrition needs vary by age, sex, physical activity, and reproductive status. Our approach is unique in focusing on the household as the unit that procures food and eats shared meals. It is not only a simple aggregation of members and their individual needs but incorporates the reality that a shared meal has to be of greater nutrient-density over all nutrients when eaten by individuals with differing needs than a diet that would satisfy any one member's needs alone. Therefore, household level least-cost diets calculated using subnational retail market prices identify how well national food systems are able to deliver diets that meet the needs of all members of the population in their nearest markets, at affordable prices, and in the proportions needed when families share meals.

In this paper, we run nearly 1.5 million linear models to estimate the least-cost diet and nutrient shadow prices for 3,117 real households comprised of 15,374 individuals observed in Malawi's recent Integrated Household Panel Survey (IHPS). Each household is matched to their nearest of 25 main district markets where monthly food prices are systematically collected for 51 regularly consumed food items. We use linear programming to calculate the least-cost diet meeting the household's total energy need and minimum requirements for 19 nutrients, without exceeding limits for 13 nutrients, in every month from January 2013 through July 2017. Shadow prices of individual nutrients identified from the dual result to the linear optimization problem uncover the nutrients driving the cost on the margin. We model the base case under current availability and prices and eight policy scenarios. We select the policy scenarios based on the shadow price results and analysis of current diets, to focus on food sources of the nutrients most under-consumed in present diets and costliest to obtain. The scenarios reflect stylized outcomes of feasible interventions; when compared they illustrate which efforts would be most effective in improving availability and access to nutritious diets.

Most Malawians consume diets that are poor in overall quality, which leads to risks of micronutrient deficiencies. Recent evidence of nutrient status measured directly with biological samples, showed high prevalence of zinc deficiency, moderate prevalence of anemia (low hemoglobin), iron deficiency in certain subpopulations, widespread folate deficiency among women of reproductive age, and vitamin B12 deficiency in the rural population. Coupled soil and human analysis has also demonstrated that extensive deficiency of soil selenium is associated with deficiencies in dietary intakes and low selenium status

(Hurst et al. 2013; Joy et al. 2015a; b; Phiri et al. 2019). Household survey data from Malawi have repeatedly shown that food expenditures are biased towards maize and to a lesser extent other staples, resulting in insufficient dietary intakes of many essential nutrients (Joy et al. 2015b; Aberman, Meerman and Benson 2018; Gilbert, Benson and Ecker 2019). In prior research, we found households to be consuming diets biased towards carbohydrates and inadequately dense in more than half of all nutrients, especially phosphorus, riboflavin, lipids, selenium, and vitamin B12 (Appendix B, Table B-1) (Schneider et al. 2020b).

Common inadequate intakes of certain nutrients that cause debilitating diseases of deficiency have led to their recognition as the nutrients of greatest public health concern, including vitamin A, certain B vitamins, calcium, iron, zinc, and iodine (WHO and UNICEF 1998; Martin-Prével et al. 2015). However, all essential nutrients are necessary for optimal growth and long-term health and deficiencies impede the many body functions to which each contributes directly, as well as the functions played by other nutrients with overlapping roles. For instance, selenium is an important antioxidant and deficiencies in selenium draw down the body's resources of other nutrients with this same function – e.g. vitamin C, vitamin E, and zinc – reducing the quantities available for the other functions those nutrients perform such as immunity, wound healing, metabolizing other nutrients, and growth. Similarly, riboflavin is required to metabolize energy and other micronutrients including folate and vitamin B12, which lead to non-iron deficiency anemia if unmetabolized even when dietary intakes are sufficient (Institute of Medicine of the National Academies 2006; Byrd-Bredbenner et al. 2016).

Every aspect of the food system ultimately determines the availability, quality, and price of food items and therefore the ability of consumers to access a diet complete in all essential nutrients (FAO 2013; Global Panel on Agriculture and Food Systems for Nutrition 2014, 2020; Fanzo 2014; FAO et al. 2020). Nutrient adequacy is a necessary but insufficient component of a healthy, or high quality, diet (Ruel, Harris and Cunningham 2013; FAO 2016; FAO et al. 2020; Herforth et al. 2020a). The hallmarks of a high-quality diet include nutrient adequacy, macronutrient balance, energy consumption in proportion to needs, and variety (Trijsburg et al. 2019). Achieving adequacy without exceeding macronutrient and energy intake requires many nutrient-dense foods in the overall diet. Nutrient density refers to the quantity of essential nutrients per unit of energy. Fruits, vegetables, nuts, legumes, dairy and lean meats are considered nutrient-dense while items providing the majority of energy from simple carbohydrates (e.g. sugar, refined flours) or saturated fats are not (Trijsburg et al. 2019).

Whether high quality diets are available and/or affordable is of key concern for policymakers and an active area of research (for a comprehensive discussion, see FAO et al. 2020). Globally, low-income consumers are more likely to have poorer quality diets and health outcomes than wealthier consumers; food prices are often implicated to explain this disparity in countries across the income spectrum (Darmon and

Drewnowski 2015). Many researchers have focused on classifying foods and diets as healthy or less healthy to assess their relative costs (Monsivais, Mclain and Drewnowski 2010; Rao et al. 2013; Wiggins et al. 2015; Headey and Alderman 2019). The appeal of a least-cost diet approach, in contrast, is that the food basket changes in response to availability and prices and is agnostic to the exact food mix as long as requirements are met (Masters et al. 2018; Herforth et al. 2020a). Calculating the diet cost at the household level incorporates the reality that families procure food as a unit and can be compared to incomes, typically also measured at the household level.

We argue our household least-cost diet metric is not only realistic in incorporating family food sharing, but also serves the policy information need of decision-makers across sectors. It is consistent with the information commonly used for food and social protection policy and can be modeled at the same spatial and temporal disaggregation as the underlying food price data (Masters et al. 2018; Dizon, Herforth and Wang 2019; Herforth et al. 2019; Bai et al. 2020). Retail food prices are already tracked by national agencies to monitor inflation and inform food policy decisions and offer a readily usable data source. Consumer price indices are traditionally weighted by observed household food expenditure shares, regardless of the quality of household diets (Masters et al. 2018). In countries such as Malawi where diets are heavily staple-based, changes in cereal prices dominate monthly variation in the food price index regardless of whether or not they comove with the prices of nutrient-dense foods. Least-cost diets instead demonstrate the movement of food prices in the proportions corresponding to the nutrient needs of the population.

This paper proceeds as follows. Section 2 summarizes the related literature. Section 3 presents the data, methods, linear optimization model, and policy scenarios. Section 4 presents the results. Section 5 concludes.

2 Related literature

Our study is motivated by, and extends, several existing bodies of literature. The first uses least-cost diet methods to identify the lowest cost diet that meets specific nutrition requirements or food-based dietary guidelines to track the cost of those diets (Stigler 1945; O'Brien-Place and Tomek 1983; Allen 2017; Masters et al. 2018; Herforth et al. 2019). Similar applications develop recommended cost-minimizing diets for low-income consumers (Carlson, Lino and Fungwe 2007; Chastre et al. 2009; Frega et al. 2012; WFP 2013). The second line of research aims to understand the importance of food markets to food security and nutrition relative to the importance of own production for rural, smallholder farming households where market failures are common and market access limited, and to assess the implications of retail food prices for household welfare and nutrition for low-income consumers (Hoddinott, Headey and Dereje 2015; Romeo et al. 2016; Hirvonen and Hoddinott 2017; Stifel and Minten 2017; Sibhatu and Qaim

2018b; Headey et al. 2019). The final body of literature focuses on the shadow price of individual nutrients. The majority of this literature concentrates on the demand side and aims to estimate complete demand systems or identify shadow prices from observed behavior (Drèze and Stern 1990; Beatty 2007). We contribute to the small but growing literature on shadow prices in the market relative to nutrient needs or other dietary constraints calculated using linear and non-linear programming (Darmon, Ferguson and Briend 2002; Håkansson 2015; Parlesak et al. 2016).

2.1 Least-cost Diets

Least-cost diets that meet minimum nutrient requirements calculated using linear programming are increasingly employed to track the cost of foods and nutrients and make dietary recommendations for low-income populations. Originally developed to minimize costs and provide sufficient nutrients for military readiness during World War II (Stigler 1945), the US still uses this method to calculate the “Thrifty Food Plan” underlying the calculation of household Supplemental Nutrition Assistance Program (SNAP) benefits (Carlson et al. 2007; Wilde 2013; van Dooren 2018). Least-cost diets are also used in other settings to track the cost of foods and nutrients, plan institutional menus, guide a variety of food and nutrition programs, and have been proposed for use in the calculation of poverty lines (Calkins 1981; Chastre et al. 2009; Optifood 2012; Allen 2017; Deptford et al. 2017; Akhter et al. 2018; van Dooren 2018; Masters et al. 2018; Ravallion 2020). They are also commonly used in animal nutrition (Dumas, Dijkstra and France 2008; Saxena and Khanna 2014).

Least-cost diets are relatively straightforward to compute, requiring data on the available food items, their nutrient composition (or food group for dietary diversity- or dietary guidelines-based constraints), market prices, and nutrition requirements (needed amounts of each nutrient or food group). Nutrition constraints can be specified as the quantity of each essential nutrient needed according to international standards or according to other standards of diet quality such as dietary diversity or food-based dietary guidelines (Chastre et al. 2009; Optifood 2012; Daelmans et al. 2013; Masters et al. 2018; Dizon et al. 2019; Herforth et al. 2019, 2020b; Schneider et al. 2020a; Raghunathan, Headey and Herforth 2020). Statistical or basic spreadsheet software can easily solve the mathematical minimization problem for small datasets, though high-power computing becomes required for larger datasets such as are used in this paper.

Several studies have used least-cost diets to track the cost of food and nutrients over time, across countries, or in comparison with observed consumption patterns or incomes. Two recent analysis focused on the global scale. The 2020 State of Food Insecurity in the World report focused on “Transforming food systems for affordable healthy diets” and included global estimates of 3 least-cost diets that were 1) energy-sufficient, 2) meeting the minimum nutrient needs (lower bounds) and not exceeding upper bounds,

and 3) adhering to dietary guidelines (adequate servings and variety of food groups), all estimated for the needs of a representative adult woman of reproductive age (FAO et al. 2020). In low-income countries, on average, the diets cost \$0.70, \$1.98, and \$3.82 per day for a single woman (2011 US\$ PPP). The nutrient-adequate diet was least expensive in low-income countries while the higher quality recommended diet was least expensive in high-income countries. Nutrient adequacy was estimated to be affordable by 91% of the sub-Saharan African population overall, relative to average national food expenditure per capita. However, there was substantial variation by region, with West Africa facing the least affordability and Malawi among countries where the adequate diet costs one to two times average per capita food expenditure. The recommended diet was estimated to be unaffordable in more than 70% of countries on the continent, including Malawi (FAO et al. 2020). Hirvonen et al. (2019) identified the lowest cost combination of food items that meet the EAT-Lancet Commission guidelines for sustainable diets across 159 countries based on 2011 retail food prices. The authors found that the diet cost more than per capita household income for at least 1.58 billion people worldwide (Willett et al. 2019).

Some least-cost diet studies focus on single countries or regions, tracking change over time or differences among people. For example, (O'Brien-Place and Tomek 1983) measured food price inflation in the US from 1970-1980 based on least-cost diets meeting minimum nutrient requirements for 12 population subgroups, including adults and children, both with and without palatability constraints. They found inflation in the least-cost diet to be lower than that of the consumer price index by 10-20%. Omiat and Shively (2017) calculated least-cost diets that meet the minimum nutrient needs of an adult man and woman in Uganda from 2000-2011 finding that the cost grew three to nine percent in real terms over the period. Accounting for cultural preferences increased the lowest cost at which nutrient and preference constraints could be met, resulting in a cost above the poverty line most of the time. In France, Maillot et al. (2017) found that most consumers could move from an inadequate to adequate diet without increasing total food budgets, but that the shifts required for the lowest income consumers would be difficult practically. (Masters et al. 2018) show that in Ghana, the monthly cost of meeting dietary diversity recommendations increased 10% faster than inflation from 2009-2014, while the cost of meeting nutrient adequacy doubled over that same period. In the same study, with respect to Tanzania, the authors found that seasonal fluctuations in the composition of the diet were pronounced but that the total diet cost changed only slightly from 2009-2014.

The studies above focus on individuals, while our emphasis on households is related to literature using least-cost diets as a planning tool for farms and families. Calkins (1981) uses optimization modeling to identify the optimal crop and livestock mix to maximize both profit and nutrition for a representative Nepalese household under a variety of scenarios. The study found shifting from existing cropping practices (predominantly paddy-fallow lowlands, wheat-millet or -radish then fallow in uplands) towards

greater production of potatoes, radishes, rape and a variety of other vegetal crops would provide increased nutrition and greater profit opportunity. Johnson, Masters and Preckel (2006) compute individual household optimization models of agricultural production using household surveys in Nigeria. On the nutrition side, Chastre et al. (2009) calculate least-cost diets for representative households in Bangladesh, Myanmar, Ethiopia, and Tanzania. The method used here builds on these precedents, in a way that is designed to track spatial and temporal variation in cost of meeting all nutrient needs for every individual in a nationally representative sample of households.

2.2 Role of Markets in Nutrition

The development economics literature has demonstrated a variety of possible linkages between a household or village's own agricultural production and their food consumption. The literature has shown that production and consumption decisions for most smallholder farming households in low-income countries are linked, but that when households have access to markets they become less so and consumption patterns become more diverse than households' own agricultural production (de Janvry, Fafchamps and Sadoulet 1991; Hoddinott et al. 2015). Programs trying to reach lower-income smallholder farmers have often focused on increasing households' own production of nutrient-dense foods to improve diet quality and increase micronutrient intakes (Leroy and Frongillo 2007; Talukder et al. 2010; van den Bold, Quisumbing and Gillespie 2013). Analyses of programs such as home gardening, livestock interventions, and others focused on increasing production diversity, have sometimes found positive effects on dietary diversity and other measures of nutrition, but also demonstrated a clear mediating role of household access to markets (Jones 2017; Sibhatu and Qaim 2018b; Ruel, Quisumbing and Balagamwala 2018). The magnitude of program impacts, if any, have tended to be small, even when households are quite remote and have limited market access (Masset et al. 2012; Wood et al. 2013; Kumar, Harris and Rawat 2015; Lehmann-USchner and Kraehnert 2016; Romeo et al. 2016; Sibhatu and Qaim 2017, 2018a; Fraval et al. 2020). Furthermore, the impact of household production and the mediating role of markets on diet quality may vary by household wealth as well as for different individuals within the household (Mulmi et al. 2017).

Rural food markets are increasingly recognized as important complements to a household's own farm production, especially for more perishable and nutrient-dense foods (Hirvonen and Hoddinott 2017; Sibhatu and Qaim 2018b; Headey et al. 2019). Studies have found that even in smallholder agriculture contexts where families produce and store a large share of their annual food consumption, households typically rely on purchased food to increase the diversity, stability and quality of diets above their own stocks (Koppmair, Kassie and Qaim 2016; Hirvonen et al. 2017; Sibhatu and Qaim 2018a; Gelli et al.

2019; Headey et al. 2019). Markets are particularly important complements for households that rely on nonfarm earnings to meet their food needs, but even most smallholder farmers are net buyers of food, including in rural Malawi (Dorward et al. 2004; Ivanic and Martin 2014; Headey 2016).

Beyond meeting basic food needs, policymakers and development programs focus on increasing incomes as the long-term, sustainable pathway out of poverty. But the purchasing power of that income depends on the availability and prices of foods at local markets, which may not reliably supply enough nutrients to meet the population's needs if nutrient-dense foods are not consistently and affordably present. Seasonality, lack of storage opportunities, poor market integration, and limited transport options for perishable items can lead to high and/or volatile food prices and periodic lack of availability. The combined effect of availability and prices may hinder the potential for income growth to improve diet quality and nutrition without additional food systems interventions (Herforth and Ahmed 2015; Gelli et al. 2019). Much remains to be understood about the way markets promote access to high quality diets and consumption of nutrients where intakes at present are insufficient to meet needs.

2.3 Nutrient-level drivers of diet costs

Identifying shadow prices from mathematical programming models of market prices relative to nutritional needs is rarely used in human nutritional studies, but that could potentially help track the cost and affordability of specific nutrients and of adequate diets (Håkansson 2015). Only a few similar studies have examined the shadow price of individual nutrients using observed market prices to understand the contribution of each nutrient to the total cost of a least-cost diet. In Ghana, Masters et al. (2018) found the limiting nutrients in a nutrient-adequate diet to be vitamins B12, A, E and sometimes calcium where the total diet cost was found to rise 3%, 47%, 9% and 7% on average for a 1% increase in the nutrient requirement. They found the same nutrients to be limiting in Tanzania's food system as well, but with a higher elasticity for vitamin B12 (8%) much lower for vitamin A (3%), higher for vitamin E (16%), and much higher for calcium (30%). Håkansson (2015) estimated the cost of adhering to Nordic nutrition recommendations in Sweden for only adult men and non-pregnant adult women. The authors found that the cost of meeting nutrient requirements had not increased more than food prices overall from 1980 to 2012 in Sweden, but that at an individual nutrient level the cost of meeting vitamin D, iron and selenium recommendations had increased faster than general food prices (Håkansson 2015). Earlier, Faiferlick (1985) estimated least-cost nutritionally-adequate diets for adult men and women based on retail prices from four grocery stores in Ames, Iowa. In that study, the author reports the shadow prices in dollars, noting that they are difficult to interpret as such since the nutrient requirements are specified in different units and are required in different amounts relative to one another.

Shadow prices from least-cost diets are commonly used outside of human nutrition, to guide feed formulation in the livestock industry (Saxena and Khanna 2014). Shadow prices from multiple kinds of optimization models are also frequently used in the fields of operations research and environmental management (Balakrishnan and Hung Cheng 2000; Liu, Chen and Wang 2009). To the best of our knowledge, this is the first study to analyze the shadow price of nutrients in a low-income country's rural markets to understand the relative efficiency with which the food system provides access to each of the essential nutrients. In applied economics, there is a small literature focused on understanding household demand for nutrients where estimated shadow prices reveal relative preferences for nutrients (Shonkwiler, Lee and Taylor 1987; Athanasios, Bezuneh and Deaton 1994; Huang 1996; Chen et al. 2002; Coondoo et al. 2004; Shogren 2006; Beatty 2007; Akinleye and Rahji 2007; Richards, Mancino and Nganje 2012; Shrader et al. 2014). Our objective departs from this literature in that we do not aim to explain consumer behavior, but to develop a systematic indicator to track the cost of nutrients in the food system that can be monitored over time to guide policy decisions and evaluate impacts.

Modern computing power and software enable this study's application of least-cost diet research to policy analysis for a nationally representative sample of households over a monthly, five-year time series. The ability to solve hundreds of thousands of optimization problems and report combined results corresponding to every respondent household and under multiple scenarios greatly facilitates the formulation, solution, and reporting of least-cost diet problems. Technology therefore makes it possible to expand their use in public policy analysis, human nutrition, and development economics as never before.

3 Data & Methods

3.1 Data

We use household survey panel data matched with newly compiled food composition data for Malawi, human nutrient requirements, and monthly retail market food prices.

3.1.1 Household Survey

The household data come from the Integrated Household Panel Survey (IHPS), conducted in 2010, 2013 and 2016/17, which includes, for the purposes of our analysis, information to identify individual nutrient needs (age and sex for all household members, occupational data), household food consumption to estimate nutrient shortfalls that inform policy scenario selection, and geographic identifiers which allow us to match households with markets (National Statistical Office (NSO) [Malawi] 2017). A companion study

uses IHPS data on household food consumption to study actual dietary intake and nutrient deficiencies, which we use here to formulate the policy scenarios (Schneider et al. 2020a). For this study, only the latter two rounds of the household survey are relevant, since the NSO's food price data collection was expanded and only contains sufficient nutrient-dense food items for our application beginning in January 2013 (see supplementary materials, Table A-1 for the list of food items).

Households could potentially acquire food from a variety of sources, including their own production, gifts, and informal transactions. In this study we focus on the opportunity to acquire food from their district's central market, where the NSO collects price data. Households are matched to a market based on district of residence. Where multiple markets are monitored in a single district, households are matched by the administrative unit below the district level, traditional authority (National Statistical Office (NSO) [Malawi] 2010, 2012, 2014, 2017). Our focus is the rural food system, so we exclude all households categorized as urban and also exclude the small number of households (n=126) categorized as rural but living in the same district as Malawi's four major urban centers (Blantyre, Lilongwe, Zomba and Mzuzu). Our price dataset includes 25 of the 29 markets where the NSO collects price data, those where households were observed in the survey. Our results are nationally representative for the rural population.

The IHPS includes a food consumption module, which we used in a previous study to estimate household nutrient consumption, which inform the selection of policy scenarios (Schneider et al. 2020a). Reported quantities were converted to kilograms using region-specific conversion factors provided in the IHS3 supporting data (National Statistical Office (NSO) [Malawi] 2011; Oseni, Durazo and Mcgee 2017), supplemented by volume to weight and density conversion factors from the USDA National Nutrient Database for Standard Reference, Legacy (USDA 2018). We recoded any "other" items wherever possible and converted all units wherever sufficient information was provided.

We characterize household composition by aggregated age and sex categories based on the presence of one or more members of each demographic group. We aggregate the 22 age, sex, and maternity status groups defined for nutrient requirements (discussed further below) into eight mutually exclusive groups aligned with the age thresholds for nutrient requirements. These include young children (three years and under), older children (four to 13 years), adolescents (14-18), adult male (19-69), adult female (19-69), breastfeeding adult female (19-51), breastfeeding adolescent (14-18), and older adults (70 years and above).

3.1.2 Individual Nutrient Requirements

We use individual nutrient requirements from the Dietary Reference Intakes (DRIs) (Institute of Medicine of the National Academies 2006, 2011). We apply the estimated average requirement (EAR) as the appropriate requirement level for studies of populations and groups, including all nutrients for which the EAR has been defined and measured in foods (vitamins A, C, E, B6, and B12, thiamin, riboflavin, niacin, folate, calcium, copper, iron, magnesium, phosphorus, selenium and zinc). We apply upper limits (UL) where they have been defined and can be reached with food sources (C, B6, calcium, copper, iron, phosphorus, selenium, zinc, and retinol given its use in fortified foods) and limit macronutrients (carbohydrates, protein, lipids) to within the acceptable range as a percent of total calories (AMDR) (Institute of Medicine of the National Academies 2006, 2011). We also include the Chronic Disease Risk Reduction (CDRR) as an upper limit on sodium intake (National Academies of Sciences Engineering and Medicine 2019).

We calculate energy needs using the DRIs Estimated Energy Requirement (EER) equations using WHO growth standards (children 0-5) and growth references (all others, taking the end growth median as the adult reference). We recalculate any nutrient requirements that are weight-specific using the WHO reference values. We assume an ‘active’ level of physical activity for all individuals except for men 14-59 years old engaged in manual labor such as agriculture, day labor, or construction, for whom a ‘very active’ level is applied (Schneider and Herforth 2020). We assume all children 6-23 months are continuing to breastfeed and include only their needs from food sources (Dewey 2005), and within households where infants are observed we assume their mothers are lactating. Of note, we do not make any adjustment for likely bioavailability. The nutrient constraints imposed result in diets that are by definition adequate in nutrients, and low bioavailability is of concern when diets are inadequate and imbalanced towards plant-based foods (Institute of Medicine of the National Academies and Institute of Medicine 2001; WHO and FAO 2004; Institute of Medicine of the National Academies 2006).

Further discussion of the nutrient requirements specification can be found in Schneider and Herforth (2020).

3.1.3 Food Prices

We use monthly food prices systematically collected by the NSO to calculate the Consumer Price Index (CPI) and monitor inflation. The data include a standardized list of 51 items from January 2013 through August 2017 in the 29 main market centers outside of Malawi’s four largest cities. The monitored food items include anything that accounted for more than 0.02% of total household expenditure in 2010 from

the cross-sectional Third Integrated Household Survey (IHS3), a subset of whom are the baseline households tracked in the IHPS. The food list includes foods from all food groups, though not all foods are available in all markets and all months. Kaiyatsa et al. (2019) describes the data collection, imputation, and cleaning process in detail. While some of the values in the dataset have been imputed by the NSO, these records are not identified. We do not carry out any further imputation of prices and least-cost diet solutions have chosen from among the food items where a price was observed in the given market and month.

3.1.4 Food Composition

We match all the foods available in the markets to their food composition using the recently compiled Malawi Food Composition Table (MAFOODS 2019). The nutrient content of foods varies based numerous biological factors including natural genetic diversity within and between crop varieties, soil and environmental conditions, processing, storage, and preparation methods. Local food composition tables contain more data on the most common local crop varieties, reflect the local environmental conditions in which the foods in the given place are grown, locally produced processed and packaged items, and items by processing levels available in local markets (Greenfield and Southgate 2012; Charrondière et al. 2013). For example, in Malawi the local data reflects lower selenium and higher copper and iron nutrient density in many plant-based foods because of the composition of Malawian soils as well as the nutrient composition of locally processed maize flour according to cultural preferences for very white flour with no bran or germ remaining (Dickinson et al. 2014; Joy et al. 2015a; b, 2017; Mlotha et al. 2016; Ligowe et al. 2020a).

Best practices in the nutrition literature emphasize using local tables wherever possible and numerous global efforts are ongoing to improve the quality and coverage of national food composition databases. Where unavoidable, supplementary data from high quality databases can be used (Greenfield and Southgate 2012; Charrondière et al. 2013; Micha et al. 2018). In our case, we supplement with the USDA National Nutrient Database for Standard Reference food composition data for edible portions, foods not contained in the Malawi table, and to replace missing retinol and vitamin A content (in RAE units) only where a food item match can be confidently made (USDA 2018). From the food price dataset Maheu (a fermented maize, milk, and sugar beverage) and three types of tea (conferring no essential nutrients in their commodity form) were excluded for lack of food composition data.

3.2 Household Nutrient Requirements

Nutrient needs differ by age, sex, reproductive status, and physical activity level, so the lowest cost method for a family to secure a nutritionally adequate diet would be to eat tailored diets that meet each individual member's own unique needs. In practice, however, families in Malawi commonly eat a shared meal. Infants and young children may be fed separately at other times, but in Malawi as elsewhere most household members eat together and social norms strongly favor food sharing (Gelli et al. 2019; Hjertholm et al. 2019). Our 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). However, it is also theoretically consistent with Rawls' maximin principle, 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 (Rawls 1971; Ravallion 2016).

In this study we define each household's shared diet based on the needs of all members aged four and above. For a shared meal to meet the needs of each household member, its composition must accommodate variation in their individual requirements (Schneider et al. 2020b; a). The household's total energy requirement is a simple sum over all members' energy needs, and all other requirements depend on which individuals are present and their needs in terms of nutrient density, the quantity of nutrient required per unit of energy. We define the shared requirement based on the most restrictive member. The person with the highest nutrient density needs to meet minimum requirements defines the household lower bound. Conversely, the member with the lowest nutrient density tolerance to reach their limit defines the household upper bound, which ensures the household diet does not exceed any individuals' safe intakes. We then define the lower and upper nutrient bounds in terms of quantities by multiplying the nutrient density for each nutrient at each bound by the total household energy need. Finally, we add the individual requirements of each child aged three and below to the household total, under the assumption that each would be fed an individualized diet. We assume that children are breastfed to two years of age in line with WHO recommendations, and count only those nutrient requirements that must be met from complementary foods.

Formally, we define the household nutrient requirements under the presumption of family food sharing by the individual needs of each household's members (m) for density of each nutrient (j), using the most restrictive of their nutrient density requirements for each upper and lower bound, and meeting total energy needs (E/e):

$$HHLower_j = \sum_m E_m * \max_m \{MinimumNeed_{j,m}/E_m\}, j = 1, \dots, 19 \quad (1)$$

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

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

We term the household bounds as HHE, HHLower, and HHUpper, to distinguish them clearly from the energy balance, minimum needs and maximum tolerances that have been defined based on biomedical evidence for individuals. The lower bounds used here are defined for 19 nutrients (three macronutrients and 16 micronutrients), by the EAR and AMDR lower bound. Of those, 13 also have upper bounds (three macronutrients and ten micronutrients), defined by their UL, CDRR, and AMDR upper bound. Each individual's requirements then depend on their demographic group by age, sex and maternity status, and the household's overall needs depends on the number, specific demographic groups present, and diversity of demographic groups over its members.

3.3 Least-cost Diets

Using linear programming, we attempt to solve for a diet minimizing total cost subject to the household nutrient requirement upper and lower bounds and meeting total household-level energy requirements, as specified above. The resulting total diet cost per household-month is the Household Cost of Nutrient Adequacy (HHCoNA). Formally, the linear optimization model minimizes total cost over all foods (i) within upper and lower bounds for all nutrients (j) and meets the specified energy budget (HHE). Notation is as for equations (1), (2) and (3), adding data on price for each food (pi) and its nutrient contents (aij):

$$HHCoNA: \text{minimize } C = \sum_i p_i * q_i \quad (4)$$

Subject to:

$$\sum_i a_{ij} * q_i \geq HHLower_j, j = 1, \dots, 19$$

$$\sum_i a_{ij} * q_i \leq HHUpper_j, j = 1, \dots, 13$$

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

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

Equation (4) is solved for each household every month, using the foods and prices reported for their local market. The primary outcomes for analysis are the percent of household-months where available foods can meet all nutrient needs, and the resulting cost for the household as a whole (HHCoNA) as well as per person in the household and per 1,000 calories of dietary energy. Least-cost diets also identify the specific food items and the quantities thereof that provide the requisite nutrients. The total cost of the diet

in each month is one cost observation, specific to each household, its composition, and market. We convert all costs into 2011 US purchasing power parity (PPP) dollars, 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; ILO/IMF/OECD/UNECE/Eurostat/World Bank 2004; World Bank 2015).

To obtain nationally representative results over both survey rounds, we produce a monthly time series for every household allowing composition to change in January 2016 and forward, based on the observed composition of the household at the second survey observation, and for new households observed in the 2016/17 round to enter the sample in 2016. Individuals in the baseline (2010) survey were tracked forward into new households should they leave the baseline household and all members of the new household were brought into the sample. This resulted in an unbalanced panel of households and individuals by design. Even households whose member roster remains unchanged age between rounds and this changes the nutrient requirements. Therefore, we treat the data as two separate cross-sectional samples, each with a monthly time series that is specific to the survey round.¹

3.4 Nutrient Shadow Prices

A useful feature of least-cost diets is that the calculation also identifies the shadow price for each nutrient, which measures the sensitivity of cost to small changes in that requirement. The set of shadow prices is the dual result of the linear programming solution. Formally, each shadow price is the Lagrangian multiplier in the corresponding (dual) solution to the optimization problem (Håkansson 2015). Rewriting equation (4) to define all constraints as negative by rearranging so the right-hand side value is equal to 0, the problem becomes:

$$HHCoNA: \text{minimize } C = \sum_i p_i * q_i \quad (5)$$

Subject to:

$$-(\sum_i a_{ij} * q_i) + HHLower_j \leq 0, \quad j = 1, \dots, 19$$

$$\sum_i a_{ik} * q_i - HHUpper_j \leq 0, \quad j = 1, \dots, 13$$

$$\sum_i a_{ie} * q_i - HHE = 0$$

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

¹ Technically since the data are a longitudinal survey, our monthly time series forms a pseudo-panel. Households observed in the 2013 data round have a monthly time series from January 2013 to December 2015 reflecting their nutrient requirements as observed at the time of survey in 2013. Then those households with the new composition (or simply older members) observed in the 2016/17 round plus any new households observed in that round each have a time series from January 2016 to July 2017. However, given that inference is not our objective, the panel nature of the data does not figure into our analysis.

Next, defining a non-negative dual variable for the inequality constraints and an unrestricted variable for the equality constraint gives:

$$\lambda_1(-(\sum_i a_{ij} * q_i) + HHLower_j) \quad (6)$$

$$\lambda_2(\sum_i a_{ik} * q_i - HHUpper_j) \quad (7)$$

$$\lambda_3(\sum_i a_{ie} * q_i - HHE) \quad (8)$$

Where each λ is the Lagrangian multiplier indicating the incremental amount that the objective function changes for a one-unit increase in the nutrient requirement (HHLower, HHE) or upper bound limit (HHUpper). A non-zero Lagrange multiplier means that the constraint is binding, meaning a change in the right-hand side value would change the result. A zero-value multiplier means the opposite, that the constraint is met automatically when meeting others and would not change the total cost result if it were to move up or down on the margin (Lahaie 2015; Håkansson 2015). In almost all cases, the number of non-zero shadow prices is equal to the number of unique foods included in the least-cost diet. The shadow price is then interpreted as the amount that the total diet cost increases for a one unit increase in the lower bound constraint or the amount that it decreases for a one unit increase in the upper bound constraint.

Because measurement units vary, we transform each marginal cost into semi-elasticities. Nutrient semi-elasticities are interpreted as the amount the total diet cost changes for each percentage change in the amount of that nutrient required. Lower bounds are interpreted as a change in cost for a percentage increase in the requirement, which will have a positive sign for all nutrients whose minimum constraints are binding on the margin. Upper bounds are interpreted as a percentage change in cost also for a percentage increase in the limit, or in other words relaxing the upper bound constraints, and are expected to have a negative sign for all upper limits that are binding on the margin. As above, we convert the semi-elasticities into 2011 US PPP dollars.

3.5 Policy Scenarios

We model eight policy scenarios that illustrate how government and private sector actions could improve access to nutritious diets, choosing a range of realistic actions. In earlier work, we identified the nutrients in shortest supply in current rural households' diets observed in 2013 and 2016/17 to be phosphorus, riboflavin, lipids, selenium, and vitamin B12 (Schneider et al. 2020b). Figure B-1 in Appendix B presents the energy-adjusted adequacy ratios of current household diets relative to their shared needs. Those data reflect the extent to which observed diets are dense enough in each nutrient to meet the needs of every family member, regardless of whether the diet contained sufficient energy or not. In a preview of

our results below, we found that riboflavin, vitamin B12, and selenium along with vitamin E and niacin are also the nutrient requirements to which least-diet costs are most sensitive. As such, these nutrients guided our selection of policy scenarios.

We identified the best food sources of the multiple nutrients lacking in diets and expensive in the food system to be fresh and powdered milk (riboflavin, lipids), eggs (riboflavin, B12, lipids), fish (B12, niacin), cooking oil (vitamin E, lipids), and groundnuts (vitamin E, lipids, niacin) (Kaiyatsa et al. 2019; MAFOODS 2019). Given the current availability and prices, we selected the following scenarios to reflect realistically achievable changes in availability, price, or both, for products in value chains that could be prioritized for investment. In addition, we also selected selenium soil biofortification of maize which was recently tested and shown to be a pragmatic and cost-effective way to increase selenium availability in Malawi's food system (Chilimba 2011; Chilimba et al. 2012b; a; Chilimba, Young and Joy 2014; Joy et al. 2019; Ligowe et al. 2020b). Further background and information on the policy scenarios is provided in Appendix B. In brief, the resulting scenarios are characterized as:

1. **Lower price of eggs:** Eggs are available in all markets and months and at A) 10%, B) 15%, and C) 20% lower price than observed in that market and month under baseline conditions.
2. **Increased availability of dried fish:** Dried fishes are available in all markets at months at the median price currently observed.
3. **Increased availability and lower price of groundnuts:** Groundnuts are available in all markets and months and at a 10% lower price than observed in that market and month under baseline conditions.
4. **Lower price of fresh milk:** Fresh milk is available in all markets and months and at a 10% reduction than observed in that market and month under baseline conditions.
5. **Increased availability of powdered milk:** Powdered milk is available in all markets and months at the median price currently observed.
6. **Soil biofortification (for maize):** Selenium soil biofortification is applied to all maize fields resulting in maize grain and flour with selenium content as observed in field trials (Chilimba 2011; Chilimba et al. 2012b; a, 2014; Joy et al. 2019; Joy 2020a; Ligowe et al. 2020b).

Eggs and fresh milk are already available in most markets and months, while fish, groundnuts and powdered milk are unavailable in a large proportion of markets and months (see Appendix B, Figures B-2 to B-6). Where the items are not currently available and the scenario assumes universal availability and a price reduction (eggs, fresh milk, groundnuts), we first impute the missing price as the median price in that same month over remaining markets where it is present. We then reduce the price by the specified percentage relative to the observed or imputed price in each market and month. For the selenium biofortification scenario, we adjust the food composition of maize grain and flours based on the amount that resulted from the experimental intervention; 11.3 mcg selenium per 100 g edible portion in whole maize grain and whole grain flour, and 5.1 mcg in degermed and dehulled flour, a 55% reduction in selenium content due to the removal of the germ and bran (Chilimba 2011; Chilimba et al. 2012b; a, 2014; Joy et al. 2019; Joy 2020a; Ligowe et al. 2020b). This amount was guided by conventional fortification decision process that consider the quantity of food item consumed on average, required amounts, and upper limits not to be exceeded to identify a fortification level that will be both adequate and safe when consumed in typical amounts by the whole population (WHO and FAO 2006).

As mentioned previously, these scenarios are stylized outcomes that could result from numerous policy actions. Increased efficiency in the fresh milk and egg value chains could arise from investments to improve animal health and productivity or might respond to increased demand where supply increases are possible with current technology and herd/flock size. For fish, investments in aquaculture could increase production while storage infrastructure could potentially smooth stocks throughout the year. Groundnuts availability and price could be affected by breeding and agronomic investments, as well as investments in storage and safety (to reduce loss due to aflatoxin contamination).²

² Nutritionists are also concerned with the acceptability and safety of nutritious (often perishable) foods to consumers so in addition to the agricultural and food policy feasibility of these scenarios, we also point out that they are likely to be acceptable to consumers. Current evidence suggests that consumers prefer milk, eggs, fish, and groundnuts and would eat more at lower prices but consider these foods to be expensive and prioritize food spending towards staples (Ecker and Qaim 2011; Akaichi, Chalmers and Revoredo-Giha 2016; Simtowe, Shiferaw and Abate 2016; Gelli et al. 2019; Stewart et al. 2019). Further, it warrants brief consideration of alternatives to food-based policies that could also improve access to nutritious diets. For instance, cash transfers would be the most straightforward mechanism to improve the affordability of the whole diet and increase demand for the items currently preferred but considered too expensive by low-income consumers. Where such policies are not feasible, subsidizing nutrient-dense foods would be an alternative. Given the large proportion of the population served by school meals and other government feeding programs, public sector purchase of nutrient-dense foods could increase consumption and the government purchase could affect supply response and/or prices as a source of structured demand. However, even at higher incomes, dietary preferences in rural Malawi are heavily biased towards excess carbohydrates and the nutrient-dense foods like fish and groundnuts are commonly eaten in small amounts in traditional dishes. Therefore, comprehensive nutrition-sensitive food systems policies would contain a cohesive mix of actions that address supply constraints and prices of nutrient-dense foods, real incomes, and consumer behavior with respect to food choice (e.g. nutrition education, behavior change communication, taxes and subsidies to influence the healthfulness of food choices).

4 Results

Table 1 presents the characteristics of the households and food prices in our sample. Our sample includes 1,424 households from January 2013–December 2015 and 1,693 households from January 2016–July 2017. Of these, 1,062 are unique households are observed at both time points, however the composition of those households, and therefore their nutrient requirements, changes in January 2016, so these are best thought of as two consecutive, but separate panels of households and individuals.

Table 1. Summary Statistics

	2013		2016/17		Overall	
	Mean	(SE)	Mean	(SE)	Mean	(SE)
<i>Households*</i>						
Observations						
Households	1,424		1,693		3,117	
Individuals [†]	7,153		8,221		15,374	
Household size	4.76	(0.12)	4.98	(0.11)	4.90	(0.11)
Age-sex groups cohabitating (max=22)	4.31	(0.09)	4.51	(0.08)	4.44	(0.08)
Daily food expenditure per cap (2011 US\$)	2.35	(0.12)	3.37	(0.93)	3.00	(0.60)
Median	1.72	(0.09)	1.50	(0.06)	1.58	(0.05)
Food as % total expenditure	71.97	(0.80)	70.27	(0.62)	70.89	(0.52)
			2013 – 2017			
<i>Markets & Foods</i>			Mean	(SD)		
Foods available per market-month			39.71	(4.82)		
Total foods monitored			51			
Cereals, roots & tubers			9			
Eggs, fish & meat			9			
Dairy			2			
Legumes			5			
Oils & fats			2			
Dark green leafy vegetables			3			
Vitamin A-rich fruits & vegetables			5			
Other fruits & vegetables			9			
Other foods [‡]			7			
Market centers			25			
Nutrients included			22			
Total months			55			

* Population statistics corrected using sampling weights. [†] Excludes infants under six months (exclusive breastfeeding).

[‡] Other foods: sugar, biscuits, fried dough, salt, Coca-cola.

4.1 Shared Household Nutrient Requirements

Figure 1 illustrates how the shared diet changes the total nutrient requirements relative to what would be sufficient to meet each person's own needs as scientifically defined (DRIs) based on age, sex, physical activity, and maternity status. For example, consider a household of five people (the average size) of the

modal composition with mother (breastfeeding) and father and three children: a 13-month old son, seven-year-old daughter, nine-year-old daughter. The breastfeeding mom needs only 6.5 mg of iron per day to meet her own minimum requirement, but because of the composition of her household the level of iron-density in the shared diet eaten in proportion to her energy needs will provide her with 8.9 mg of iron per day – 37% more iron than needed to meet her individual minimum need. In this family, the nine year old daughter has the defining need for nutrient density, so the quantity she needs to meet her minimum needs is the same amount she would consume with the shared diet while all other members will eat the amount of iron per calorie that she needs, in the total amount that provides enough calories to meet their own energy need. Averaging the amount needed per nutrient to meet individual needs over the whole population, appropriately weighted to reflect population shares, is the baseline to which the lower bound difference in Figure 1 is compared.

In the example household described above, the parents have a higher upper tolerance per unit of energy than their children and the seven-year-old daughter defines the maximum amount that is allowed into the shared diet so that eating enough calories from the family meal to satisfy her energy needs will not cause her to consume more than her 40 mg per day upper bound limit on iron and all other members will stay well below their own individual upper bounds. The individual upper bounds averaged over the population are the baseline against which the difference in upper bounds are compared in Figure 1. The shared requirement results in a higher need of 50% or more, on average, for only a few nutrients: vitamin C, iron, phosphorus, and zinc. On the upper bound, the shared diet reduces the upper limit the most for copper, zinc, retinol, and vitamin C, all by 30% or more. Taken together, the range tightens the most for iron and zinc. Table C-1 in the supplementary materials presents the full results showing the difference in population average needs per 1,000 calories under the DRIs (individual requirements), under household sharing, and the percent difference between the two illustrated by Figure 1.

Figure 1. Percent Difference in Nutrient Bounds from Individual Diets to Household Sharing

Population statistics corrected using sampling weights.

4.2 Base Case

Table 2 presents the results of our base case scenario, the least-cost diet and shadow prices resulting from currently observed food item availability and prices. We find that a diet sufficient in total quantity and in terms of nutrient density to meet the needs of the entire household when sharing meals costs \$2.32 per person per day (\$2.23 at median) over the period January 2013–July 2017. This is well above the international poverty line of \$1.90.

We find the cost is driven by three nutrients, with riboflavin standing out as far more expensive than any other. A 1% increase in a household's riboflavin requirement increases the diet cost by \$2.57 per day for the average household – greater than the cost of adding an entire additional family member. Riboflavin is found in animal-source and plant-based foods, and there are many items rich in riboflavin in Malawi's retail markets (Appendix A, Table A-2). Riboflavin may not commonly be considered a nutrient of public health concern, but serious health consequences of deficiency are possible. Riboflavin is needed

for energy metabolism, growth and development, and the metabolism of other compounds in the body including those that activate vitamin A and metabolize other B vitamins. Deficiency causes inflammation and cracking of the skin, especially around the mouth and affects the red blood cells, which can result in anemia, fatigue, confusion, and headaches. It is especially dangerous for pregnant women; riboflavin deficiency can lead to preeclampsia, congenital heart defects, and low birthweight (Institute of Medicine of the National Academies 2006).

Table 2. Diet Cost, Feasibility and Nutrient Semi-Elasticities

	Mean	(SE)
Household cost per day (2011 US\$)	10.06	(0.28)
Per 1,000 kcal	1.21	(0.01)
Per person	2.32	(0.03)
Diet Feasible (% HH-Months)	59.37	(1.58)
Semi-elasticities – Lower Bound*		
Riboflavin	2.57	(0.19)
Niacin	0.01	(0.00)
Vitamin B12	0.14	(0.01)
Selenium	0.01	(0.00)
Semi-Elasticities – Upper Bound*		
Copper	-0.24	(0.01)
Iron	-0.01	(0.00)
Zinc	-0.01	(0.00)

Population statistics corrected using sampling weights.

Heteroskedasticity robust standard errors clustered at the enumeration area level.

Outliers, defined as households with a HHCoNA more extreme than 1.5 times the IQR, excluded. *Only non-zero shadow prices are shown.

The next most costly nutrient pales in comparison to riboflavin; the least-cost diet rises a mere \$0.14 for 1% increase in the requirement for vitamin B12. B12 is only found in animal source foods and deficiency causes a form of anemia because it is needed to metabolize proteins, as well as certain fatty acids. Importantly, it is also necessary to metabolize folate, so a B12 deficiency can cause a folate deficiency even if sufficient folate is consumed in the diet. Folate insufficiency in a mother at conception causes neural tube defects.

The diet cost rises \$0.01 for a 1% increase in niacin and selenium requirements. Niacin is found in grains and in animal source foods. It is required for the basic cycle of energy metabolism and deficiency causes problems of the skin, dementia, diarrhea and can lead to death. Selenium is found in animal source and plant-based foods but the selenium content in plants is driven entirely by the levels of selenium in the soils where the foods were grown. It is an important antioxidant and is required to synthesize thyroid hormones. Deficiency does not cause a specific disease, but it is associated with the development of heart problems and some evidence in animals suggests that selenium adequacy is protective against the harmful

effects of exposure to aflatoxin, a carcinogenic mycotoxin known to be widespread in maize and groundnuts in Malawi (Shi et al. 1994, 2012; Institute of Medicine of the National Academies 2006; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans 2009; Monyo et al. 2012; Diaz Rios 2013; Wang et al. 2013; Matumba et al. 2014; Misihairabgwi et al. 2017; Limaye et al. 2018; Zhao et al. 2019).

Regarding the upper bounds, we find that copper and to a lesser extent iron are binding constraints, meaning that a lower total cost could be achieved if the upper limits on these minerals were relaxed. In other words, taking copper as an example, in the process of solving the linear optimization, the copper upper bound is reached before other nutrient requirements have been satisfied, which then reduces the food item options to provide those remaining nutrients to include only items that have no copper. Allowing 1% more copper into the diet would decrease the total cost by \$0.24 per household per day.

4.2.1 Influence of Household Size & Composition

Since the household adequate diet is defined by the combination of different types of members, it is possible that only certain compositions account for the high cost or infeasible results. If this is the case and many households face very affordable diets while some face very unaffordable diets due to their composition or size, the policy remedies to improve access to affordable diets might better be targeted. However, if the most common configurations of household members face the highest diet costs, policy remedies that operate throughout the food system would appropriate. To better understand the way in which household composition and size affects our results, we present summary statistics disaggregated by family size, the number of distinct individual types living together in a household, and total household size.

In Table 3, we illustrate the diet feasibility and cost by household composition, for the five most frequent compositions (50% of the population in total), and the most and least feasible and costly.³ In Table 2 above, we found 60% average feasibility and \$1.21 average cost per 1,000 calories, which is very close to the results for just the half of the population living in the most common types of households, demonstrating the most common family types drive our results. However, we also see that household composition drives the feasibility of a solution to the linear programming more than the cost. If a solution is possible the cost per 1,000 calories does not show as much variation across household compositions.

³ Full results for all compositions observed in five or more households provided in the Supplementary Materials, Table C-1.

Table 3. Household Composition, Diet Feasibility, and Diet Cost

	House- holds (%)	Feasibility (%)		Cost per 1,000 kcal (2011 US\$)	
		Mean	SE	Mean	SE
<i>Most common compositions</i>					
Older child(ren), adolescent(s), male and fe- male adults	15.6	38.67	(2.78)	1.32	(0.02)
Older child(ren), male and female adults	12.0	69.93	(2.61)	1.28	(0.02)
Young child(ren), older kid(s), male and fe- male adults	8.7	82.02	(2.36)	1.19	(0.02)
Young child(ren), older child(ren), male and breastfeeding female adults	7.0	55.04	(2.65)	1.31	(0.02)
Young child(ren), older child(ren), adoles- cent(s), male and female adults	5.8	61.58	(2.10)	1.28	(0.02)
Total	49.4	58.99	(1.85)	1.27	(0.01)
<i>Feasibility Extremes</i>					
Most: Older child(ren), adult male(s)	0.2	100.00	(.)	0.89	(0.03)
Least: Adolescent(s), male and female adults, older adult(s)	0.4	3.48	(3.27)	1.33	(0.02)
<i>Cost Extremes</i>					
Most: Young child(ren), adult female(s)	0.4	44.16	(11.35)	1.96	(0.05)
Least: Adolescent(s)	0.1	86.27	(11.99)	0.74	(0.17)

Population statistics corrected using sampling weights. Composition types sorted by frequency observed.

Definition of age groups aggregates the age groups in the DRIs as follows: Young children = 3 and below, Older children = 4-13, Adolescent = 14-18, Adult = 19-69, Older adult = 70 and above.

In Figure 3, we illustrate the relationship between household size and the complexity of composition and resulting diet cost. Each additional household member of a different type (age, sex, or maternity status) than already present could increase the required diet quality if that new member has a greater need for nutrient density for any nutrient than others.⁴ We observe household composition increases with household size up to about ten members, after which additional members are less likely to change the nutrient density requirements. In other words, household size and complexity of membership are interrelated so that larger households are not just scaled up smaller households, but they are likely to require greater nutrient density because they also have more complex membership.

Figure 3 also illustrates that as households grow in size and complexity, higher income is necessary to purchase 1,000 calories of the diet that meets the household's basic nutrient needs. Economists have long been concerned with economies of scale in household consumption, which are critical to comparing levels of welfare across households of differing size and composition to draw conclusions about poverty and inequality (Deaton and Paxson 1998; Gibson 2002; Browning, Chiappori and Lewbel 2013). Our results

⁴ The converse is also true, whereby the new member may decrease the household's upper bound tolerance for a nutrient.

extend this literature taking a cost of basic needs approach, which suggests there exists a diseconomy of size, resulting from the diversity in nutrient requirements when household complexity increases, at least where families share food.⁵

Figure 3. Household Size, Composition, and Cost per 1,000 calories

Population statistics corrected for survey weights. Vertical line reflects mean household size of five people. Fit line reflects quadratic fit.

We next consider whether the nutrient shadow values may be driven by the use of the shared nutrient requirements, meaning that solving the linear programming for individuals in the same food system

⁵ Theory of household public goods posits that a larger household will have higher per capita expenditure on private goods than a smaller household of equivalent per capita resources (Barten 1964; Deaton and Paxson 1998). Empirical evidence, however, appears to present a paradox whereby holding household composition constant, larger households have lower per capita food expenditure than smaller households of equivalent income (Deaton and Paxson 1998; Logan 2011). Differing prices (bulk discounts and more expensive, smaller, more frequent quantities as a rationing device) and measurement error have been put forth and supported empirically (Gibson 2002; Gibson, Le and Kim 2017; Gibson and Kim 2018; Dillon, De Weerd and O'Donoghue 2020). Our analysis has shown that the cost of meeting basic nutrient needs differs with both household size and composition, due to needs for higher diet quality by certain age and sex groups. Therefore where the objective is to estimate or identify households living in poverty, an alternative approach would be to compare observed incomes to flexible poverty lines that incorporate variation in nutrient requirements by household size and composition. Allen (2017) demonstrates how least-cost diets can be used to define the food component for internationally comparable poverty lines, and our approach could extend that application with a justified selection of nutrients necessary for optimal growth and long-term health and the nutrient density approach to define household diet quality to estimate poverty lines flexible to household composition..

would find different nutrients to be the costliest or binding on the upper margin. Bearing in mind that the costliest nutrients (riboflavin, B12, niacin, selenium) on the lower bound are not among those where the family food sharing increased the requirement or tightened the range by a larger percent than for most other nutrients (iron, zinc, vitamin C, phosphorus), we argue our results are likely an accurate reflection of the relative cost of nutrients in the food system on the lower margin (meeting the minimum requirement).

Of the nutrients we found binding on the upper bound (copper, iron, zinc), iron and zinc are among those most altered by defining a shared household nutrient requirement. Therefore, estimate of the extent to which avoiding excess intake drives up the cost of the whole diet may be biased upwards for these two nutrients. In other words, some individuals could actually tolerate more copper, iron, or zinc in their diet without exceeding their individual upper limit but are constrained by the lower nutrient density tolerated by other family members with whom they share meals under our definition of shared household requirements. However, in the case where family food sharing is the dominant cultural norm, we argue the benchmark diet costed for policy information should be one that would not risk exposing any member to a nutrient quantity that would produce symptoms of toxicity if simply eating a share of the family meal sufficient to meet their energy needs.

4.3 Policy Scenarios

Policy simulations revealed the striking finding of this paper that selenium is the nutrient constraining the availability of nutrient-adequate diets. Figure 4 demonstrates the impact of each simulated scenario on the diet cost for the same households, markets, and months where it was feasible under the base case (current conditions). No interquartile range boxes are visible under the eggs, fish, and powdered milk scenarios as the difference in diet cost for most household-months is negligible. This means that even with the price and availability change, those foods remain more costly sources of nutrients than the alternatives already selected into the diets under the base case. The fresh milk and groundnut scenarios result in a greater range of diet cost change relative to the base case, though neither results in greater than 1% decrease for the lower (greatest change) quartile. Selenium soil biofortification stands out clearly with a median decrease in diet cost of 50% and half of household months demonstrating a diet cost decrease between 40% and 60%.

Figure 4. Change in Diet Cost Relative to Base Case, by Household and Month

Population statistics corrected using sampling weights. Outliers excluded.

Table 4 presents the full results of the policy scenarios. It illustrates that for most of the individual food approaches (eggs, groundnuts, fish, powdered milk), an increasing availability where currently unavailable and a decrease in cost of eggs or groundnuts had no meaningful impact on any of the metrics, including the shadow cost of the most expensive nutrients. Decreasing the cost of fresh milk by 10% substantially reduces the shadow cost of riboflavin but does not change the diet cost overall, percent of time which it is feasible, or the shadow cost of any other nutrients. Soil biofortification of maize with selenium, not only reduces the total diet cost almost in half but also results in near universal feasibility of the diet (95% of household-months become feasible).

Biofortification nearly eliminated the shadow cost of selenium, as might be expected, but it also reduces that of B12 by one third and that of niacin by approximately 80%. The food level implications of the comparison are discussed further below, but in brief is explained by legumes supplying a large share of selenium under the base case scenario. Though legumes contain protein, niacin, energy, and other nutrients in addition to selenium, they are likely to be a more costly source of these other nutrients than alternatives. However other food sources of selenium (leafy greens, vitamin A-rich fruits) do not contain as

much energy, carbohydrates or any protein so the total diet cost would be higher (and potentially not feasible without exceeding other upper bounds) if energy and macronutrients came from other sources and selenium from these fruits and vegetables.

Most interestingly, selenium biofortification nearly eliminates the shadow price of copper and reduces the other upper bound constraints. This means that the greater availability of selenium in maize prevents the need to meet selenium and other requirements from foods that are dense in copper, or from more expensive foods that are not dense in copper and enter the diet to supply remaining nutrients while staying within the copper upper bounds. While the selenium cost did appear to be binding on the lower margin in the base scenario, the cost with respect to requirements was much smaller than for the other binding nutrients (with the exception of niacin to which it was equivalent) and small in practical terms at only \$0.01 for a 1% increase in selenium requirements. What these results reveal is that the costliest nutrients in the market when an adequate diet is available may not be the same as the nutrients that limit whether or not there is a feasible solution to begin with.

Table 4. Cost, Feasibility and Nutrient Elasticities by Policy Scenario

	Base case		Eggs -10%		Eggs -15%		Eggs -20%		Fish	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Household cost/day (2011 US\$)	10.07	(0.28)	10.06	(0.28)	10.06	(0.28)	10.06	(0.28)	10.05	(0.28)
Per person	2.32	(0.03)	2.32	(0.03)	2.32	(0.03)	2.32	(0.03)	2.32	(0.03)
Diet Feasible (% HH-Months)	59.40	(1.58)	59.43	(1.58)	59.40	(1.58)	59.41	(1.58)	59.41	(1.58)
Semi-Elasticities – Lower Bound*										
Riboflavin	2.57	(0.19)	2.79	(0.24)	2.78	(0.24)	2.76	(0.24)	2.58	(0.19)
Niacin	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)
Vitamin B12	0.14	(0.01)	0.14	(0.01)	0.14	(0.01)	0.13	(0.01)	0.13	(0.01)
Selenium	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)
Semi-Elasticities – Upper Bound*										
Copper	-0.24	(0.01)	-0.24	(0.02)	-0.24	(0.02)	-0.24	(0.02)	-0.24	(0.01)
Iron	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)
Zinc	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)
	Base case		Groundnuts		Fresh milk		Powdered milk		Soil fortification	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Household cost/day (2011 US\$)	10.07	(0.28)	10.03	(0.28)	10.13	(0.27)	10.06	(0.28)	5.91	(0.18)
Per person	2.32	(0.03)	2.30	(0.03)	2.31	(0.03)	2.32	(0.03)	1.22	(0.02)
Diet Feasible (% HH-Months)	59.40	(1.58)	59.92	(1.54)	60.88	(1.58)	59.46	(1.58)	94.94	(0.52)
Semi-Elasticities – Lower Bound*										
Riboflavin	2.57	(0.19)	2.59	(0.20)	1.99	(0.16)	2.37	(0.18)	2.62	(0.17)
Niacin	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.00	(0.00)
Vitamin B12	0.14	(0.01)	0.15	(0.01)	0.13	(0.01)	0.14	(0.01)	0.10	(0.01)
Selenium	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.01	(0.00)	0.00	(0.00)
Semi-Elasticities – Upper Bound*										
Copper	-0.24	(0.01)	-0.24	(0.01)	-0.23	(0.01)	-0.24	(0.01)	-0.01	(0.00)
Iron	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.00	(0.00)
Zinc	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)	-0.01	(0.00)

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

Outliers excluded. * Only non-zero shadow prices are shown.

To understand why the diet cost changes so dramatically under soil selenium biofortification, we examine the composition of the diet by food group under the base case and selenium biofortification scenarios. The left panel of Figure 5 illustrates the difference in percent of energy from each food group. It shows the greatest difference in between the two scenarios is the proportion of diet comprised of legumes and cereals. In the base case, a large percent of energy (>50% at the median) comes from legumes and a lower share from cereals (10%) than would be expected given they are generally the lowest cost source of energy and carbohydrates. The stylized intuition behind this result is that the base case diet gets energy and carbohydrates from a more expensive source of those nutrients (legumes vs. cereals) because the legumes must enter in to supply other nutrients. Even though they may be a more expensive source of energy and carbohydrates, they would enter instead of cereals if they are the least expensive source of the additional nutrients present in legumes that are not present (in large enough amounts) in cereals: protein, lipids, vitamin E, riboflavin, folate, copper, selenium, and zinc. When the selenium shortage is alleviated through soil biofortification of maize, the diet gets much more energy from cereals. Fish and other vegetables appear least in the diet under either scenario. Eggs, meat, oils, and fats supply a larger share of the diet and change little across scenarios.

On the right panel, Figure 5 shows the distribution of total frequency (over the 55-month time series) that each food group appears in households' diets. Almost all food groups appear more frequently under the biofortification scenario because there is a solution for nearly every household in every month. The key insight in the panel on the right is the clear divide with certain food groups rarely offering the lowest cost source of essential nutrients under either scenario: roots and tubers, other fruits and vegetables, meat, eggs, and vitamin-A rich fruits. To further contextualize these results, Appendix A contains all the food items in the price dataset by food group (Table A-1), the items that supply each nutrient (quantity per 100g edible portion and by nutrient density) (Table A-2), and the mean price per kg (2011 \$US) (Table A-3).

Figure 5. Difference in Diet Composition by Food Group

Population statistics corrected using sampling weights. Outliers excluded.
Sorted from left to right on y-axis variable.

Modeling scenarios aids in uncovering the sensitivity of the level estimates to changes in a single parameter. As a data envelopment technique, linear programming results are only sensitive to changes in the data that affect the optimization on the margin, i.e. the price or nutrient content of the lowest cost item. We found that limited changes to prices and availability for eggs, powdered milk, and fish had no impact on the results. What this indicates is that those foods supply nutrients that were already available at relatively lower cost in other foods, and the change in price or availability was not sufficient to alter that relative costliness. Where the change in price affected the item already selected as the lowest cost source of a nutrient, one could expect a more linear relationship with the change in diet cost, keeping in mind that all foods contain multiple nutrients so the change in price could alter the relative nutrient costs across foods resulting in a shift in the composition of the food basket and a potentially non-linear related change in the total diet cost. We emphasize overall that the value of these methods lies not in the level estimate they produce but in the comparison over time, space and under different policy conditions, when collected and estimated systematically.

5 Conclusions

In this paper, we demonstrate how food prices and the availability of food items can be used to diagnose how well a food system currently facilitates access to a nutrient-adequate diet for all members of a family eating together from shared meals in rural Malawi. We calculate the cost of an adequate diet – one that is sufficient in total energy, meets minimum micronutrient limits, is balanced in macronutrients, and does not exceed upper bounds – for rural Malawian households in their nearest district central market, accounting for the higher nutrient density required when families share food. Aggregating individual requirements based on the actual demographic composition of each household is particularly useful for analysis of food systems, measuring whether local markets provide a sufficient diversity of nutrient-dense foods to meet the population's needs at each time and place.

We find that at food availability and prices prevailing from January 2013–July 2017, the diet is available in 60% of all household-months at an average cost of \$10.06 per day per household, or \$2.32 per person. Riboflavin is by far the costliest nutrient to obtain in rural Malawi's food system. The cost of an adequate diet increases \$2.57 on average for a 1% increase in the riboflavin requirement. Vitamin B12 is the next most costly, increasing the diet cost by \$0.14, on average, for a 1% increase in the requirement. Niacin, and selenium also raise the diet cost but only by \$0.01, on average, for a 1% increase in their requirement. At the same time, allowing 1% more copper into the diet would reduce the cost by \$0.24 on average, with a \$0.01 reduction for similar relaxation of the upper limits on iron and zinc. We find that our

results are driven by the most common household composition and that there appears to be a diseconomy of size in the cost of meeting basic needs as households grow in size because they also tend to grow in complexity. We demonstrate a positive linear relationship between household size and the diet cost per 1,000 calories, irrespective of composition, and an inverse linear relationship with the availability of the adequate diet.

Our findings highlight that the diet cost and nutrient shadow price analysis can only reveal how well the food system facilitates access to a nutrient-adequate diet when the available food items can be combined at some cost to meet the nutrient requirement constraints. However, when the diet is not feasible at all, scenario modeling is an effective way to identify the nutrients that are in too short supply in the food system. While we found riboflavin and B12 to be the nutrients whose cost was binding on the margin to meet minimum requirements and copper binding on the upper bound margin when the diet is feasible, we clearly identified that selenium is the constraining nutrient with respect to whether the diet is possible to begin with and also contributed to driving up the average cost. Introducing selenium soil biofortification of maize, we found would increase the percent of household-months where the diet is feasible from 60% to 95%.

We note that the food composition data do have some gaps, which may be consequential for our conclusions regarding selenium. There are more food items with missing selenium data than for any other nutrient, so by necessity that requires us to assume the food contains no selenium. If that is wrong, then more selenium may be available than we estimate. Our estimate of the diet cost might then be higher than the truth and estimated feasibility lower than the truth, but only if items missing selenium data that actually contain selenium would have been selected into the least cost diet had the information about the selenium quantity been present. However, we rest our confidence that little selenium composition reflects low selenium presence in foods on the findings of Joy et al. (2015a; b) and Phiri et al. (2019) who measured the presence of selenium in soils, foods, and deficiency in the population. Their conclusions support that there is little selenium present and available to consumers. However, additional food composition analysis is warranted before supporting a soil biofortification program.

Our study contributes to a large body of research on least-cost diets. However, we make a unique contribution by estimating requirements for whole households who commonly eat together from shared meals, ensuring that the specific needs of every individual in the household are met. We argue this is not only realistic, but also serves the policy information need of decision-makers beyond the health sector who are generally concerned with households. Furthermore, using observed household composition results in an estimate of the diet cost that reflects the relative nutrition requirements of all age and sex groups in their representative proportions relative to the population pyramid. Though a similar population

level metric could be computed as a weighted average of individual sub-group diet costs, doing so would not reflect the typical composition of households and the fact that families share meals.

Ours is among few studies of nutrient shadow prices particularly in low-income countries, which we use to identify the nutrients driving the total diet cost. This is arguably an underutilized tool in the human nutrition and food policy domain, though it only reveals information about the food system when the diet meeting specified constraints is feasible. We further extend the existing literature with the only analysis to date, to the best of our knowledge, using scenario simulations to identify the drivers of both diet cost and feasibility and to model realistic policy scenarios to assess the potential effects on total diet cost.

We hope our study demonstrates a salient and useful metric to diagnose the needs of the population and the ability of the food system to meet those needs. One clear policy implication for Malawi emerges: rural households are not reliably able at present to access a nutritionally adequate diet. We demonstrate that the higher level of diet quality required when families share food may not be possible given current food items available. Even when available, the cost per capita exceeds the international poverty line under which many rural Malawians live. However, we also demonstrate that selenium biofortification of maize, the country's main food security crop and the main focus of much of its food security policy and budget, could dramatically reduce the cost of nutritious diets. This is feasible, in part, through the existing Farm Input Subsidy Program (FISP) which is an existing channel through which selenium-fortified fertilizer could be made available to farmers (Joy 2020a; b). Beyond Malawi, the approaches we demonstrate in this paper can augment the growing toolkit of least-cost diet methods for food and nutrition policymaking and contribute to the evidence-based selection of policy options that can support food systems' transformation to become nutrition-sensitive and increase access to affordable, nutritious diets for all.

References

- Aberman, N.-L., J. Meerman, and T. Benson eds. 2018. *Agriculture, Food Security and Nutrition in Malawi*. Washington, D.C.: International Food Policy Research Institute.
- Akaichi, F., N. Chalmers, and C. Revoredo-Giha. 2016. “Consumers’ attitudes and willingness to pay for safer milk in Malawi.” In *5th International Conference of AAAE*. Addis Ababa, Ethiopia.
- Akhter, N., N. Saville, B. Shrestha, D.S. Manandhar, D. Osrin, A. Costello, and A. Seal. 2018. “Change in cost and affordability of a typical and nutritionally adequate diet among socio-economic groups in rural Nepal after the 2008 food price crisis.” *Food Security* 10(3):615–629.
- Akinleye, S.O., and M.A.Y. Rahji. 2007. “Nutrient elasticities among nigerian households differentiated by income.” *Agrekon* 46(2):274–288.
- Allen, R.C. 2017. “Absolute Poverty: When Necessity Displaces Desire.” *American Economic Review* 107(12):3690–3721.
- Athanasios, A., M. Bezuneh, and B.J. Deaton. 1994. “Impacts of FFW (Food-for-Work) on Nutrition in Rural Kenya.” *Agricultural Economics* 11(2):301–309.
- Bai, Y., R. Alemu, S.A. Block, D. Headey, and W.A. Masters. 2020. “Cost and affordability of nutritious diets at retail prices: Evidence from 177 countries.” *Food Policy*:101983.
- Balakrishnan, J., and C. Hung Cheng. 2000. “Discussion: Theory of constraints and linear programming: A re-examination.” *International Journal of Production Research* 38(6):1459–1463.
- Barten, A.P. 1964. “Family Composition, Prices and Expenditure Patterns.” In P. E. Hart, G. Mills, and J. K. Whitaker, eds. *Econometric Analysis for National Economic Planning*. London: Butterworths.
- Baur, I., L. Tabin, M.L. Banda, D. Chiumia, and M. Lips. 2017. “Improving dairy production in Malawi: a literature review.” *Tropical Animal Health and Production* 49(2):251–258.
- Beaton, G.H. 1995. “Fortification of Foods for Refugee Feeding: Final report to the Canadian International Development Agency.”
- Beatty, T.K.M. 2007. “Recovering the shadow value of nutrients.” *American Journal of Agricultural Economics* 89(1):52–62.
- van den Bold, M., A. Quisumbing, and S. Gillespie. 2013. “Women’s Empowerment and Nutrition: An Evidence Review.”
- Browning, M., P.-A. Chiappori, and A. Lewbel. 2013. “Estimating consumption economies of scale, adult

- equivalence scales, and household bargaining power.” *Review of Economic Studies* 80(4):1267–1303.
- Byrd-Bredbenner, C., G. Moe, J. Bernin, and D. Kelley. 2016. *Wardlaw’s Perspectives in Nutrition* 10th Editi. New York, NY: McGraw-Hill Education.
- Calkins, P.H. 1981. “Nutritional Adaptations of Linear Programming for Planning Rural Development.” *American Journal of Agricultural Economics* 63(2):247–254.
- Carlson, A., M. Lino, and T. Fungwe. 2007. “The Low-Cost, Moderate-Cost, and Liberal Food Plans, 2007 (CNPP-20).” (November):80.
- Charrondière, U.R., B. Stadlmayr, D. Rittenschober, B. Mouille, E. Nilsson, E. Medhammar, T. Olango, S. Eisenwagen, D. Persijn, K. Ebanks, V. Nowak, J. Du, and B. Burlingame. 2013. “FAO/INFOODS food composition database for biodiversity.” *Food Chemistry* 140(3):408–412.
- Chastre, C., A. Duffield, H. Kindness, S. LeJeune, and A. Taylor. 2009. *The minimum cost of a healthy diet: Findings from piloting a new methodology in four study locations*. London: Save the Children.
- Chen, S.-N., J.F. Shogren, P.F. Orazem, and T.D. Crocker. 2002. “Prices and health: Identifying the effects of nutrition, exercise and medication choices on blood pressure.” *American Journal of Agricultural Economics* 84(January):273–282.
- Chilimba, A.D.C. 2011. *Potential for safe and efficient biofortification of maize crops with selenium*. University of Nottingham.
- Chilimba, A.D.C., S.D. Young, C.R. Black, M.C. Meacham, J. Lammel, and M.R. Broadley. 2012a. “Agronomic biofortification of maize with selenium (Se) in Malawi.” *Field Crops Research* 125:118–128.
- Chilimba, A.D.C., S.D. Young, C.R. Black, M.C. Meacham, J. Lammel, and M.R. Broadley. 2012b. “Assessing residual availability of selenium applied to maize crops in Malawi.” *Field Crops Research* 134:11–18.
- Chilimba, A.D.C., S.D. Young, and E.J.M. Joy. 2014. “Agronomic biofortification of maize, soybean and groundnut with selenium in intercropping and sole cropping systems.” *African Journal of Agricultural Research* 9(50):3620–3626.
- Coondoo, D., A. Majumder, G. Lancaster, and R. Ray. 2004. “Derivation of Nutrient Prices from Household level Consumption Data : Methodology.”
- Daelmans, B., E. Ferguson, C. Lutter, N. Singh, H. Pachón, H. Creed-Kanashiro, M. Woldt, N.

- Mangasaryan, E. Cheung, R. Mir, R. Pareja, and A. Briend. 2013. "Designing appropriate complementary feeding recommendations: Tools for programmatic action." *Maternal and Child Nutrition* 9(S2):116–130.
- Darmon, N., and A. Drewnowski. 2015. "Contribution of food prices and diet cost to socioeconomic disparities in diet quality and health: A systematic review and analysis." *Nutrition Reviews* 73(10):643–660.
- Darmon, N., E. Ferguson, and A. Briend. 2002. "Linear and nonlinear programming to optimize the nutrient density of a population's diet: An example based on diets of preschool children in rural Malawi." *American Journal of Clinical Nutrition* 75(2):245–253.
- Deaton, A., and C. Paxson. 1998. "Economies of Scale, Household Size, and the Demand for Food." *Journal of Political Economy* 106(5):897–930.
- Denton, F.T. 1971. "Adjustment of monthly or quarterly series to annual totals: An approach based on quadratic minimization." *Journal of the American Statistical Association* 66(333):99–102.
- Deptford, A., T. Allieri, R. Childs, C. Damu, E. Ferguson, J. Hilton, P. Parham, A. Perry, A. Rees, J. Seddon, and A.J. Hall. 2017. "Cost of the Diet: a method and software to calculate the lowest cost of meeting recommended intakes of energy and nutrients from local foods." *BMC Nutrition* 3(1):26.
- Dewey, K.G. 2005. "Complementary Feeding." In B. Caballero, L. H. Allen, and A. M. Prentice, eds. *Encyclopedia of Human Nutrition, Volume 2*. Elsevier, pp. 465–470.
- Diaz Rios, L. 2013. *Malawi Programme for Aflatoxin Control (MAPAC): Advancing Collaboration for Effective Aflatoxin Control in Malawi*. Lilongwe, Malawi.
- Dickinson, N., J. Rankin, M. Pollard, K.M. Maleta, C. Robertson, and A. Hursthouse. 2014. "Evaluating environmental and social influences on iron and zinc status of pregnant subsistence farmers in two geographically contrasting regions of Southern Malawi." *Science of the Total Environment* 500–501:199–210.
- Dillon, B., J. De Weerd, and T. O'Donoghue. 2020. "Paying More for Less: Why Don't Households in Tanzania Take Advantage of Bulk Discounts?" *The World Bank Economic Review*.
- Dizon, F., A. Herforth, and Z. Wang. 2019. "The cost of a nutritious diet in Afghanistan, Bangladesh, Pakistan, and Sri Lanka." *Global Food Security* 21:38–51.
- van Dooren, C. 2018. "A Review of the Use of Linear Programming to Optimize Diets, Nutritiously, Economically and Environmentally." *Frontiers in Nutrition* 5:48.

- Dorward, A., J. Morrison, S. Robinson, and H. Tchale. 2004. "Differential Household Responses in a Poor Agricultural Economy: Implications for Agricultural Policy Analysis." In *7th Annual Conference on Global Economic Analysis*. Washington, D.C.
- Drèze, J., and N. Stern. 1990. "Policy reform, shadow prices, and market prices." *Journal of Public Economics* 42(1):1–45.
- Dumas, A., J. Dijkstra, and J. France. 2008. "Mathematical modelling in animal nutrition: A centenary review." *Journal of Agricultural Science* 146(2):123–142.
- Ecker, O., and M. Qaim. 2011. "Analyzing Nutritional Impacts of Policies: An Empirical Study for Malawi." *World Development* 39(3):412–428.
- Faiferlick, C.J.P.P. 1985. "Extensions of least-cost diets through linear programming: three essays." :91.
- Fanzo, J.C. 2014. "Strengthening the engagement of food and health systems to improve nutrition security: Synthesis and overview of approaches to address malnutrition." *Global Food Security* 3(3–4):183–192.
- FAO. 2013. *Food Systems for Better Nutrition*. Rome: Food and Agriculture Organization of the United Nations.
- FAO. 2016. *Influencing food environments for healthy diets*. Rome: Food and Agriculture Organization of the United Nations.
- FAO, IFAD, UNICEF, WFP, and WHO. 2020. *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets*. Rome: Food and Agriculture Organization of the United Nations.
- Fraval, S., V. Yameogo, A. Ayantunde, J. Hammond, I.J.M. De Boer, S.J. Oosting, and M.T. van Wijk. 2020. "Food security in rural Burkina Faso: the importance of consumption of own-farm sourced food versus purchased food." *Agriculture & Food Security* 9(1):2.
- Frega, R., J.G. Lanfranco, S. De Greve, S. Bernardini, P. Geniez, N. Grede, M.W. Bloem, and S. de Pee. 2012. "What linear programming contributes: world food programme experience with the 'cost of the diet' tool." *Food and nutrition bulletin* 33(3 Suppl).
- Gelli, A., J. Donovan, A. Margolies, N.-L. Aberman, M. Santacroce, E. Chirwa, S. Henson, and C. Hawkes. 2019. "Value chains to improve diets: Diagnostics to support intervention design in Malawi." *Global Food Security*.
- Gibson, J. 2002. "Why does the Engel method work? Food demand, economies of size and household

- survey methods.” *Oxford Bulletin of Economics and Statistics* 64(4):341–359.
- Gibson, J., and B. Kim. 2018. “Economies of scale, bulk discounts, and liquidity constraints: comparing unit value and transaction level evidence in a poor country.” *Review of Economics of the Household* 16(1):21–39.
- Gibson, J., T. Le, and B. Kim. 2017. “Prices, engel curves, and time-space deflation: Impacts on poverty and inequality in Vietnam.” *World Bank Economic Review* 31(2):504–530.
- Gilbert, R., T. Benson, and O. Ecker. 2019. “Are Malawian Diets Changing? An assessment of nutrient consumption and dietary.” Malawi Strategy Support Program Working Paper No. 30,
- Global Fortification Data Exchange. 2020a. “Dashboard: Malawi Fortification.” Available at: <https://fortificationdata.org/country-fortification-dashboard/> [Accessed July 7, 2020].
- Global Fortification Data Exchange. 2020b. “Quantity and Proportion of Food Vehicle that is Fortified - Malawi.” Available at: <https://fortificationdata.org/map-proportion-of-food-vehicle-that-is-fortified/> [Accessed July 7, 2020].
- Global Panel on Agriculture and Food Systems for Nutrition. 2020. *Future Food Systems: For people, our planet, and prosperity*. London, UK.
- Global Panel on Agriculture and Food Systems for Nutrition. 2014. “How can Agriculture and Food System Policies improve Nutrition?” Technical Brief. London, UK: Global Panel on Agriculture and Food Systems for Nutrition.
- Greenfield, H., and D.A.. Southgate. 2012. *Food Composition Data: Production, Management and Use* 2nd editio. Rome: Food and Agriculture Organization of the United Nations.
- Håkansson, A. 2015. “Has it become increasingly expensive to follow a nutritious diet? Insights from a new price index for nutritious diets in Sweden 1980-2012.” *Food & Nutrition Research* 59(1):1–9.
- Headey, D.D. 2016. “Food Prices and Poverty.” *The World Bank Economic Review* 32(3):lhw064.
- Headey, D.D., and H.H. Alderman. 2019. “The Relative Caloric Prices of Healthy and Unhealthy Foods Differ Systematically across Income Levels and Continents.” *Journal of Nutrition* 149(11):2020–2033.
- Headey, D.D., K. Hirvonen, J. Hoddinott, and D. Stifel. 2019. “Rural Food Markets and Child Nutrition.” *American Journal of Agricultural Economics* 101(5):1311–1327.
- Herforth, A., and S. Ahmed. 2015. “The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions.” *Food Security* 7:505–520.

- Herforth, A., Y. Bai, A. Venkat, K. Mahrt, A. Ebel, and W.A. Masters. 2020a. “Cost and affordability of healthy diets across countries.” Background paper for the State of Food Security and Nutrition in the World 2020
- Herforth, A., W. Masters, Y. Bai, and D. Sarpong. 2019. “The Cost of Recommended Diets: Development and Application a Food Price Index Based on Food-Based Dietary Guidelines (P10-033-19).” *Current Developments in Nutrition* 3(Supplement_1).
- Herforth, A.W., D. Wiesmann, E. Martínez-Steele, G. Andrade, and C.A. Monteiro. 2020b. “Introducing a Suite of Low-Burden Diet Quality Indicators that Reflect Healthy Diet Patterns at Population Level.” *Current Developments in Nutrition*.
- Hirvonen, K., Y. Bai, D.D. Headey, and W.A. Masters. 2019. “Affordability of the EAT–Lancet reference diet: a global analysis.” *The Lancet Global Health* (19):1–8.
- Hirvonen, K., and J. Hoddinott. 2017. “Agricultural production and children’s diets: evidence from rural Ethiopia.” *Agricultural Economics* 48(4):469–480.
- Hirvonen, K., J. Hoddinott, B. Minten, and D. Stifel. 2017. “Children’s Diets, Nutrition Knowledge, and Access to Markets.” *World Development* 95:303–315.
- Hjertholm, K.G., G. Holmboe-Ottesen, P.O. Iversen, I. Mdala, A. Munthali, K.M. Maleta, Z. Shi, E. Ferguson, and P. Kamudoni. 2019. “Seasonality in associations between dietary diversity scores and nutrient adequacy ratios among pregnant women in rural Malawi – a cross-sectional study.” *Food & Nutrition Research* 63(2712).
- Hoddinott, J., D.D. Headey, and M. Dereje. 2015. “Cows, Missing Milk Markets, and Nutrition in Rural Ethiopia.” *Journal of Development Studies* 51(8):958–975.
- Huang, K.S. 1996. “Nutrient Elasticities in a Complete Food Demand System.” *American Journal of Agricultural Economics* 78(1):21–29.
- Hurst, R., E.W.P. Siyame, S.D. Young, A.D.C. Chilimba, E.J.M. Joy, C.R. Black, E.L. Ander, M.J. Watts, B. Chilima, J. Gondwe, D. Kang’Ombe, A.J. Stein, S.J. Fairweather-Tait, R.S. Gibson, A.A. Kalimpira, and M.R. Broadley. 2013. “Soil-type influences human selenium status and underlies widespread selenium deficiency risks in Malawi.” *Scientific Reports* 3.
- Iannotti, L.L. 2018. “The benefits of animal products for child nutrition in developing countries.” *Revue scientifique et technique (International Office of Epizootics)* 37(1):37–46.
- Iannotti, L.L., M. Chapnick, J. Nicholas, C.A. Gallegos-Riofrio, P. Moreno, K. Douglas, D. Habif, Y. Cui, C. Stewart, C.K. Lutter, and W.F. Waters. 2019. “Egg intervention effect on linear growth no

- longer present after two years.” *Maternal and Child Nutrition* (November):1–10.
- Iannotti, L.L., C.K. Lutter, D.A. Bunn, and C.P. Stewart. 2014. “Eggs: the uncracked potential for improving maternal and young child nutrition among the world’s poor.” *Nutrition Reviews* 72(6):355–368.
- Iannotti, L.L., C.K. Lutter, C.P. Stewart, C.A.G. Riofrío, C. Malo, G. Reinhart, A. Palacios, C. Karp, M. Chapnick, K. Cox, and W.F. Waters. 2017. “Eggs in early complementary feeding and child growth: A randomized controlled trial.” *Pediatrics* 140(1).
- IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. 2009. *A review of human carcinogens. Part F: Chemical agents and related occupations*. Lyon, France: World Health Organization.
- ILO/IMF/OECD/UNECE/Eurostat/World Bank. 2004. *Consumer price index manual: Theory and practice*. Geneva: International Labour Office.
- Institute of Medicine. 2000. *Dietary Reference Intakes: Applications in Dietary Assessment. A Report of the Subcommittee on Interpretation and Uses of Dietary Reference Intakes and the Standing Committee on the Scientific Evaluation of Dietary Reference Intakes*. Washington, D.C.: National Academy Press.
- Institute of Medicine of the National Academies. 2006. *Dietary Reference Intakes: the essential guide to nutrient requirements* J. J. Otten, J. P. Hellwig, and L. D. Meyers, eds. Washington, DC: National Academies Press.
- Institute of Medicine of the National Academies. 2011. *Dietary Reference Intakes for Calcium and Vitamin D*. Washington, DC: National Academies Press.
- Institute of Medicine of the National Academies, and Institute of Medicine. 2001. *Dietary Reference Intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc: a report of the Panel on Micronutrients*. Washington, DC: National Academies Press.
- Ivanic, M., and W.J. Martin. 2014. “Short- and long-run impacts of food price changes on poverty.” Policy Research Working Paper No. 7011,
- de Janvry, A., M. Fafchamps, and E. Sadoulet. 1991. “Peasant Household Behaviour with Missing Markets: Some Paradoxes Explained.” *The Economic Journal* 101(409):1400–1417.
- Johnson, M.E., W.A. Masters, and P. V. Preckel. 2006. “Diffusion and spillover of new technology: A heterogeneous-agent model for cassava in West Africa.” *Agricultural Economics* 35(2):119–129.

- Jones, A.D. 2017. “Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries.” *Nutrition Reviews* 75(10):769–782.
- Joy, E.J.M. 2020a. “Personal Communication.”
- Joy, E.J.M. 2020b. “Primary Findings of the Addressing Hidden Hunger with Agronomy (AHHA) Trial.” In *ANH 2020: Agriculture, Nutrition and Health Academy Week*. Virtual.
- Joy, E.J.M., M.R. Broadley, M.J. Watts, A.D.C. Chilimba, S. Young, L. Ander, and C.R. Black. 2015a. “Estimates of Dietary Mineral Supply in Malawi Based on Soil Type and Household Survey Data.” *European Journal of Nutrition & Food Safety* 5(5):642–643.
- Joy, E.J.M., A.A. Kalimpira, D. Gashu, E.L. Ferguson, J. Sturgess, A.D. Dangour, L. Banda, G. Chiutsi-Phiri, E.H. Bailey, S.C. Langley-Evans, R.M. Lark, K. Millar, S.D. Young, L. Matandika, J. Mfutso-Bengo, J.C. Phuka, F.P. Phiri, J. Gondwe, E.L. Ander, N.M. Lowe, P.C. Nalivata, M.R. Broadley, and E. Allen. 2019. “Can selenium deficiency in Malawi be alleviated through consumption of agro-biofortified maize flour? Study protocol for a randomised, double-blind, controlled trial.” *Trials* 20(1):795.
- Joy, E.J.M., D.B. Kumssa, M.R. Broadley, M.J. Watts, S.D. Young, A.D.C. Chilimba, and E.L. Ander. 2015b. “Dietary mineral supplies in Malawi: spatial and socioeconomic assessment.” *BMC Nutrition* 1(1):42.
- Joy, E.J.M., E. Louise Ander, M.R. Broadley, S.D. Young, A.D.C. Chilimba, E.M. Hamilton, and M.J. Watts. 2017. “Elemental composition of Malawian rice.” *Environmental Geochemistry and Health* 39(4):835–845.
- Kaiyatsa, S., Y. Bai, K. Schneider, A. Herforth, and W.A. Masters. 2019. “Do remote rural people pay higher prices for more nutritious foods? Evidence from 130,975 price observations at rural markets in Malawi, 2007-2017.” In *2019 Agricultural & Applied Economics Association Annual Meeting*. Atlanta, GA.
- Kaneene, J.B., D. Thiagarajan, F. Chigwa, T. Gondwe, L. Gunaseelan, M. Thirunavukkarasu, M. Babu, V. Balakrishnan, D. Kambewa, R. Mvula, J. Dzanja, O. Bakili, V. Mlotha, M. Kakwera, M. Chmombo, A. Mwangela, S.N. Sivaselvam, R. Miller, S.A. Asokan, R. Palanidurai, S. Prathaban, K. Kumanan, R. Ramesh Saravanakumar, and P.S. Mohan Kumar. 2016. “A tri-lateral capacity building approach to strengthen the dairy value chain in Malawi: Overview of the design and implementation.” *Livestock Research for Rural Development* 28(9).

- Kim, S.S., P.H. Nguyen, Y. Yohannes, Y. Abebe, M. Tharaney, E. Drummond, E.A. Frongillo, M.T. Ruel, and P. Menon. 2019. "Behavior change interventions delivered through interpersonal communication, agricultural activities, community mobilization, and mass media increase complementary feeding practices and reduce child stunting in Ethiopia." *Journal of Nutrition* 149(8):1470–1481.
- Koppmair, S., M. Kassie, and M. Qaim. 2016. "Farm production, market access and dietary diversity in Malawi." *Public Health Nutrition* 20(02):1–11.
- Kumar, N., J. Harris, and R. Rawat. 2015. "If They Grow It, Will They Eat and Grow? Evidence from Zambia on Agricultural Diversity and Child Undernutrition." *Journal of Development Studies* 51(8):1060–1077.
- Lahaie, S. 2015. "How to take the Dual of a Linear Program."
- Lehmann-USchner, K., and K. Kraehnert. 2016. "Food Intake and the Role of Food Self-Provisioning." *The Journal of Development Studies*:1–20.
- Leroy, J.L., and E. a Frongillo. 2007. "Can interventions to promote animal production ameliorate undernutrition?" *The Journal of nutrition* 137(10):2311–2316.
- Ligowe, I.S., F.P. Phiri, E.L. Ander, E.H. Bailey, A.D.C. Chilimba, D. Gashu, E.J.M. Joy, R.M. Lark, V. Kabambe, A.A. Kalimbira, D.B. Kumssa, P.C. Nalivata, S.D. Young, and M.R. Broadley. 2020a. "Selenium deficiency risks in sub-Saharan African food systems and their geospatial linkages." In *Proceedings of the Nutrition Society*. Cambridge University Press, pp. 1–11.
- Ligowe, I.S., S.D. Young, E.L. Ander, V. Kabambe, A.D.C. Chilimba, E.H. Bailey, R.M. Lark, and P.C. Nalivata. 2020b. "Selenium biofortification of crops on a Malawi Alfisol under conservation agriculture." *Geoderma* 369.
- Limaye, A., R.C. Yu, C.C. Chou, J.R. Liu, and K.C. Cheng. 2018. "Protective and detoxifying effects conferred by dietary selenium and curcumin against AFB1-mediated toxicity in livestock: A review." *Toxins* 10(1).
- Liu, X., X. Chen, and S. Wang. 2009. "Evaluating and predicting shadow prices of water resources in China and its nine major river basins." *Water Resources Management* 23(8):1467–1478.
- Logan, T.D. 2011. "Economies of scale in the household: Puzzles and patterns from the american past." *Economic Inquiry* 49(4):1008–1028.
- Lutter, C.K., L.L. Iannotti, and C.P. Stewart. 2016. "Cracking the Egg Potential During Pregnancy and Lactation." *Sight and Life*:75–81.

- MAFOODS. 2019. *Malawian Food Composition Table* 1st Editio. A. van Graan, J. Chetty, M. Jumat, S. Masangwi, A. Mwangwela, F. P. Phiri, L. M. Ausman, S. Ghosh, and E. Marino-Costello, eds. Lilongwe, Malawi.
- Maillot, M., F. Vieux, F. Delaere, A. Lluch, and N. Darmon. 2017. "Dietary changes needed to reach nutritional adequacy without increasing diet cost according to income: An analysis among French adults" J. Adams, ed. *PLoS ONE* 12(3):e0174679.
- Malawi Bureau of Standards. 2017. *Catalogue of Malawi Standards*. Blantyre, Malawi: Malawi Bureau of Standards.
- Martin-Prével, Y., P. Allemand, D. Wiesmann, M. Arimond, T. Ballard, M. Deitchler, M.-C. Dop, G.L. Kennedy, W.T.K. Lee, and M. Moursi. 2015. *Moving Forward: On choosing a standard operational indicator of women's dietary diversity*. Rome: FAO.
- Masset, E., L. Haddad, A. Cornelius, and J. Isaza-Castro. 2012. "Effectiveness of agricultural interventions that aim to improve nutritional status of children: systematic review." *BMJ* 344(7843):d8222.
- Masters, W.A., Y. Bai, A. Herforth, D. Sarpong, F. Mishili, J.L. Kinabo, and J. Coates. 2018. "Measuring the Affordability of Nutritious Diets in Africa: Price Indexes for Diet Diversity and the Cost of Nutrient Adequacy." *American Journal of Agricultural Economics* 100(5):1285–1301.
- Matumba, L., M. Monjerezi, T. Biswick, J. Mwatseteza, W. Makumba, D. Kamangira, and A. Mtukuso. 2014. "A survey of the incidence and level of aflatoxin contamination in a range of locally and imported processed foods on Malawian retail market." *Food Control* 39(1):87–91.
- Micha, R., J. Coates, C. Leclercq, U.R. Charrondière, and D. Mozaffarian. 2018. "Global Dietary Surveillance: Data Gaps and Challenges." *Food And Nutrition Bulletin* 39(2):1–31.
- Misihairabgwi, J.M.M., C.N.N. Ezekiel, M. Sulyok, G.S.S. Shephard, R. Krska, C.N.N. Ezekiel, R. Krska, M. Sulyok, and J.M.M. Misihairabgwi. 2017. "Mycotoxin contamination of foods in Southern Africa: A 10-year review (2007–2016)." *Critical Reviews in Food Science and Nutrition* 59(1):1–16.
- Mlotha, V., A.M. Mwangwela, W. Kasapila, E.W.P. Siyame, and K. Masamba. 2016. "Glycemic responses to maize flour stiff porridges prepared using local recipes in Malawi." *Food Science and Nutrition* 4(2):322–328.
- Monsivais, P., J. McLain, and A. Drewnowski. 2010. "The rising disparity in the price of healthful foods: 2004-2008." *Food Policy* 35(6):514–520.

- Monyo, E.S., S.M.C. Njoroge, R. Coe, M. Osiru, F. Madinda, F. Waliyar, R.P. Thakur, T. Chilunjika, and S. Anitha. 2012. "Occurrence and distribution of aflatoxin contamination in groundnuts (*Arachis hypogaea* L) and population density of Aflatoxigenic *Aspergilli* in Malawi." *Crop Protection* 42:149–155.
- Morris, S.S., K. Beesabathuni, and D.D. Headey. 2018. "An egg for everyone: Pathways to universal access to one of nature's most nutritious foods." *Maternal & Child Nutrition* 14(July):1–9.
- Mulmi, P., W.A. Masters, S. Ghosh, G. Namirembe, R. Rajbhandary, S. Manohar, B. Shrestha, K.P. West, and P. Webb. 2017. "Household food production is positively associated with dietary diversity and intake of nutrient-dense foods for older preschool children in poorer families: Results from a nationally-representative survey in Nepal" M. A. Cardoso, ed. *PLoS ONE* 12(11):e0186765.
- National Academies of Sciences Engineering and Medicine. 2019. *Dietary Reference Intakes for Sodium and Potassium* V. A. Stallings, M. Harrison, and M. Oria, eds. Washington, DC: The National Academies Press.
- National Statistical Office (NSO) [Malawi]. 2014. "Malawi Integrated Household Panel Survey (IHPS) 2013: Basic Information Document."
- National Statistical Office (NSO) [Malawi]. 2017. "Malawi Integrated Household Panel Survey (IHPS) 2016: Basic Information Document."
- National Statistical Office (NSO) [Malawi]. 2010. *Population and Housing Census 2008*. Zomba, Malawi: NSO.
- National Statistical Office (NSO) [Malawi]. 2012. "Third Integrated Household Survey (IHS3) 2010/11 Basic Information Document."
- National Statistical Office (NSO) [Malawi]. 2011. "Third Integrated Household Survey 2010-2011, Market Questionnaire with Conversion Factors."
- O'Brien-Place, P.M., and W.G. Tomek. 1983. "Inflation in Food Prices as Measured by Least-Cost Diets." *American Journal of Agricultural Economics* 65(4):781–784.
- Omer, A. 2020. "Poultry interventions and child nutrition status in low-income countries." *African Journal of Food, Agriculture, Nutrition and Development* 20(04):16013–16028.
- Omiat, G., and G. Shively. 2017. "Charting the cost of nutritionally-adequate diets in Uganda, 2000-2011." *African Journal of Food, Agriculture, Nutrition and Development* 17(01):11571–11591.
- Optifood. 2012. "Optifood, An Approach to Improve Nutrition." NCT01646710. ClinicalTrials.gov.

- Oseni, G., J. Durazo, and K. Mcgee. 2017. “Annex II: Malawi: Library of nonstandard unit conversion factors and reference photos.”
- Parlesak, A., I. Tetens, J.D. Jensen, S. Smed, M.G. Blenkuš, M. Rayner, N. Darmon, and A. Robertson. 2016. “Use of linear programming to develop cost- minimized nutritionally adequate health promoting food baskets” C. M. Schooling, ed. *PLoS ONE* 11(10):e0163411.
- Phiri, F.P., E.L. Ander, E.H. Bailey, B. Chilima, A.D.C. Chilimba, J. Gondwe, E.J.M. Joy, A.A. Kalimbira, D.B. Kumssa, R.M. Lark, J.C. Phuka, A. Salter, P.S. Suchdev, M.J. Watts, S.D. Young, and M.R. Broadley. 2019. “The risk of selenium deficiency in Malawi is large and varies over multiple spatial scales.” *Scientific Reports* 9(1):1–8.
- Raghunathan, K., D. Headey, and A. Herforth. 2020. “Affordability of nutritious diets in rural India.” *Food Policy*:101982.
- Rao, M., A. Afshin, G. Singh, and D. Mozaffarian. 2013. “Do healthier foods and diet patterns cost more than less healthy options? A systematic review and meta-analysis.” *BMJ Open* 3(12):e004277.
- Ravallion, M. 2020. “On Measuring Global Poverty.” *Annual Review of Economics* 12(1):167–188.
- Ravallion, M. 2016. *The Economics of Poverty: History, Measurement, and Policy*. New York, NY: Oxford University Press.
- Rawls, J. 1971. *A theory of justice* Revised ed. Cambridge, MA: The Belknap Press of Harvard University Press.
- Revoredo-Giha, C. 2019. “An analysis of the tax incidence of VAT to milk in Malawi.” In *6th African Conference of Agricultural Economists*. Abuja, Nigeria.
- Richards, T.J., L. Mancino, and W. Nganje. 2012. “Nutrient Demand in Food Away from Home.” *Forum for Health Economics & Policy* 15(2).
- Romeo, A., J. Meerman, M. Demeke, A. Scognamillo, and S. Asfaw. 2016. “Linking farm diversification to household diet diversification: evidence from a sample of Kenyan ultra-poor farmers.” *Food Security* 8(6):1069–1085.
- Ruel, M.T., J. Harris, and K. Cunningham. 2013. “Diet quality in developing countries.” In P. V. Preedy V., Hunter LA., ed. *Diet Quality: An Evidence-Based Approach, Volume 2*. New York, NY: Humana Press, pp. 239–261.
- Ruel, M.T., A.R. Quisumbing, and M. Balagamwala. 2018. “Nutrition-sensitive agriculture: What have we learned so far?” *Global Food Security* 17:128–153.

- Saxena, P., and N. Khanna. 2014. "Animal feed formulation: Mathematical programming techniques." *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 9(035).
- Schneider, K., L. Christiaensen, P. Webb, and W.A. Masters. 2020a. "Availability, affordability, and seasonality of nutritious diets for all household members year-round in Malawi."
- Schneider, K., and A. Herforth. 2020. "Software tools for practical application of human nutrient requirements in food-based social science research." *Gates Open Research* 4(179).
- Schneider, K., P. Webb, L. Christiaensen, and W.A. Masters. 2020b. "Assessing diet quality when families share their meals: Evidence from Malawi."
- Sen, P., A. Mardinogulu, and J. Nielsen. 2017. "Selection of complementary foods based on optimal nutritional values." *Scientific Reports* 7(1):5413.
- Shi, C.Y., S.C. Chua, H.P. Lee, and C.N. Ong. 1994. "Inhibition of aflatoxin B1-DNA binding and adduct formation by selenium in rats." *Cancer Letters* 82(2):203–208.
- Shi, D., S. Guo, S. Liao, R. Su, J. Pan, Y. Lin, and Z. Tang. 2012. "Influence of selenium on hepatic mitochondrial antioxidant capacity in ducklings intoxicated with aflatoxin B 1." *Biological Trace Element Research* 145(3):325–329.
- Shogren, J.F. 2006. "Economics of diet and health: Research challenges." *Food Economics - Acta Agriculturae Scandinavica, Section C* 2(3–4):117–127.
- Shonkwiler, J.S., J. Lee, and T.G. Taylor. 1987. "An empirical model of the demand for a varied diet." *Applied Economics* 19(10):1403–1410.
- Shrader, R.R., H.H. Chouinard, J.T. LaFrance, and P.R. Wandschneider. 2014. "A Century of Eating: Revealed preferences for nutrients and foods in the United States." In *Agricultural & Applied Economics Association's 2014 AAEA Annual Meeting*. Minneapolis, MN.
- Sibhatu, K.T., and M. Qaim. 2018a. "Farm production diversity and dietary quality: Linkages and measurement issues." *Food Security* 10:47–59.
- Sibhatu, K.T., and M. Qaim. 2018b. "Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households." *Food Policy* 77:1–18.
- Sibhatu, K.T., and M. Qaim. 2017. "Rural food security, subsistence agriculture, and seasonality" B. Shankar, ed. *PLoS ONE* 12(10):e0186406.
- Simtowe, F., B. Shiferaw, and T. Abate. 2016. "Assessment of the current situation and future outlooks

for the groundnut sub-sector in Malawi.”

- Stark, H., A. Omer, A. Wereme N’Diaye, A.C. Sapp, E. V. Moore, and S.L. McKune. 2020. “The Un Oeuf study: Design, methods and baseline data from a cluster randomised controlled trial to increase child egg consumption in Burkina Faso.” *Maternal and Child Nutrition*.
- Stewart, C.P., B. Caswell, L. Iannotti, C. Lutter, C.D. Arnold, R. Chipatala, E.L. Prado, and K.M. Maleta. 2019. “The effect of eggs on early child growth in rural Malawi: The Mazira Project randomized controlled trial.” *American Journal of Clinical Nutrition* 110(4):1026–1033.
- Stifel, D., and B. Minten. 2017. “Market Access, Well-being, and Nutrition: Evidence from Ethiopia.” *World Development* 90:229–241.
- Stigler, G.J. 1945. “The cost of subsistence.” *Journal of Farm Economics* 27(2):303–314.
- Talukder, A., N.J. Haselow, A. Osei, E. Villate, D. Reario, H. Kroeun, L. Sokhoing, A. Uddin, S. Dhungel, and V. Quinn. 2010. “Homestead food production model contributes to improved household food security and nutrition status of young children and women in poor populations lessons learned from scaling-up programs in Asia (Bangladesh, Cambodia, Nepal and Philippines).” *Field Actions Science Reports* (1).
- Trijsburg, L., E.F. Talsma, J.H.M. de Vries, G.L. Kennedy, A. Kuijsten, and C.M.C. Brouzes. 2019. “Diet quality indices for research in low- and middle-income countries: a systematic review.” *Nutrition Reviews* 77(8):515–540.
- United Nations Department of Economic and Social Affairs, S.D. “UN Comtrade: International Trade Statistics.” Available at: <https://comtrade.un.org/data> [Accessed July 7, 2020].
- USDA. 2018. *USDA National Nutrient Database for Standard Reference, Legacy (2018)*. Beltsville, Maryland: USDA Agricultural Research Service Nutrient Data Laboratory.
- Wang, F., G. Shu, X. Peng, J. Fang, K. Chen, H. Cui, Z. Chen, Z. Zuo, J. Deng, Y. Geng, W. Lai, F. Wang, G. Shu, X. Peng, J. Fang, K. Chen, H. Cui, Z. Chen, Z. Zuo, J. Deng, Y. Geng, and W. Lai. 2013. “Protective Effects of Sodium Selenite against Aflatoxin B1-Induced Oxidative Stress and Apoptosis in Broiler Spleen.” *International Journal of Environmental Research and Public Health* 10(7):2834–2844.
- WFP. 2013. *Minimum Cost of a Nutritious Diet (CoD): First Results in Indonesia*. Geneva: World Food Programme.
- WHO, and FAO. 2006. *Guidelines on food fortification with micronutrients* L. H. Allen, B. de Benoist, O. Dary, and R. Hurrell, eds. Geneva: World Health Organization and Food and Agriculture

- Organization of the United Nations.
- WHO, and FAO. 2004. *Vitamin and Mineral Requirements in human nutrition* Second Edi. Geneva and Rome: World Health Organization and Food and Agriculture Organization of the United Nations.
- WHO, and UNICEF. 1998. *Complementary feeding of young children in developing countries: A review of current scientific knowledge*. Geneva: World Health Organization.
- Wiggins, S., S. Keats, E. Han, S. Shimokawa, J. Alberto, V. Hernández, and R.M. Claro. 2015. *The Rising Cost of a Healthy Diet*. London, UK: Overseas Development Institute.
- Wilde, P.E. 2013. *Food Policy in the United States: An Introduction*. New York: Routledge.
- Willett, W.C., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F.A.J. DeClerck, A. Wood, M. Jonell, M.A. Clark, L.J. Gordon, J.C. Fanzo, C. Hawkes, R. Zurayk, J.A. Rivera, W. De Vries, L. Majele Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E.L. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S.E. Cornell, K. Srinath Reddy, S. Narain, S. Nishtar, and C.J.L. Murray. 2019. “Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems.” *The Lancet* 393(10170):447–492.
- Wood, B.D.K., C.H. Nelson, T. Kilic, and S. Murray. 2013. “Up in Smoke? Agricultural Commercialization, Rising Food Prices and Stunting in Malawi.” World Bank Policy Research Working Paper No. 6650,
- World Bank. 2015. *Purchasing Power Parities and the Real Size of World Economies: A Comprehensive Comparison International Report of the 2011 Program*. Washington, D.C.: World Bank.
- Zhao, L., Y. Feng, J. Deng, N.-Y. Zhang, W.-P. Zhang, X.-L. Liu, S.A. Rajput, D.-S. Qi, and L.-H. Sun. 2019. “Selenium Deficiency Aggravates Aflatoxin B1–Induced Immunotoxicity in Chick Spleen by Regulating 6 Selenoprotein Genes and Redox/Inflammation/Apoptotic Signaling.” *The Journal of Nutrition* 149(6):894–901.

Supplementary Material

A. Food Items Identification and Nutrient Composition

Table A-1. Food Items by Food Group in Price Dataset

Food Group	Items	Food Group	Items
Cereals & Cereal Products	Maize flour (dehulled)	Vitamin-A rich fruits	Mangoes
	Maize flour (whole grain)		Oranges
	Maize grain		Papaya
	Maize grain, Admarc		Tomatoes
	Rice grain	Vit-A rich Vegetables	Pumpkin
	White bread		Other Fruits
Dark Green Leafy Vegetables	Chinese cabbage		Banana
	Pumpkin leaves		Guava
	Rape leaves	Other Vegetables	Okra
Eggs	Chicken eggs		Onions
Fish & Seafood	Cichlid (<i>Utaka</i> , dried)		Cabbage
	<i>Oreochromis lidole</i> , dry [†]		Cucumber
	<i>Oreochromis lidole</i> , fresh [†]		Eggplant
	Sardine (<i>Usipa</i> , sun dried)		Green beans
Flesh Meat	Beef	Roots & Tubers	Cassava
	Goat		Irish potatoes
	Live chicken		Sweet potatoes
	Pork	Salty & fried foods	Mandazi
Legumes	Brown beans	Sweets & Confectionary	Biscuits
	Cowpeas		Brown sugar
	Groundnuts		White buns
	Pigeon peas		White sugar
	White beans	Stimulants, Spices, & Condiments*	Salt
Milk & Milk Products	Fresh milk	Caloric beverages*	Coca-cola
	Powdered milk		
Oils & Fats	Cooking oil	Total items (N)	
	Cooking oil refill		
		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 A-2. 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 <i>Usipa</i> , Cowpeas, Rice	Cooking oil, Groundnuts, Powdered milk, Biscuits, Sugar, Maize flour, Pigeon peas, Dried <i>Usipa</i> , 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 <i>Chambo</i> , Dry <i>Usipa</i> , <i>Utaka</i> , Powdered milk, Brown beans, Groundnuts, Cowpeas, Pigeon peas, White beans, Chicken	Dry <i>Chambo</i> , Beef, Dry <i>Usipa</i> , Chicken, Fresh <i>Chambo</i> , <i>Utaka</i> , Goat, Eggs, Pumpkin leaves, Brown beans, Pork
Lipids	Cooking oil, Groundnuts, Powdered milk, Pork, Biscuits, <i>Utaka</i> , Avocado, Goat, Eggs, Dry <i>Usipa</i>	Cooking oil, Avocado, Pork, Groundnuts, Eggs, Goat, Fresh milk, Powdered milk, <i>Utaka</i> , 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 <i>Usipa</i> , Eggs, Goat, Dry <i>Chambo</i> , Brown beans, Pork, White beans, Beef, Pigeon peas	Powdered milk, Eggs, Rape leaves, Pumpkin leaves, Fresh milk, Cucumber, Beef, Okra, Dried <i>Usipa</i> , Goat
Niacin	Dry <i>Usipa</i> , Groundnuts, Beef, Goat, Pork, Chicken, Dry <i>Chambo</i> , Cowpeas, Pigeon peas, Maize grain	Dried <i>Usipa</i> , 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 <i>Usipa</i>	Guava, Dried <i>Usipa</i> , 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 <i>Usipa</i> , Dry <i>Chambo</i> , Eggs, Powdered milk, Beef	Dried <i>Usipa</i> , Dry <i>Chambo</i> , Beef, Eggs, Goat, Fresh milk, Powdered milk, Pork, Chicken
Calcium	Rape leaves, Pumpkin leaves, <i>Utaka</i> , Dry <i>Chambo</i> , Dry <i>Usipa</i> , Cabbage, Papaya, Powdered milk	Pumpkin leaves, Rape leaves, Cabbage, Papaya, Tomatoes, Onions, <i>Utaka</i> , Dry <i>Chambo</i> , Chinese cabbage, Dried <i>Usipa</i>
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 <i>Chambo</i> , Cabbage, Rape leaves, <i>Utaka</i>	Pumpkin leaves, Cabbage, Rape leaves, Tomatoes, Dry <i>Chambo</i> , Onions, Papaya, Beef, <i>Utaka</i>
Magnesium	Pumpkin leaves, <i>Utaka</i> , Papaya, Rape leaves, Cabbage	Pumpkin leaves, Cabbage, Rape leaves, Papaya, Onions
Phosphorus	Dry <i>Usipa</i> , Dry <i>Chambo</i> , Powdered milk, White beans, Brown beans, Cowpeas, Groundnuts, Pigeon peas, Rice, Maize grain	Dried <i>Usipa</i> , Dry <i>Chambo</i> , 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 <i>Usipa</i> , Rape leaves, Pumpkin leaves, Dry <i>Chambo</i> , Onions, Pork, Cabbage, Goat, Powdered milk, Brown beans	Rape leaves, Pumpkin leaves, Tomatoes, Cabbage, Onions, Dried <i>Usipa</i> , Chinese cabbage, Papaya, Goat, Beef
Sodium	Salt, White bread, White buns, Biscuits, Powdered milk, Dry <i>Chambo</i> , Dry <i>Usipa</i>	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 A-3. Food Item Mean Cost per kg (2011 US\$ PPP)
2013 – 2017, Mean over All Markets and Months

Food Item	Cost (\$)	Food Item	Cost (\$)
Maize grain	1.34	Papaya	2.19
Maize grain, Admarc*	0.82	Guava	1.61
Maize flour (dehulled)	3.32	Avocado	2.44
Maize flour (whole grain)	2.42	Mangoes	1.56
Rice grain	3.43	Chicken (live)	17.82
Irish potatoes	2.44	Oreochromis lidole, fresh (<i>Chambo</i>)	17.37
Sweet potatoes	1.42	Oreochromis lidole, dry (<i>Chambo</i>)	31.52
Cassava	1.37	Cichlid (<i>Utaka</i>)	25.00
White beans	4.41	Sardine (<i>Usipa</i> sun dried)	18.71
Brown beans	4.87	Salt	2.12
Pigeon peas	3.82	White bread	2.92
Cowpeas	3.40	White buns	7.53
Groundnuts	5.39	Biscuits	4.71
Onions	4.55	Mandazi	7.29
Tomatoes	2.56	Beef	13.42
Cucumber	2.02	Goat	12.34
Pumpkin	1.03	Pork	14.46
Cabbage	1.11	Fresh milk	4.64
Pumpkin leaves	4.74	Powdered milk [†]	18.65
Green beans	3.26	Eggs	10.57
Chinese cabbage	1.63	Cooking oil	15.43
Okra	3.21	Cooking oil refill	56.87
Rape leaves	2.04	White sugar	4.07
Eggplant	2.06	Brown Sugar	4.38
Banana	2.89	Coca-cola	3.03
Oranges	2.46		

* Maize grain sold by the parastatal Agricultural Development and Marketing Corporation (Admarc).

† With 1 kg powder yielding approximately 8 liters of liquid milk (1 liter equals 1.01 kg), the mean cost per kg liquid added is \$2.35.

B. Policy Scenarios Further Background Information

In this appendix, we provide additional supporting information used to select and define the policy scenarios. Figure A-1 depicts the energy-adjusted nutrient adequacy ratios, demonstrating the nutrients most under-consumed in current diets. We then proceed with a detailed summary of the context of current availability and prices for all of the food items modeled.

Figure B-1. Nutrient Density Adequacy of Household Diets, 2013 & 2016/17

Notes: Black line marks an adequacy ratio of 1 indicating 100% of needs met. Excludes outside values. Adjusted for survey weights.

Eggs are already available in nearly all markets and months at a median price of \$10.12/kg (approximately \$6.31 per dozen eggs). Only a few markets stand out for lack of availability: Phalombe, Mchinji, and to a lesser extent Nkhatabay and Mitundu (Figure A-2). We chose to model multiple levels of percentage price reduction because eggs often are singled out among animal-source foods by development and nutrition interventions as the (usually) lowest cost, nutrient-dense, and safest item to increase ASFs in the diet (Iannotti et al. 2014, 2017, 2019; Lutter, Iannotti and Stewart 2016; Sen, Mardinogulu and

Nielsen 2017; Iannotti 2018; Morris, Beesabathuni and Headey 2018; Stewart et al. 2019; Kim et al. 2019; Omer 2020; Stark et al. 2020).

Figure B-2. Eggs Availability

Several varieties of dried fish are monitored in the price dataset. These include very small, dried cichlid (known locally as *utaka*), sardine (known locally as *usipa*), and *oreochromis lidole* (known locally as *chambo*, and commonly as tilapia). Though there is a fishing ban during spawning season in the country's two largest lakes, the dried fish are storable and could ostensibly be available in all markets and months with adequate storage even under existing biologically- and policy-constrained supply. At present there is a wide range in dried fish availability by market, with eight markets having fish available over 90% of the time while the remainder range from 31-85% (median 69%; Figure A-3). There is large variation in price for each of the three items, with variation not clearly explained by market or season but somewhat by

year. Median price per kg is \$31.39 for *utaka*, \$24.22 for *chambo* and \$17.91 for *usipa* with standard deviations of the price ranging from \$7 to \$11.

Figure B-3. Dried Fish Availability

Groundnuts are available in nearly all months for two-thirds of all markets and ranging from 61-86% of months for nine of the ten remaining markets. Nsalu is an outlier with only 26% of months where groundnuts are available (Figure A-4). Median price is \$5.27 per kg.

Figure B-4. Groundnuts Availability

The milk scenarios require a bit more background as powdered milk is a politically sensitive value chain. The government and donors have long supported the development of Malawi's dairy sector and seen powdered milk as a competitor since there is no domestic production (Kaneene et al. 2016). However, from a nutritional perspective, fresh and powdered milk are nutritionally equivalent products with alternative value chains and potential policy approaches. Fresh milk is available in most markets in almost all months at a median price of \$2.06/kg (\$2.04/liter) (Figure A-5). A small proportion of markets have more limited availability (Jali, Mangochi, Phalombe, Balaka, Ntcheu, Mitundu). However, the fresh milk value chain suffers from a number of on-farm inefficiencies limiting production and productivity (e.g. animal distribution through a donor-driven pass-on scheme focused on pure exotic breeds, feed shortage, lack of access to animal health services), concentration of market power for pasteurization, and a large proportion sold unsafely on the informal market. Therefore numerous challenges face the sector and improving safe supply substantially enough to lower consumer prices would require a number of coordinated actions along the value chain (Baur et al. 2017; Revoredo-Giha 2019).

Powdered milk has the triple advantages that it is non-perishable, poses low food safety risk if mixed with clean water, and in being centrally processed can be fortified with additional nutrients. At present there has been a wide range in the frequency of availability of fresh and powdered milk over the January 2013–July 2017 period (Figure A-6). Powdered milk is always available in a few markets (Thyolo, Lunzu, Mwanza, Nchalo) but also never available in a few others (Nsanje, Mangochi, Jali; the latter two

of these have limited fresh milk as well). On average, it is available 60% of the time over all markets and months at a median price of \$17.08/kg (2011 US\$ PPP) in the concentrated powdered form, with one kg powder yielding approximately eight liters of liquid milk the median price is equivalent to \$2.14/liter, nearly the same as that for fresh milk. The current trade policy imposes no barriers at the border, though stakeholders in the domestic dairy sector have lobbied for such.⁶

Figure B-5. Fresh Milk Availability

⁶ Main trading partners from 2014 – 2017 were Ireland (accounting for nearly half of all powdered milk imports by quantity), the UK (25%), Malaysia (21%), Belgium (17%), South Africa (14%), the Netherlands (13%), Sweden (13%), and Singapore (10%) (United Nations Department of Economic and Social Affairs). Food composition data reflects South African food composition (MAFOODS 2019).

Figure B-6. Powdered Milk Availability

The final scenario we model is soil biofortification with selenium. The selenium content of plants is largely determined by soil mineral content, and both soil minerals and household diets have been shown to be seriously deficient in selenium, consistent with our findings in prior research (Chapter 4 and Figure B-1, this appendix) (Hurst et al. 2013; Joy et al. 2015a; Phiri et al. 2019; Ligowe et al. 2020a). Field trials were carried out over the last ten years to determine the optimal dosing that results in desirable selenium content in the edible maize grain. The trials were designed to achieve optimal fortification composition whereby needs are met for most of the population while risk of excess intakes given current levels of consumption are low (Chilimba 2011; Chilimba et al. 2012b; a, 2014; Joy et al. 2019; Ligowe et al. 2020b).

Emerging results from the human nutrition trial of the consumption of soil-biofortified maize has shown it to be effective and safe in increasing women's selenium status (Joy et al. 2019; Joy 2020a; b). Based on those studies and confirmation with the researchers, we model a scenario where the selenium composition of whole maize and whole grain flour are 11.3 mcg per 100 g edible portion and 5.3 mcg per 100 g edible portion for dehulled maize flour (ufa woyera) (Joy 2020a). For this scenario, we make no changes to availability or prices. Maize is considered the primary food security crop in Malawi and is universally available in at least some form; maize flour is available in 99% of all market-months while whole grain maize is present 80% of the time. Furthermore, Malawi already has a large input subsidy program including fertilizer and maize seed, and therefore the potential to augment the nutrient blend with selenium through the existing production and distribution system is plausible.

We considered modeling the obvious case of universal compliance with existing fortification law, but determined it was not among the most feasible options or possible to model for several reasons. Current policy since 2011 mandates the fortification of all maize and wheat flour as well as rice to be fortified with micronutrients. However, only 15% of maize flour and 0% of rice are industrially processed and the opportunity for fortification is considered low by the Global Fortification Data Exchange (2020). The most realistic compliance scenario for the fortification law would be that all wheat flour and processed products made from wheat adhere to the fortification policy. The policy requires the following micronutrient composition per kilogram of wheat flour: 30 mg iron, 2 mg folate, 50 mg niacin, 80 mg zinc, 6 mg riboflavin, 9 mg thiamin, 0.02 mg vitamin B12, one mg vitamin A (Malawi Bureau of Standards 2017; Global Fortification Data Exchange 2020a).

Straight wheat flour is not included in the list of food items for which prices are collected, meaning households spent less than 0.02% of total expenditure on wheat flour in 2010. There are four items made from wheat flour: white bread, white buns, mandazi (fried dough) and biscuits. Though white buns and mandazi are generally made at the local level, the wheat flour from which they are made would almost certainly be centrally processed. As of September 2018, the Ministry of Health reported 20% of wheat flour – based on household and market samples – was fortified in compliance with the law. White bread is centrally processed, however given low reported compliance with the wheat fortification law we suspect the samples used for the composition analysis were unlikely to reflect a high level of compliance with the law. We do acknowledge fortification could occur at the bread factory and would not be reflected in the statistics regarding compliance in wheat flour and therefore remain uncertain about whether the food composition data already reflect fortification or not. No Malawi-specific food composition data are available for biscuits and therefore we use a generic unenriched butter cookie from USDA data and therefore our results might be sensitive to this choice.

C. Household Composition

Figure C-1. Diet Feasibility and Cost by Household Composition

Inf=Infant <7mo YC=Young child(ren) <3y OC=Older child(ren) 4-13y ALS=Adolescent(s) 14-18y MA=Male adult(s) 19-69y
FA=Female adult(s) 19-69y BFA=Breastfeeding female adult(s) BALS=Breastfeeding adolescent(s) OA=Older Adult 70+

Population statistics corrected using sampling weights. Outliers excluded. Compositions observed in <1% of all households in the population not shown. "Other" accounts for 2.5% of the total population but contains compositions observed in fewer than five households each.

Table C-1 summarizes the average nutrient requirements at the population level with person-level survey data, presenting survey weighted averages over the entire population. Column 1 reflects average lower and upper bound nutrient requirements as defined by the DRIs. Column 2 reflects the lower and upper bounds under the shared household diet. Column 3 shows the percentage difference between Column 1 and Column 2.

Table C-1. Household Composition Frequencies

<i>Composition</i>	Households (%)	Feasibility (%)		Cost per 1,000 kcal (2011 US\$)	
		Mean	(SE)	Mean	(SE)
Older kid(s), adolescent(s), male and female adults	16.8	38.67	(2.78)	1.32	(0.02)
Older kid(s), male and female adults	12.1	69.93	(2.61)	1.28	(0.02)
Young kid(s), older kid(s), male and female adults	7.8	82.02	(2.36)	1.19	(0.02)
Young kid(s), older kid(s), male and breastfeeding female adults	6.8	55.04	(2.65)	1.31	(0.02)
Young kid(s), older kid(s), adolescent(s), male and female adults	5.9	61.58	(2.10)	1.28	(0.02)
Young kid(s), older kid(s), adolescent(s), male and breastfeeding female adults	4.4	32.75	(3.17)	1.36	(0.02)
Male and female adults	3.9	77.47	(4.12)	1.17	(0.06)
Older kid(s), adolescent(s), adult female(s)	3.6	65.89	(4.98)	1.14	(0.02)
Older kid(s), adult female(s)	3.4	47.45	(5.86)	1.31	(0.04)
Young kid(s), male and breastfeeding female adults	2.7	88.00	(1.93)	1.13	(0.03)
Adolescent(s), male and female adults	2.6	36.87	(5.10)	1.32	(0.04)
Other	2.5	41.80	(4.36)	1.23	(0.04)
Young kid(s), male and female adults	2.4	99.69	(0.17)	0.88	(0.03)
Adult male(s)	2.3	95.07	(1.09)	1.08	(0.03)
Adult female(s)	2.0	99.21	(0.38)	1.01	(0.05)
Adolescent(s), female adult(s)	1.9	51.05	(7.13)	1.06	(0.04)
Older adult(s)	1.5	83.35	(3.15)	1.14	(0.04)
Young kid(s), older kid(s), adult female(s)	1.5	94.80	(1.38)	1.22	(0.05)
Young kid(s), older kid(s), adolescent(s), older adult(s)	1.1	89.79	(2.10)	1.39	(0.04)
Adult female(s), older adult(s)	1.1	18.47	(4.93)	1.23	(0.05)
Working age couple, older adult(s)	1.0	71.91	(5.39)	1.19	(0.03)
Young kid(s), older kid(s), adult female(s), breastfeeding	1.0	16.34	(4.90)	1.46	(0.04)
Infant, older kid(s), male and breastfeeding female adults	1.0	36.31	(4.71)	1.15	(0.06)
Older kid(s), older adult(s)	1.0	44.78	(11.26)	1.24	(0.04)
Young kid(s), older kid(s), adolescent(s), adult female(s)	1.0	69.69	(4.53)	1.20	(0.04)

<i>Composition</i>	House- holds (%)	Feasibility (%)		Cost per 1,000 kcal (2011 US\$)	
		Mean	(SE)	Mean	(SE)
Adolescent(s), adult female(s), older adult(s)	0.8	47.63	(8.32)	1.23	(0.05)
Older kid(s), adolescent(s), older adult(s)	0.7	38.10	(15.82)	1.11	(0.11)
Older kid(s), adult female(s), older adult(s)	0.6	16.79	(6.41)	1.09	(0.03)
Older kid(s), adolescent(s), male and female adults, older adult(s)	0.6	39.50	(9.01)	1.27	(0.04)
Adolescent(s), male and female adults, older adult(s)	0.6	7.27	(3.89)	1.54	(0.12)
Adolescent(s), older adult(s)	0.5	40.31	(6.91)	1.09	(0.04)
Young kid(s), older kid(s), adolescent(s), adult female(s), breastfeeding	0.5	55.73	(5.42)	1.31	(0.04)
Infant, male, and breastfeeding female adults	0.5	3.48	(3.19)	1.33	(0.02)
Older kid(s), adolescent(s), adult male(s)	0.5	63.18	(11.08)	1.21	(0.07)
Adolescent(s), male and female adults, older adult(s)	0.4	77.25	(11.11)	1.21	(0.05)
Young kid(s), adolescent(s), male and female adults	0.4	90.41	(4.05)	1.02	(0.07)
Young kid(s), adult female(s)	0.4	14.27	(4.86)	1.26	(0.08)
Older kid(s), adolescent(s), male and breast- feeding female adults	0.3	3.72	(3.64)	1.57	(.)
Young kid(s), adult female(s), breastfeeding	0.3	78.87	(5.75)	1.11	(0.04)
Young kid(s), older kid(s), adolescent(s), male and female adults, older adult(s), breastfeed- ing	0.3	44.16	(10.92)	1.96	(0.05)
Young kid(s), older kid(s), male and female adults, older adult(s), breastfeeding	0.3	18.54	(7.93)	1.28	(0.03)
Older kid(s), adult male(s)	0.2	53.97	(7.40)	1.00	(0.02)
Adolescent(s), adult male(s)	0.2	85.66	(3.18)	1.33	(0.07)
Young kid(s), adolescent(s), breastfeeding	0.2	72.04	(10.36)	1.13	(0.04)
Young kid(s), adolescent(s), male and breast- feeding female adults	0.2	17.03	(4.54)	1.14	(0.14)
Adult male(s), older adult(s)	0.2	80.47	(9.14)	1.00	(0.09)
Young kid(s), older kid(s), male and female adults, older adult(s)	0.1	37.61	(18.13)	1.47	(0.08)
Young kid(s), adolescent(s), adult male(s)	0.1	36.80	(7.73)	1.28	(0.04)
Adolescent(s), breastfeeding	0.1	100.00	(.)	0.89	(0.02)
Adolescent(s)	0.1	86.27	(11.53)	0.74	(0.16)

Population statistics corrected using sampling weights. Composition types sorted by frequency observed.

Definition of age groups aggregates the age groups in the DRIs as follows: Young = 3 and below, Older kids = 4-13, Adolescent = 14-18, Adult = 19-69, Older adult = 70 and above.

D. Supplementary Results

Table D-1 summarizes nutrient requirements for Malawi's rural population (individual level data), using survey weights to obtain nationally representative averages. Column 1 reflects the lower and upper bounds that would apply for individual diets, while column 2 shows the lower and upper bounds that result for individuals when eating the diet shared with other members of their household. Column 3 shows the difference between 1 and 2, in percentage terms.

Table D-1. Nutrient Requirements and Upper Limits Per 1,000 kcal

	(1)		(2)		(3)	
	Individual		Household		% Diff	
	Mean	(SE)	Mean	(SE)	Mean	(SE)
Panel A: Lower Bounds						
Carbohydrate* (g)	112.50	(0.00)	113.15	(0.03)	0.6	(0.03)
Protein (g)	24.03	(0.04)	25.07	(0.00)	8.2	(0.33)
Lipids (g)	24.87	(0.05)	29.13	(0.11)	18.7	(0.32)
Vitamin A (mcg)	231.30	(0.49)	288.89	(1.44)	29.0	(0.71)
Vitamin C (mg)	23.99	(0.11)	33.64	(0.14)	61.5	(1.36)
Vitamin E (mg)	5.12	(0.01)	6.43	(0.01)	31.4	(0.29)
Thiamin (mg)	0.40	(0.00)	0.48	(0.00)	23.6	(0.25)
Riboflavin (mg)	0.42	(0.00)	0.50	(0.00)	21.2	(0.32)
Niacin (mg)	4.90	(0.01)	5.79	(0.01)	22.0	(0.22)
Vitamin B6 (mg)	0.47	(0.00)	0.63	(0.00)	43.2	(0.71)
Folate (mcg)	135.76	(0.33)	174.02	(0.35)	33.4	(0.35)
Vitamin B12 (mcg)	0.82	(0.00)	1.04	(0.00)	32.8	(0.29)
Calcium (mg)	463.87	(1.80)	606.22	(2.23)	41.2	(0.56)
Copper (mg)	0.29	(0.00)	0.38	(0.00)	35.2	(0.41)
Iron (mg)	3.31	(0.02)	7.09	(0.02)	143.6	(0.75)
Magnesium (mg)	112.05	(0.49)	142.20	(0.38)	36.3	(0.61)
Phosphorus (mg)	352.05	(1.55)	527.48	(3.55)	67.9	(1.04)
Selenium (mcg)	18.75	(0.04)	23.88	(0.05)	32.7	(0.32)
Zinc (mg)	3.42	(0.01)	6.46	(0.02)	96.0	(0.65)

* Carbohydrate range does not change under household sharing, slight differences due to rounding.

	(1) Individual (DRIs)		(2) Household Sharing		(3) % Diff	
	Mean	(SE)	Mean	(SE)	Mean	(SE)
Panel B: Upper Bounds[†]						
Carbohydrate* (g)	162.50	(0.00)	163.15	(0.03)	0.41	(0.02)
Protein (g)	78.68	(0.16)	68.03	(0.43)	-12.37	(0.39)
Lipids (g)	39.32	(0.02)	39.08	(0.01)	-0.49	(0.04)
Retinol (mcg)	1083.87	(5.34)	673.91	(6.94)	-31.83	(0.30)
Vitamin C (mg)	721.37	(3.58)	463.75	(4.70)	-30.74	(0.32)
Vitamin B6 (mg)	37.29	(0.15)	27.33	(0.14)	-22.57	(0.15)
Calcium (mg)	1486.71	(10.03)	917.15	(4.10)	-28.93	(0.32)
Copper (mg)	3.30	(0.02)	1.82	(0.03)	-37.85	(0.52)
Iron (mg)	24.98	(0.20)	16.57	(0.07)	-23.89	(0.28)
Phosphorus (mg)	1997.10	(6.45)	1435.39	(5.42)	-23.24	(0.26)
Selenium (mcg)	154.45	(0.60)	104.30	(0.95)	-28.31	(0.34)
Zinc (mg)	14.08	(0.07)	8.64	(0.10)	-33.06	(0.35)
Sodium (mg)	1037.13	(2.22)	811.27	(2.59)	-18.66	(0.18)

Population statistics corrected using sampling weights. Heteroskedasticity robust standard errors in parentheses.

[†] Only relevant nutrients shown, excluded nutrients have no upper bound.

* Carbohydrate range does not change under household sharing, slight differences due to rounding.