Micronutrient adequacy of diets and contributions of large-scale interventions: secondary analyses of household surveys

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ABSTRACT

Despite advancements in several micronutrient innovations to improve diet quality, addressing population micronutrient needs with interventions that can reach target groups with the right micronutrients in adequate quantities is challenging. A dearth in dietary intake data to identify needs and measure the impact of micronutrient interventions, especially in sub-Saharan Africa, currently limits the design of effective micronutrient policies and programmes. Household survey systems generate a particular kind of dietary data and exist in most countries, but understanding how to assess diets and model micronutrient contributions from interventions using these data remains undefined.

This thesis explores the uses of existing national household survey systems to assess the micronutrient adequacy of current diets and the potential contributions that large micronutrient programmes can have to meet needs. First, a description of data sources and a systematic literature review identified the kinds of dietary micronutrient metrics used from Household Consumption and Expenditure Surveys (HCES) and comparability to other dietary assessment methods. A secondary data analysis was then conducted to conceptualise how different metrics can be used together to characterise vulnerable populations. Based on this, a model was then built using data from Malawi to understand the potential contributions of large-scale food fortification to meet micronutrient needs. Finally, an additional secondary data analysis explored whether information gaps from other relevant micronutrient interventions could be filled using data from other household surveys.

These results demonstrate that household survey systems hold unexploited potential when generating evidence to help inform micronutrient policies and programmes, despite data limitations and heterogeneity between survey systems. These information, when interpreted appropriately, can help identify micronutrient needs for vulnerable populations and geographies and are useful for targeting monitoring efforts and guiding resource distribution. Recent investments have galvanised interest in leveraging existing data systems to understand impacts from micronutrient interventions, but additional investments in primary data collection should focus on vulnerable population poorly represented by household surveys.

This thesis presents a method to answer two fundamental questions when designing micronutrient policies and programmes: who has the greatest unmet micronutrient needs and how can these needs be met through public policy and programmes? Future research refining these methods in other countries and for other micronutrient interventions would further strengthen this body of evidence. New primary data investments are also necessary to fill micronutrient data gaps that are present in current household survey systems.

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The COVID19 pandemic was formally declared by the WHO six months after I started this PhD. From the fear, uncertainty, and rampant spreading of misinformation emerged epidemiologists and public health experts who helped define to me how our skills can be applied to make a meaningful impact in our communities. Rationalised through the mantra of one of the most consequential, "*You stay completely apolitical and non-ideological, and you stick to what it is that you do. I'm a scientist and that's it.*" – Dr. Anthony Fauci

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ABBREVIATIONS

95% CI	95% Confidence Interval
AFE	Adult female equivalent
AME	Adult male equivalent
AR	Average requirement
BMGF	Bill & Melinda Gates Foundation
CND	Critical nutrient density
DALY	Disability-adjusted life year
DHS	Demographic and Health Surveys
DPT	Diphtheria, pertussis, and tetanus vaccine
EPI	Essential programme on Immunisation
FAO	Food & Agriculture Organization of the United Nations
FBS	Food balance sheet
FCT	Food composition table
GATHER	Guidelines for Accurate and Transparent Health Estimates Reporting
GAVA	Global Alliance for Vitamin A
GBD19	2019 Global Burden of Disease study
H-AR	Harmonised average requirement
HCES	Household Consumption & Expenditure Survey
IHS4	Fourth Integrated Household Survey of Malawi
IMAPP	Intake Monitoring, Assessment, and Planning Program
LMIC	Low-Middle-Income Country
LSFF	Large scale food fortification
LSHTM	London School of Hygiene & Tropical Medicine
LSMS	Living Standards & Measurement Study
MAPS	Micronutrient Action Policy Support project
MCV	Measles conjugate vaccine
MDER	Mean daily energy requirement
MICS	Multiple Indicator Cluster Survey
MINIMOD	Micronutrient Intervention Modelling Project
MN	Micronutrient
NRV	Nutrient intake reference value
PIMII	Prevalence of Inadequate Micronutrient Intake Index
PSC	Pre-school children
RDA	Recommended daily allowance
SEP	Socioeconomic position
SWPER	Survey-based Women's Empowerment index
UL	Tolerable upper limit
UN	United Nations
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
VAS	Vitamin A supplementation
WHO	World Health Organization

PART I

Context

CHAPTER 1

Background: Healthy diets, micronutrients, food systems, & justice

CHAPTER SUMMARY

This chapter provides a background to the thesis, setting the scene for how this body of work fits within the broader scientific and political landscape. Here, I argue that healthy diets, which can be measured by their micronutrient adequacy, are largely influenced by an unjust food systems that leads to restricted access to micronutrient dense foods among vulnerable populations. Therefore, corrective political action through micronutrient policies and programmes with a clear intent to make food systems more equitable is essential to ensure that vulnerable populations who are most discriminated by food systems can assume their right to healthy, nutritious diets.

Healthy diets & measuring diet quality

A healthy diet is one that infers a low risk of major chronic diseases, and promotes healthy growth, development, and overall well-being[1,2]. Identifying the precise components of a healthy diet for population assessment and monitoring is challenging when considering the diverse measures of what makes a diet healthy. Some approaches isolate constituent nutrients summed across all foods to evaluate if diets provide adequate quantities of nutrients to support growth, development, and healthy life while minimising risk of negative health outcomes[3]. Other approaches argue for broad assessments of diets by whole foods or mixtures of whole foods to acknowledge the complex interactions between nutrients and recognise other dietary components important for health that are not exclusively classified as nutrients[4]. While proposed diet quality typologies have recognised that global targets need to reflect dimensions of the diet extending beyond energy sufficiency[5] (Figure 1.1), choosing or consolidating information describing nutrient adequacy, abidance to food-based dietary guidelines, and other characteristics that define healthy diets continues to be debated. Furthermore, there are considerable data limitations, resulting in a reliance on imperfect or proxy data on selected indicators of diet quality. These debates are underpinned by a great sense of urgency; it is estimated that improving the quality of diets globally to ensure they are 'healthy' has the potential to avoid 10.9 million deaths per year, and there are 255 million disability-adjusted life-years (DALYs) attributable to dietary risk factors annually[6]. However, around the world, diets and food systems are not getting healthier and continue to inflict harmful pressures on the health of people and the planet[7].

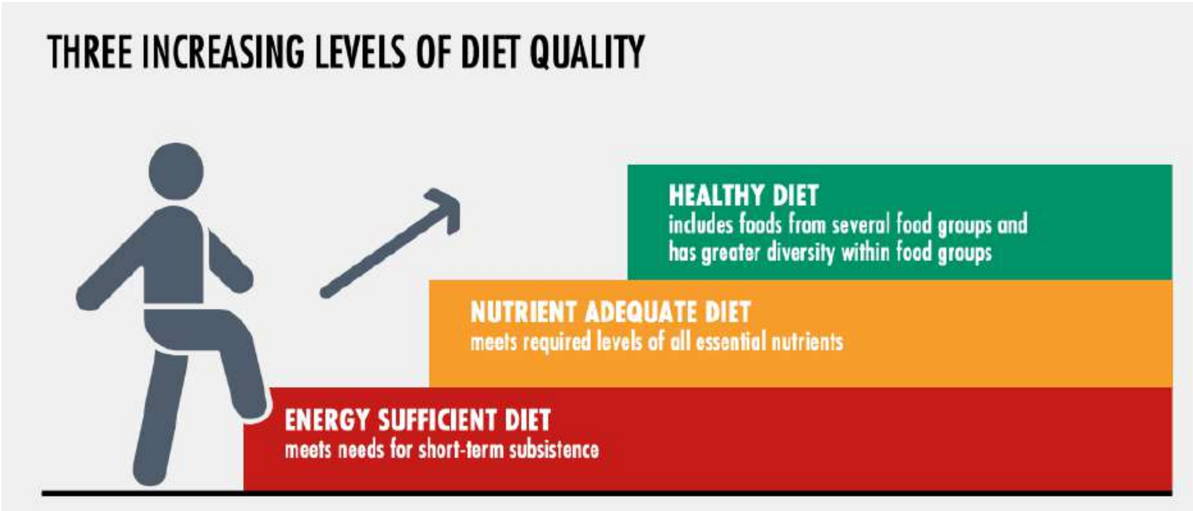


Figure 1.1 Framework to describe diet quality in three increasing levels: energy sufficient, nutrient adequate, and healthy (Ref. FAO 2020)

Despite the relevance for population health and environmental impacts, diets and measures of their quality are not adequately reflected in key global development targets, such as the second Sustainable Development Goal ("Zero hunger") which omits indicators that reflect diet quality, or "hidden hunger". Insufficient recognition of the importance of healthy diets in global development targets results in insufficient systematic monitoring necessary to identify needs and vulnerabilities, maintain accountability, measure progress, and identify shortfalls. Increasingly, the content, cost or affordability of 'healthy' or 'nutritious' *modelled* diets are being used as a metric for assessing nutrition access and vulnerability by researchers, governments and international agencies[8,9] but assessments of *current* diets and their quality remains underexploited. High-level interest has been expressed by normative agencies to include indicators of diet quality into future revisions of global development targets[10], with some recent incremental progress[11]. To facilitate the development of these targets and to ensure policies and programmes are guided by best-available evidence, practical recommendations supported by rigorous research are necessary to best characterise diet quality for global monitoring.

Micronutrient undernutrition in individuals & populations

Micronutrients (also known as vitamins and minerals) are a diverse array of dietary components which are required by our bodies in small quantities yet are essential for human health. Micronutrients are needed for a variety of functions and in quantities that vary between individuals that depends on age, life-stage, and sex. Their biological roles include as coenzymes or prosthetic groups, or as biochemical substrates or hormones, where all roles are fundamental to human survival, growth, and reproduction[12]. Most dietary micronutrients need to be ingested in quantities that fall within a physiologic adequacy window that is not too low to avoid deficiency and not too high to avoid toxicity.

Individuals with dietary micronutrient intakes that are inadequate to meet requirements present potential risks for developing micronutrient undernutrition. Micronutrient undernutrition is characterised by stages of severity (Table 1.1), where the magnitude of intake inadequacy combined with a variety of other factors all contribute to how the body responds when depleted of micronutrients[13]. While later stages of micronutrient undernutrition can be assessed and diagnosed using a variety of biochemical, clinical, and anthropometric tests, dietary intake inadequacy typically precedes these more advanced stages of micronutrient undernutrition[3]. Dietary micronutrient assessment can contribute a valuable perspective when characterising those with micronutrient undernutrition and identifying those who are potentially at risk. For those who already present signs and symptoms of advanced stages of micronutrient undernutrition, an understanding of the micronutrient adequacy of their diet can help identify drivers of these conditions to better design treatment strategies. For those with subclinical symptoms or who do not present signs of micronutrient undernutrition, an understanding of the micronutrient adequacy of diets can help identify populations with the greatest risk potential to help design strategies for prevention. For some micronutrients, such as zinc, the symptoms of prolonged deficiency may be non-specific – such as reduced linear growth – and dietary assessment is important to identify deficiency risk in a population. While data describing all stages of micronutrient undernutrition is important, this thesis will focus on the added value of assessing the earlier stages of micronutrient undernutrition, or dietary micronutrient intake inadequacy, and how this information is relevant to the design of strategies for prevention.

Table 1.1. Generalised outline of the stages of micronutrient undernutrition adapted from Gibson (2005) with specific examples for vitamin A[14] and iron[15].

Severity stage of micronutrient undernutrition	Method(s) used for assessment	Example (vitamin A)	Example (iron)
1. Dietary intake inadequacy	Dietary	Usual intake below age, sex, and life stage specific nutrient reference value (e.g., RDA)	Usual intake below age, sex, and life stage specific nutrient reference value accounting for bioavailability (e.g., RDA)
2. Pre-clinical signs (e.g., decreased level in reserve tissue, decreased level in bodily fluids, decreased functional level in tissues)	Biochemical	MRDR (deficiency if ≥0.060) Low serum/plasma retinol*$^{\lambda}$ Low retinol binding protein*$^{\lambda}$ Low breastmilk retinol	Low serum ferritin*$^{\alpha}$ High zinc protoporphyrin
3. Functional change (clinical)	Behavioural/ Physiological	Dark adaptation test, electroretinography, pupillary threshold test	Anaemia, social-emotional behavior scale
4. Clinical signs & symptoms	Clinical	Xerophthalmia (blindness, night blindness, Bitot's spots, corneal scar)	Fatigue, weakness

RDA = recommended daily allowance
MRDR = Modified Relative Dose Response
*Require adjustments for infection status or inflammation.
$^{\lambda}$ Only for pre-school children
$^{\alpha}$ For pre-school children and women of reproductive age

The epidemiology of micronutrient undernutrition is complicated, where developing precise estimates of the global burden is challenging for a variety of reasons. Recent research characterising the epidemiology of micronutrient undernutrition places emphasis on micronutrient deficiencies, which requires validated biomarkers, consensus on appropriate cut-offs, appropriate adjustments for interactive factors, and representative biomarker survey data for each micronutrient of interest. Recent research has estimated that 372 million pre-school aged children, or 56% or the world population, present with at least one of three sentinel micronutrient deficiencies (iron, zinc, vitamin A), and 1.2 billion non-pregnant women of reproductive age, or 69% of the world population, present with at least one of three sentinel deficiencies (iron, zinc, folate)[16]. Additional modelled estimates of the global burden of micronutrient deficiencies and attributable disease outcomes are presented in Table 1.2, where the global impact in 2019 was estimated to be a loss of 2.4 million DALYs attributable to iodine deficiency, a loss of 28.5 million DALYs attributable to dietary iron deficiency, a loss of 259,000 DALYs attributable to zinc deficiency, and a loss of 3.3 million DALYs attributable to vitamin A deficiency[17]. However, these estimates likely understate the true extent of micronutrient deficiencies due to the limited availability of micronutrient biomarker survey data and, therefore, these estimates heavily rely on proxies and complex statistical modelling as the next best option to compensate for data gaps. Other modelling studies focusing on vitamin A and zinc have indicated that the greatest burden of micronutrient deficiencies is in Africa, exacerbating mortality due to diarrhoea, measles, malaria, and pneumonia [18,19]. As micronutrient inadequate diets are one of the most attributable risk factors contributing to micronutrient deficiencies in Africa, further exploration into variations in diets for groups at risk is necessary.

Table 1.2 The estimated prevalence (95% CI) of iodine, dietary iron, iron, zinc, and vitamin A deficiency and the associated global burden (in deaths, DALYs, and YLDs[1]) according to the Global Burden of Disease Study in 2019 (Reference: Hess et al. 2021).

	Iodine deficiency[2]	Dietary iron deficiency[3]	Iron deficiency[4]	Zinc deficiency[5]	Vitamin A deficiency[6]
Prevalence of deficiency					
Ages 1-4 y	0.0011 (0.0007, 0.0016)	0.29 (0.27, 0.30)	-	0.09 (0.03, 0.18)	0.16 (0.14, 0.17)
All ages	0.024 (0.019, 0.029)	0.14 (0.14, 0.15)	-	n/a	0.063 (0.061, 0.066)
Deaths (thousands) due to deficiency)	-	-	42 (15, 70)	2.8 (0.7, 6.5)	24 (3, 50)
YLDs (thousands) due to deficiency	2439 (1373, 4239)	28,535 (19,128, 41,139)	28,798 (19,425, 41,492)	17 (5, 39)	1222 (833, 1711)
DALYs (thousands) due to deficiency	2439 (1373, 4239)	28,535 (19,128, 41,139)	31,263 (21,272, 43,987)	259 (67, 597)	3297 (1347, 5594)
SEV due to deficiency	-	-	19.57 (18.11, 21.12)	8.78 (2.89, 17.60)	15.01 (13.55, 16.86)
Total DALYs due to deficiency, %	0.10% (0.06%, 0.16%)	1.12% (0.80%, 1.51%)	1.20% (0.91%, 1.60%)	0.01% (0.003%, 0.02%)	0.13% (0.06%, 0.22%)

1 DALY, disability-adjusted life-year; GBD, Global Burden of Disease; n/a, not available; SEV, summary exposure value; YLD, year lived with disability.
2 Iodine deficiency modeled based on visible goiter.
3 Risk exposure for dietary iron deficiency modeled based on hemoglobin concentration below the anemia cutoff after accounting for other known anemia causes, and after accounting for known causes of iron
deficiency (such as hookworm, schistosomiasis, upper gastrointestinal bleeding, and gynecologic conditions).
4 Risk exposure for iron deficiency modeled based on hemoglobin concentration below the anemia cutoff after accounting for other known anemia causes.
5 Zinc deficiency modeled based on dietary zinc inadequacy estimated from dietary surveys and FAO Supply Utilization Accounts. The GBD estimates for zinc deficiency are modeled for children aged 1–4 y only.
6 Vitamin A deficiency defined as serum retinol concentration < 70 µmol/L.

Diet quality and the influences of the food system

The micronutrient adequacy of diets is underpinned by the food system that links the production of foods to the end consumers, and the influences of broader socioeconomic and environmental interactions[20,21]. Certain foods, such as fruits, vegetable, legumes, nuts/seeds, whole grains, edible oil high in unsaturated fat, and animal-sourced foods (in LMIC contexts), are the most micronutrient dense and can contribute the largest proportion of food-based micronutrients to diets[22]. The global supply per capita of these micronutrient dense foods is greatest in high-income countries, where LMICs in Africa and elsewhere have the lowest supply[23] (Figure 1.2) and subsequently low intake. Lower supply of micronutrient dense foods in these countries is likely due to a variety of factors inhibiting production including poor post-harvest practices, limited access to necessary technology, unfavourable climatic conditions (e.g., extreme temperatures, drought, depleted soil quality), and political/market influences on production (e.g., government subsidies/higher capital gains from cash crops)[24–26]. Within LMICs, this likely leads to barriers in accessibility especially for the poorest, most rural least formally educated populations[27], where these barriers potentially contributing to gaps in diet quality (Figure 1.3A) and manifestations from micronutrient deficiencies, such as stunting (Figure 1.3B). Barriers to healthy diets for the most vulnerable can also be understood from an economics perspective, where in Africa alone, over one billion people are unable to afford a healthy, micronutrient adequate diet[11]. Obstructed access to a healthy diet within as well as across countries and promotion of poor-quality diets, such as through marketing of energy-dense processed foods, are products of the deep inequities that arise from an unjust food system, which inadvertently benefits the populations who are included in the social and economic order over those who are not[27].

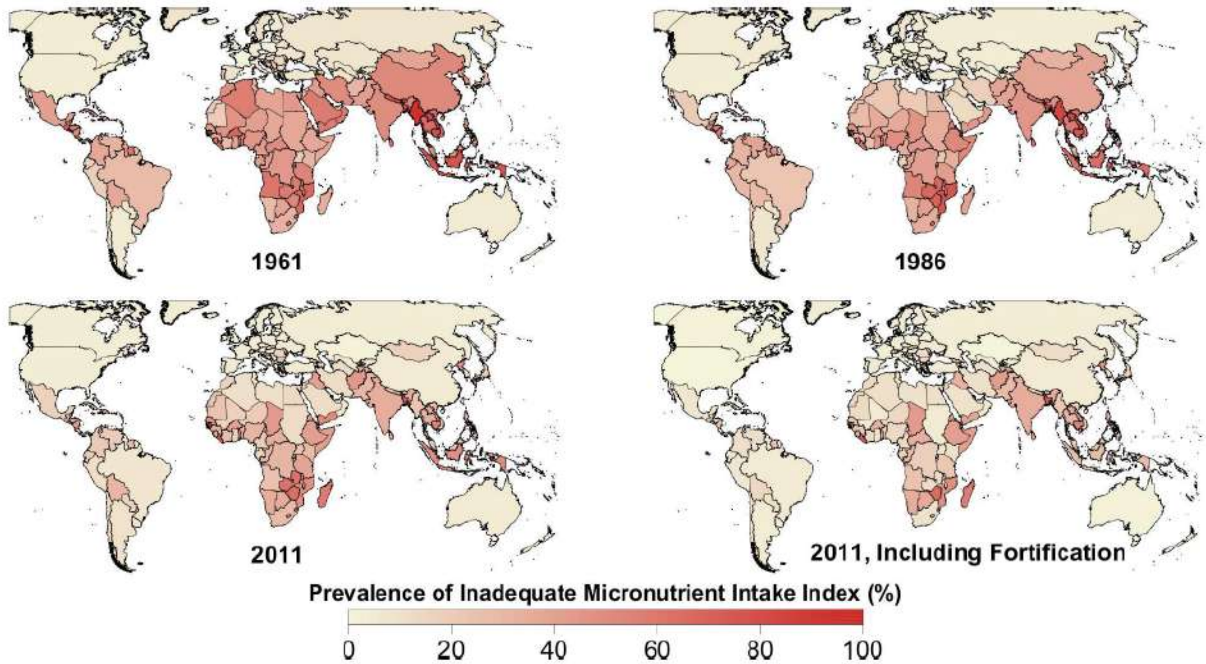
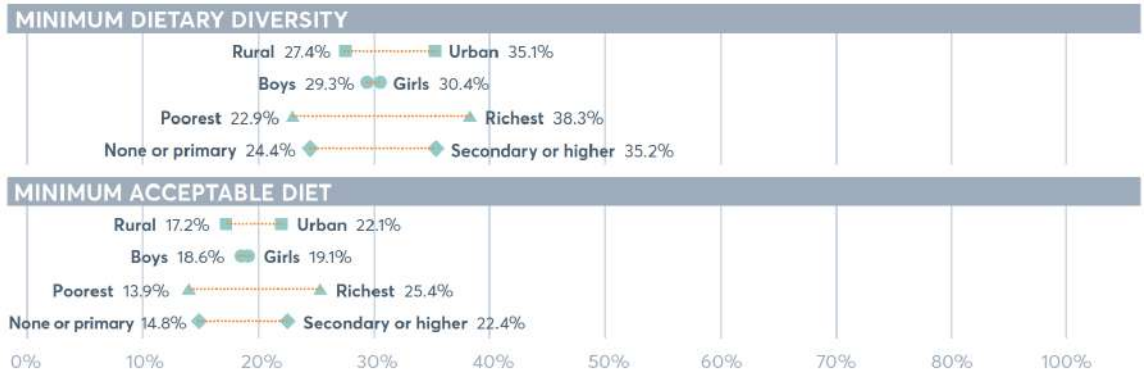


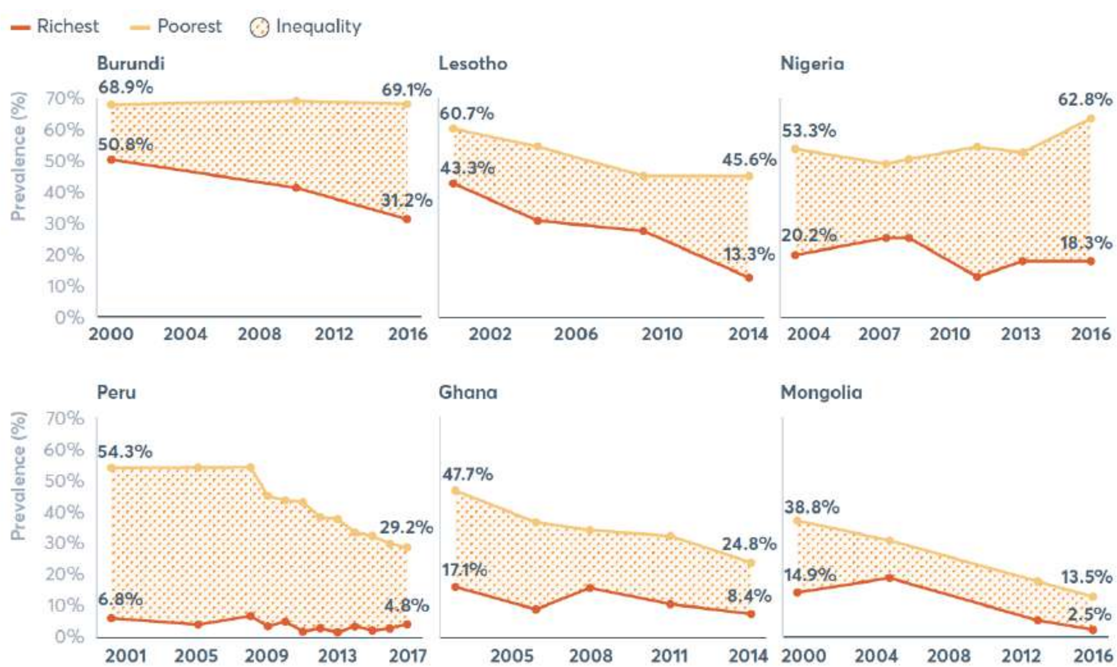
Figure 1.2 National-level estimate of the Prevalence of Inadequate Micronutrient Intake Index (PIMII) for the years 1961, 1986, and 2011 (with and without fortification based on country-specific standards). The PIMII estimates apparent national micronutrient supply inadequacy by combining 14-equally weighted micronutrient inadequacy estimates using national food accounts from FAO Food Balance Sheets and UN population estimates (Reference: Beal et al. 2017).

a.



Source: UNICEF global databases Infant and Young Child Feeding, 2019.
Notes: Prevalence (%) estimates are based on population-weighted means of between 70 and 85 countries, using latest available data across all population groups by indicator (number of countries varies by indicator due to differences in available surveys). Inferences may be affected by the different number of included countries. Location is classified as 'urban' and 'rural' (as defined in the survey). Wealth is asset-based wealth scores at the household level and is classified as 'poor' (lowest wealth quintile) and 'rich' (highest wealth quintile). Education is classified as 'none or primary' and 'secondary or higher' and refers to educational level of the mother. Definitions of all indicators can be found in Appendix 1.

b.



Source: UNICEF/WHO/World Bank Joint Child Malnutrition Estimates Expanded Database: Stunting, Wasting and Overweight (March 2019, New York).
Notes: Countries with greatest increases and decreases in the gap between the highest and lowest wealth quintiles for stunting are chosen using the earliest and latest post-2000 data points and calculating the absolute change in gap. Wealth quintiles are determined by asset-based wealth scores at the household level, where highest refers to the most wealthy quintile and lowest to the least wealthy.

Figure 1.3 Gaps in (a) some indicators reflecting diet quality for young children and (b) stunting between wealthiest and poorest household wealth quintiles for infants, young children and adolescents within low middle income countries (Reference: Global Nutrition Report 2020).

Equitable approaches to address inadequate micronutrient intake

National governments must choose to adopt and adhere to equitable micronutrient intervention strategies that aim to counter micronutrient inadequate diets that manifest from unjust national and global food systems. There are several micronutrient interventions that can be implemented at the national-level including large-scale food fortification (LSFF), variations of biofortification, efforts to promote dietary diversification, food-based social protection, and micronutrient supplementation. The efficacy and effectiveness of some micronutrient interventions have been studied using randomised controlled trials in clinical and programmatic settings[28–30]. Each intervention has unique strengths and limitations regarding the populations they are targeting, the micronutrients they can provide, and the relative cost to public health impact, where the success of different interventions will vary between contexts and depending on the outcomes prioritised. With no single intervention capable of providing a silver bullet to provide healthy diets for all, this naturally must mean the need for comprehensive strategies that may require the overlapping of interventions across sectors.

The concept of equity can be understood through the lens of John Rawls' Theory of Justice[31]. Rawls' theory emphasizes the importance of a fair distribution of social goods and resources, such as healthy nutritious foods, in promoting social justice and the well-being of individuals and communities. Rawls argues that a just society is one where basic institutions are designed to promote the well-being of the least advantaged. In the context of public health nutrition, I interpret this as ensuring that individuals and communities who are most vulnerable to malnutrition in all its forms have access to the resources necessary to achieve optimal health.

This theoretical foundation promotes a just distribution of resources, or advocating for public policy that is intentionally designed to improve the nutritional status for the least advantaged and breaking down structural barriers that prevent them from accessing healthy nutritious foods.

A common evaluation of public health programmes characterises success by maximising health impact for the greatest number at the lowest cost [32,33]. For micronutrient programmes embedded within unjust food systems, Rawls would argue that programmes should not be classified as successful if they have wide coverage but perpetuate inequity by predominantly servicing the most advantaged populations or failing to reach the most vulnerable. To address this, public health programmes should be designed, monitored, and evaluated abiding by Rawls' *difference principle*, where a programme's success is determined by how well it improves the health of the *least advantaged* members of society[31]. To illustrate, in the example of a rice fortification programme, this would require a national-level needs assessment to identify priority populations with the greatest micronutrient needs, a rice acquisition assessment (e.g., home production vs market purchase, product acceptability, branding/labelling preference) to identify potential entry points for fortification, and monitoring and evaluation of rice fortification impact on these priority populations[34]. Interventions designed according to the *difference principle* can be used by governments as an equalising mechanism to shape a society where everyone, regardless of where in society one falls, has an equal opportunity to a healthy life. This moral argument is furthered by one that is economical: programme investments will not be as effective if they do not identify and target the most vulnerable populations that have the greatest needs.

If driven by programme and population data, governments can systematically monitor how well programmes are reaching these least advantaged target populations. Yet, similar to food systems inequities, data inequities exists where populations with the greatest needs but fewest resources have the least data available to help inform priorities, practice, and progress.

Data-driven decision-making for micronutrient policy and programmes

A data-driven national micronutrient strategy requires nationally representative data of various types to help inform prioritisation of interventions and target populations The uptake and application of evidence into nutrition policy is subject to various political and institutional influences that may either facilitate or hinder the use of certain types of evidence [35,36]. Some key questions about the political context must be addressed to best position data and evidence alongside advocacy and government decision-making processes. How concentrated is power over national public health programmes? Is micronutrient undernutrition a priority when compared to other issues of public health concern? Do government institutions have the mechanisms and expertise in place to act on available evidence? Is there any resistance to micronutrient interventions (moral, cultural, political) from influential stakeholders? Are data being used by different parties to contest or recommend alternative courses of action? What is the role of donors and how aligned is their agenda with that of the national government? The approach to integrating data into a micronutrient strategy will depend on these political factors. Yet, bridging the chasm between evidence and policy can be possible through strong partnerships between researchers, advocates, and policymakers: co-design of research topics, co-ownership of outputs, and constant clear communication between stakeholders responsible for evidence generation and stakeholders burdened with decision-making.

National level indicators are important to drive a national agenda, but it is equally important to conduct analyses at a sub-national level to evaluate whether the least advantaged populations are being reached. Sub-populations are often defined by geopolitical borders to facilitate the distribution of resources to least advantaged regions, but also should be defined by characteristics that help understand aspects of vulnerability (e.g., poverty, race, gender, age, elevated nutrient needs, settlement status) to ensure the least advantaged populations within a geographical limit are targeted and benefitting the most from any interventions and recognising gaps in current programming. While this is an appealing proposition in theory, a growing interest in quantifying dietary micronutrient intake has highlighted concerns related to the availability of and costs associated with dietary intake data for population assessment[10,37].

For my Ph.D., I present a body of work that aims to understand how existing national household survey systems can be leveraged to assess the micronutrient adequacy of diets at sub-national levels to guide the design of micronutrient programmes to meet the needs of the least advantaged populations. My approach will draw from my background in public health nutrition, epidemiology, and statistics, with influences from the fields of economics and demography.

CHAPTER 2

Thesis overview

CHAPTER SUMMARY

This chapter presents a comprehensive overview intended to outline the existing research gap this thesis addresses and the approach necessary to generate this knowledge. This includes the rationale for the body of research, the thesis aim and objectives, the broad structure for this thesis, my contributions and the contributions of my collaborators, funding supporting this work, a list of research outputs including publications, and ethics. Further supporting documents demonstrating processes completed as part of the PhD are available as appendices.

2.1 Rationale for the thesis

Robust data on what people eat in a country is one of the most important sources of information for identifying populations at risk for diseases and chronic conditions attributable to micronutrient inadequate diets. However, there is a global dearth in nationally representative dietary data that can be used to identify and distinguish between populations with the greatest additional micronutrient needs. Recent investments have been committed to increase the availability of individual-level food consumption data in some countries, but the time and resources needed to generate these data means that it will be years until they are available in all countries where they are needed. There is an urgent need for more immediate data to inform current micronutrient policies and programmes. Proxy food consumption data from existing household surveys systems have potential to serve as an alternative to individual-level food consumption data, but the kinds of information that these data can provide must be well defined to ensure that data-driven decision-making drawing from these household surveys, as the name suggests, remains driven by quality data.

In most cases, national household survey systems are not designed to collect proxy household-level food consumption data, but rather generate monitoring indicators to track other national policy priorities[38]. While these data have been used in secondary analyses for population dietary micronutrient assessment[39,40], recent scholarship has predominantly focused on documenting the several limitations and assumptions that must be taken into account when using household surveys for dietary assessment [41–44]. This thesis aims to take a pragmatic approach, exploring what household survey data can reveal about micronutrients in diets, while acknowledging that other sources of data will be required to triangulate and complement this information in the design of relevant policies and programmes. In other words, this thesis will focus on how micronutrient intervention decision-making can be better informed using proxy food consumption data from household surveys, how to communicate to end-users of this data the extent to which these data are appropriate for dietary assessment, and how to recognise the limitations that have been highlighted as concerns in prior scholarship. This thesis is a modest attempt to address some of the core questions related to the use of proxy food consumption data from established household surveys for population dietary micronutrient assessment. It may be helpful to readers of this thesis to state some of these core questions from the start.

First, *how do micronutrient assessment estimates from household survey data compare to similar estimates using individual-level dietary data?* This is one of the more fundamental questions relevant to this thesis. While it is important to introduce the different kinds of data used to assess the micronutrient adequacy of diets (Chapter 3), the angle most relevant here is understanding if and how household-level food consumption data should be used to assess the micronutrient adequacy of diets in country contexts where individual level intake data does not exist. Since the use of household-level food consumption data for micronutrient assessment has been debated in academia over the last two decades[45–47], this core question can be answered by reviewing past scholarship that have used household-level food consumption data for micronutrient assessment and compares results to estimates using individual-level intake data.

Second, *what kinds of information can household-level food consumption data provide and does this vary between countries?* While prior scholarship has demonstrated examples of how household-level food consumption data can be used for micronutrient assessment, no guidelines exist to standardise methodological assumptions or metrics used. Furthermore, prior scholarship has not defined how the results of various metrics and modelled scenarios should be brought together into a cohesive narrative to facilitate the uptake of these data for decision-making. Due to heterogeneity in assumptions made and metrics used in the existing scholarship, answering this question will require an analysis using household-level food consumption data to assess the micronutrient adequacy of diets using various metrics to characterise inadequacy, compared between a variety of country settings, and maintaining relative consistency with the assumptions for comparability.

Third, *how can these data most appropriately inform national-level decision-making to facilitate the equitable design of micronutrient policy and programmes?* While understanding the nuances of household-level food consumption data is central to this thesis, it is equally important to demonstrate an application of these types of analyses to inform micronutrient decision-making. This is necessary to argue for the political relevance of these kinds of analyses by demonstrating an application of how analyses of these household survey data can inform a pressing national micronutrient policy issue.

Fourth, *how can we fill information gaps important to micronutrient assessment using existing sources of relevant household survey data or new population data investments?* The kinds of data household surveys collect vary between types of surveys, countries, and implementation years. As secondary users of this data, identifying relevant variables from different surveys and survey types, and triangulating the results of different analyses together is required to best inform a micronutrient policy or programme. Where gaps in knowledge exist even after a broadly conducted analysis, a case can be made to either modify current surveys to generate this information or for entirely new data investments.

The focus of this thesis is on dietary approaches to assessing micronutrient intake adequacy with the intent to guide decision-making for micronutrient interventions. This is in contrast to assessing biological markers of micronutrient deficiencies from micronutrient surveys to define morbidity burdens. The dietary assessment approach presents an opportunity to measure important aspects of the diet (e.g., foods consumed, nutrient compositions), to model scenarios of proposed micronutrient interventions and their potential effectiveness, and ultimately generate valuable insights for national-level policy or programme decision-making. Dietary assessments and biomarkers could potentially be used in tandem, where dietary assessment can help to understand whether dietary shortfalls are an underlying risk factor of a deficiency. However, biomarker data bring their own limitations: reliable biomarkers do not exist for many nutrients, survey data may be scarce, and often analyses require careful adjustments for multiple confounding and interacting factors. While understanding the relationship between biomarkers and dietary intake is important, these questions lie outside the scope of this thesis.

2.2 Aim and objectives of this thesis

Overall aim

The aim of this thesis is to provide guidance on the use of existing national household survey systems to assess the micronutrient adequacy of current diets and to simulate the potential contributions that large micronutrient programmes can have to meet these needs.

The objectives of this thesis are as follows:

Objective 1

Describe the available sources of data used to assess the micronutrient adequacy of diets, present their potential for population micronutrient assessment, and characterise their accessibility, methodological strengths, and limitations.

Objective 2

Review existing literature on the uses of household-level food consumption data that are commonly collected in household surveys to characterize nutrient supplies as a proxy for dietary micronutrient assessment.

Objective 3

Using the findings from Objective 2, compare the uses of these metrics and describe how they should be used together, interpreted, and communicated when characterising and comparing sub-groups at-risk for inadequate micronutrient intake.

Objective 4

Using the results from Objectives 2 and 3, demonstrate a practical example of how to simulate the potential contributions of a large micronutrient intervention to meet micronutrient needs

Objective 5

Based on the findings from Objective 4, present the added value of integrating data collected from other household surveys to evaluate the equity dimensions of other large micronutrient programmes.

2.3 Structure of this thesis

This thesis is structured in the 'research papers' style, in compliance with the Research Degree Examination Guidelines of the London School of Hygiene & Tropical Medicine. In addition to the research papers, the thesis is supported by an overall summary, further description of the data used, and supporting material to link each research paper to the overall aim of the thesis.

This thesis is divided into three parts containing eight chapters in total, including two published papers, one paper undergoing peer-review by an academic journal, and one paper recently submitted to an academic journal. The chapters included in this thesis are the following:

Part 1 provides context by placing the thesis within the broader scholarship and global health policy landscape.

- **Chapter 1** provides an introduction to healthy diets, the role of micronutrients in healthy diets and their relevance for public health programming, and the rationale behind equitable public health programming.
- **Chapter 2** presents the rationale and research gap this thesis addresses, in addition to the aim, objectives, and overview of the work found in this thesis.
- **Chapter 3** summarises the different types of data used to assess the micronutrient adequacy of diets for populations, as indicated by Objective 1.

Part 2 presents the new evidence synthesised as a result of the research activities conducted as part of this thesis.

- **Chapter 4** is a published systematic review in a peer-reviewed journal on studies characterising household nutrient supplies using Household Consumption & Expenditure Surveys, as indicated by Objective 2.
- **Chapter 5** is an original research article prepared for submission to a peer-reviewed journal that explores how dietary micronutrient assessment metrics derived from Household Consumption & Expenditure Surveys can be used to characterise populations at-risk for micronutrient inadequacy, as indicated by Objective 3.
- **Chapter 6** is a published original research article in a peer-reviewed journal that demonstrates how dietary micronutrient assessment using Household Consumption & Expenditure Surveys can help inform national micronutrient policy and programmes, as indicated by Objective 4.
- **Chapter 7** is an original research article submitted to a peer-reviewed journal that demonstrates how Demographic and Health Survey data can be useful to inform national governments on how to orient a national-level high-dose vitamin A supplementation delivery strategy, as indicated by objective 5.

Part 3 presents a discussion of the key findings of the overall thesis.

- **Chapter 8** discusses the overall findings of the thesis in relation to other published scholarship and key topics, key limitations, implications for national micronutrient policies and programmes, and potential for future research in this field of study.

2.4 Candidate's involvement & funding

This PhD was designed to contribute to one component of a broader four-year research investment called the Micronutrient Action Policy Support (MAPS) project funded by the Bill & Melinda Gates Foundation (original protocol available in Appendix I). The aim of the MAPS project is to co-create a web-hosted tool to estimate sub-national burdens of micronutrient deficiencies, characterise the diets of populations that are inadequate of micronutrients, and explore pathways to improve nutrition. I joined the MAPS team in October 2019 as a full-time PhD student at the launch of the initial grant. Through discussions with my supervisors, Dr. Edward Joy and Dr. Elaine Ferguson, we agreed that food consumption and expenditure data from household surveys would remain central to my PhD research. In June 2020, I secured a part-time Research Assistant and later Research Fellow position in Nutrition and Data under the MAPS project employed by the London School of Hygiene & Tropical Medicine. My role on the MAPS team was to develop data processing scripts to clean and transform household-level dietary data, develop analyses and models to evaluate micronutrient supplies in food systems, write manuscripts for academic publication, and disseminate results through various forms of research symposia. Dr. Katherine Adams, a member of the MAPS project from the Institute for Global Nutrition from the University of California – Davis, served as a constant advisor throughout the duration of my PhD. Dr. Louise Ander, the Principal Investigator of the MAPS project, grounded the research from my PhD in the broader scientific and political environment.

Throughout my PhD, contracts for independent consultancies that directly contributed to the aim of my PhD research helped support London School tuition fees. With each independent consultancy came buy-in from technical advisors from each institution responsible for the funding, each of whom helped shape the research outputs that are presented in this thesis. First, an independent consultancy was supported by the United States Agency for International Development (USAID) through its flagship multi-sectoral nutrition project, USAID Advancing Nutrition under the terms of contract awarded to JSI Research & Training Institute, Inc. The financial support and technical guidance from USAID contributed to the research outputs presented in Chapters 4, 5, and 6 of this thesis. Second, I worked as a consultant for the Global Center for Gender Equality at Stanford University Medical School supported by the Bill & Melinda Gates Foundation Gender Integration Workstreams, where financial support and technical guidance contributed to key discussion points and limitations around the use of household survey data and gender. Third, an internship was supported by the Programme Division at UNICEF, where financial support and technical guidance contributed to the research outputs presented in Chapter 7.

More specific details regarding my contributions to each research output will be presented on the research paper cover page preceding each chapter in Part II of this thesis.

2.5 Publications & additional outputs

Published articles for this thesis

Tang K., Adams KP., Ferguson EL., Woldt M., Yourkavitch J., Pedersen S., Broadley MR., Dary O., Ander EL., Joy EJM.; Systematic review of metrics used to characterise dietary nutrient supply from household consumption and expenditure surveys. Public Health Nutrition (2022).1-13. https://doi.org/10.1017/S1368980022000118.

Tang K., Adams KP., Ferguson EL., Woldt M., Kalimbira AA., Likoswe B., Yourkavitch J., Chrisinger B., Pedersen S., Segovia De La Revilla L., Dary O., Ander EL., Joy EJM.; Modeling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys. Annals of the New York Academy of Sciences, (2021).1508 (1), 105-122. https://doi.org/10.1111/nyas.14697.

Tang K., Eilerts H., Imohe A., Adams KP., Sandalinas F., Joy EJM., Moloney G., Hasman A.; Evaluating equity dimensions of infant and child vitamin A supplementation programs using Demographic and Health Surveys from 49 countries. BMJ Open (2023) 13:e062387. **https://doi.org/**10.1136/bmjopen-2022-062387

Muleya M., **Tang K.**, Broadley MR., Salter AM., Joy EJM.; Limited Supply of Protein and Lysine Is Prevalent among the Poorest Households in Malawi and Exacerbated by Low Protein Quality. Nutrients, (2022) 14(12):2430. https://doi.org/10.3390/nu14122430.

Submitted manuscripts for this thesis

Tang K., Ferguson EL., Adams KP., Segovia De La Revilla L., Woldt M., Gashu D., Osman G., Sisay BG., Samuel F., Yourkavitch J., Pedersen S., Dary O., Ander EL., Joy EJM.; Characterizing populations at-risk for micronutrient inadequacy using apparent intake and nutrient density from Household Consumption and Expenditure Surveys. (Submitted to academic journal)

Additional outputs from thesis

Research symposia

Tang K.; Improving Diets Through Innovative Data Analysis and Modeling of Food Fortification: Evidence from Malawi. USAID-Advancing Nutrition. 20 July 2021. Public webinar (https://www.advancingnutrition.org/events/2021/07/07/webinar-improving-diets-through-innovative-data-analysis-and-modeling-food).

Tang K., Segovia de la Revilla L., Ander E.L., Broadley M.R., Joy E.J.M.; Modelling the maximum potential contributions of zinc and iron biofortified cassava using Household Consumption & Expenditure Surveys. Agriculture, Nutrition, & Health (ANH) Academy Week. 30 July 2022. Poster presentation. Brighton, UK & online (hybrid).

Tang K.; Modelling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys. 22nd IUNS International Congress of Nutrition. 6-11 December 2022. Poster presentation. Tokyo, Japan.

Frongillo E.A., Downs S., **Tang K.**, Woldt M., Herforth A., Osman G., Vogliano C., Crum J., Pedersen S., Dary O.; Advancements in methods and tools to support healthy diets. 22nd IUNS International Congress of Nutrition. 6-11 December 2022. Open symposia speaker. Tokyo, Japan.

Zezza A., Abate G.T., Sharp M., **Tang K.**; Food data in Low- and Middle-Income countries: Recent efforts to enhance their value proposition through greater harmonization, and innovative methods and uses. International Food Acquisition Research and Methods (iFARM) Workshop. 20-21 October 2022. Session speaker. College Park, Maryland, USA.

Additional publication contributions during PhD

2022

Debellut F., **Tang K**., Clark A., Pecenka C., Assao B., Guindo O., Grais RF., Isanaka S.; Impact and cost-effectiveness of rotavirus vaccination in Niger: a modelling study evaluating alternative rotavirus vaccines. BMJ Open (2022) 12:e061673. https://doi.org/10.1136/bmjopen-2022-061673.

Isanaka S., **Tang K**., Berthé F., Grais RF., Pandya A.; Cost-effectiveness of routine versus indicated antibiotic therapy in the management of severe wasting in children. Cost Effectiveness and Resource Allocation (2022) 20 (38), https://doi.org/10.1186/s12962-022-00374-z.

2021

Guwela VF., Maliro MFA., Joy EJM., **Tang K.**, Bokosi J., Hawkesford MJ., Broadley MR., King J.; Wheat value chains in Malawi: trends, gaps, challenges and opportunities. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, (2021).16 (046), https://doi.org/10.1079/pavsnnr202116046.

2019

Tang K., Berthé F., Nackers F., Hanson K., Mambula C., Langendorf C., Marquer C., Isanaka S.; Hand hygiene compliance and environmental contamination with gram-negative bacilli in a rural hospital in Madarounfa, Niger. Transactions of The Royal Society of Tropical Medicine and Hygiene, (2019).113 (12), 749-756. https://www.doi.org/10.1093/trstmh/trz070.

Isanaka S., Berthé F., Nackers F., **Tang K**., Hanson KE., Grais RF.; Feasibility of engaging caregivers in at-home surveillance of children with uncomplicated severe acute malnutrition. Maternal & Child Nutrition, (2019).16 (1), https://www.doi.org/10.1111/mcn.12876.

2.6 Ethics

Ethical review and approval for all studies included in this thesis were provided as required by the LSHTM Observational Research Ethics Committee under the main MAPS project ethical review (Ref. 21903). Confirmation of ethics review decisions and original ethics application protocol are presented in the Appendix I and II.

CHAPTER 3

Data used to assess micronutrient adequacy of diets for populations

CHAPTER SUMMARY

This chapter provides a description of the relevant sources of data used to assess the micronutrient adequacy of diets across populations and their contributions for population micronutrient assessment, including a characterisation of the accessibility, methodological strengths, and limitations of each data source. The chapter also briefly covers current new data investments that have the potential to improve the assessment of the micronutrient adequacy of diets. The aim of this chapter is to provide some context to help explain some of the nuances of the data used for population dietary assessment in order to place household surveys in the broader dietary data landscape.

3.1 Population data relevant for micronutrient assessment

A thorough assessment of the micronutrient adequacy of diets within a country requires an approach that combines various sources of data. When available, these kinds of data include food intake/consumption, food availability, micronutrient composition of foods within a country, burden of biochemical and clinical manifestations resulting from micronutrient inadequate diets, and contributions of micronutrient interventions. A variety of institutions are involved in the generation of these data driven by various motivations, which leads to a range in data types, data collection methods, data quality, and data availability. When bringing different kinds of data together, we can answer a range of questions related to micronutrient adequacy of diets for different parts of the population.

In this chapter, I present an overview of the different kinds of data relevant for dietary micronutrient assessment. For each type of data, I provide a brief background on their application, the institutions responsible for their curation, the opportunities that can be exploited, and the limits to which each should be stretched. While this thesis focuses on household surveys as a source of dietary information, this chapter will cover a variety of data sources to contextualise where household surveys fit in the broader dietary data landscape. A description of these data is necessary to lay a foundation for the rest of this thesis, which focuses on integrating these various sources of data together into a cohesive narrative to inform equitable policy. Hence, the following descriptions are by no means a full critique of each type of data (these sorts of analyses are well documented elsewhere), but rather a consolidation of the key characteristics that are most relevant to this thesis.

3.2 Individual-level intake surveys

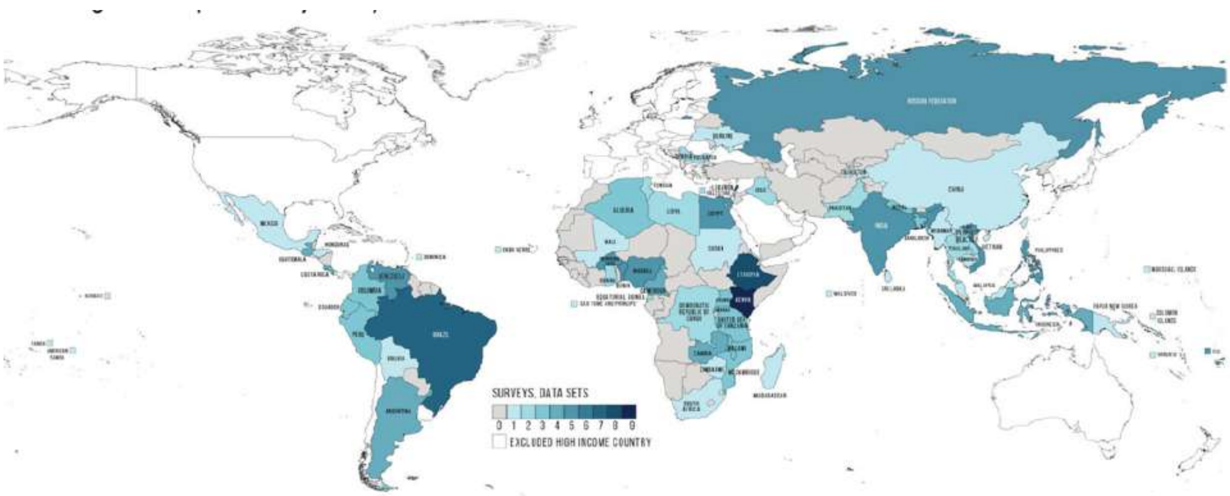
Individual-level intake surveys collect data on what and how much *individuals* eat within a defined population, providing information about current food consumption[37,48]. While there are several methods for measuring dietary intake of individuals, in LMICs individual-level intake surveys predominantly use the 24-hour recall method, where subjects or caregivers are asked by a trained enumerator to recall exact food intake quantity during the previous 24-hours[3]. Extensive research investments over the past two decades have refined the 24-hour recall method to improve the accuracy with which food intake of individuals is captured. This includes research aimed to accurately measure food quantities and reduce memory lapse error[49], convert measures of actual intake into usual intake[50], and explore the potential for scale-up using digital dietary assessment platforms[51]. For specific population demographics, measures of individual-level intake (e.g., 24-hour recall, observed-weighed food records) is the only method for generating precise, high-quality micronutrient adequacy estimates specific to these populations (e.g., children under five years, women, adolescent girls).

Greater complexity in standard operating procedures and higher costs compared to other dietary assessment methods have, until recently, impeded the periodic collection of individual-level intake data at national scales. *The Global Report on the State of Dietary Data* identified data from 191 individual-level intake surveys from 69 LMICs between 1980 – 2019, with a notable increase in the number of surveys identified in the most recent decades (Figure 3.1)[37,52]. While the greatest number of surveys were identified from Africa (n=70), all but six were conducted in certain sub-region(s) within a country and none were representative of all seasons, requiring generalisation when using to inform national-level policy. There are some contexts, such as Ethiopia and soon to be Nigeria, where individual level intake data from nationally representative surveys do exist[53], but these data are not common and often require access permission from the government agency responsible for survey implementation and data hosting. Despite a motivation to use individual-level dietary intake data as an empirical basis to inform micronutrient policy, at this moment and in most contexts, this is not possible as the data needed to answer some of the most fundamental questions about diets within a population do not exist and would not currently be feasible to collect.

In lieu of 24HR, the food frequency method offers an alternative approach to generate individual-level quantitative intake data. The approach asks individuals to estimate their usual frequency of consumption of a predefined list of foods over a given period[3]. The list of foods may focus on specific foods/groups of foods or be exhaustive to estimate certain metrics (e.g., nutrient intakes, dietary diversity). The method is semi-quantitative, where food quantities are often reported by estimating portion sizes. Food item lists must be representative of foods available in the local context, so the food lists will vary between different contexts. Despite the challenges of collecting individual-level quantitative intake data in large-scale population surveys, several mobile application-based technologies, including the Global Diet Quality Score (GDQS) app[54], have been recently trialled and tested to improve the feasibility of collecting individual-level quantitative intake data at large scales.

Several metrics can be constructed using data from individual-level quantitative intake surveys to characterise different measurements of nutrient adequacy and overall diet quality. Recently, researchers have developed a metric called the Global Diet Quality Score, a simple food-based metric that works comparably with existing metrics of diet quality, while also demonstrating the ability to represent both nutrient adequacy and diet-related risk of NCDs[55].

a.)



b.)

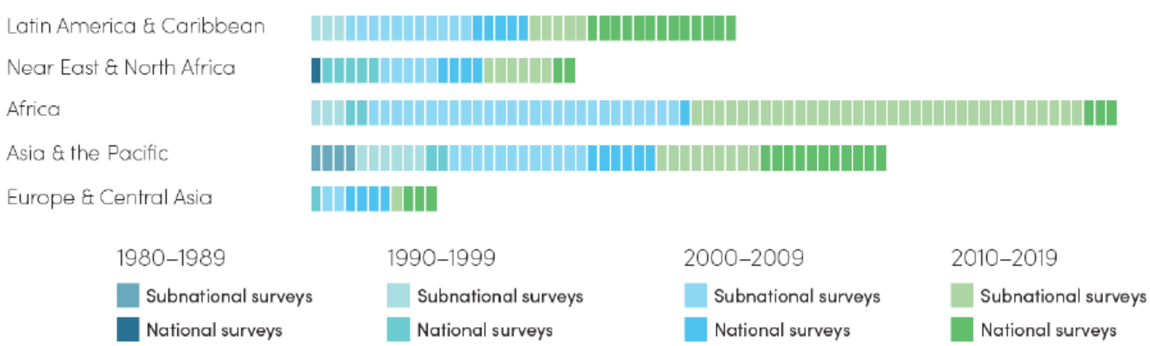


Figure 3.1 Availability of individual-level intake surveys conducted between 1980-2019 both nationally and regionally disaggregated by (a) country and (b) implementation year (Reference: FAO & Intake 2022).

While there is interest in increasing nationally representative individual-level intake surveys, it will take time to design, prepare, collect, and process these data from surveys even if there is political support and resources available. With this considered, there is value in exploring the use of secondary data from other established population survey systems to see how these data can be used as an alternative source of information in the interim.

3.3 Household surveys

Household surveys, used to measure living standards, poverty, and inequality, have been fundamental to modern economics and population studies for the last century[56]. While records of household budgets have been documented as far back as 106 BC in ancient Rome, standardized household budget surveys, as we know them today, are rooted in methods developed in the late 18th century with examples from Western Europe, North America, Russia, China, and Japan[56]. In LMIC contexts, efforts to increase and improve household survey implementation was pioneered by the World Bank, a core initiative of the 5th President of the World Bank Robert McNamara (c. 1969-1981). These efforts resulted in the establishment of the Living Standards and Measurement Study in 1980, which aimed to explore ways of improving the type and quality of household data collected by national statistical offices in LMICs[57]. When nationally implemented, microdata from household surveys can provide the public with valuable insights into how families respond to the broader economic environment. The design and implementation of these surveys is often led by national government statistics offices with technical consultation from independent research institutes and normative agencies.

Household surveys vary in the kinds of data they collect, where each are designed to answer a similar set of questions, some focus on collecting more on food consumption data than others. The definition of the term “consumption” varies depending on the academic domain, and it is important to understand the differences between these definitions[58]. Additionally, it is important to recognise the academic domains responsible for the design and implementation of household surveys to understand how to reflect the micronutrient adequacy of diets using these surveys. To an economist working in food security, food consumption refers to the quantity foods that are available for ingestion by the household, oftentimes not taking into account food storage over a period of time or food wastage. To a nutritionist and epidemiologist, food consumption refers to the quantity of food that is ingested by an individual. While household surveys are generally designed by economists, nutritionists and public health practitioners have more recently played a role in reforming these questionnaires and survey designs so that they are also relevant for public health nutritionists[59]. Therefore, the economics-defined food consumption data from these surveys are increasingly becoming more useful for public health nutritionists and epidemiologists. This presents opportunities for making public health policy more data driven as long as the important nuances due to differences in definitions, and their resulting uncertainties, are appropriately recognised.

Two categories of household surveys are explored in this thesis (Figure 3.2): Household Consumption & Expenditure Surveys and other Common Surveys. Both categories of household surveys collect data relevant to the assessment the micronutrient adequacy of diets, but there are important characteristics that distinguish the two on the kinds of information each can provide.

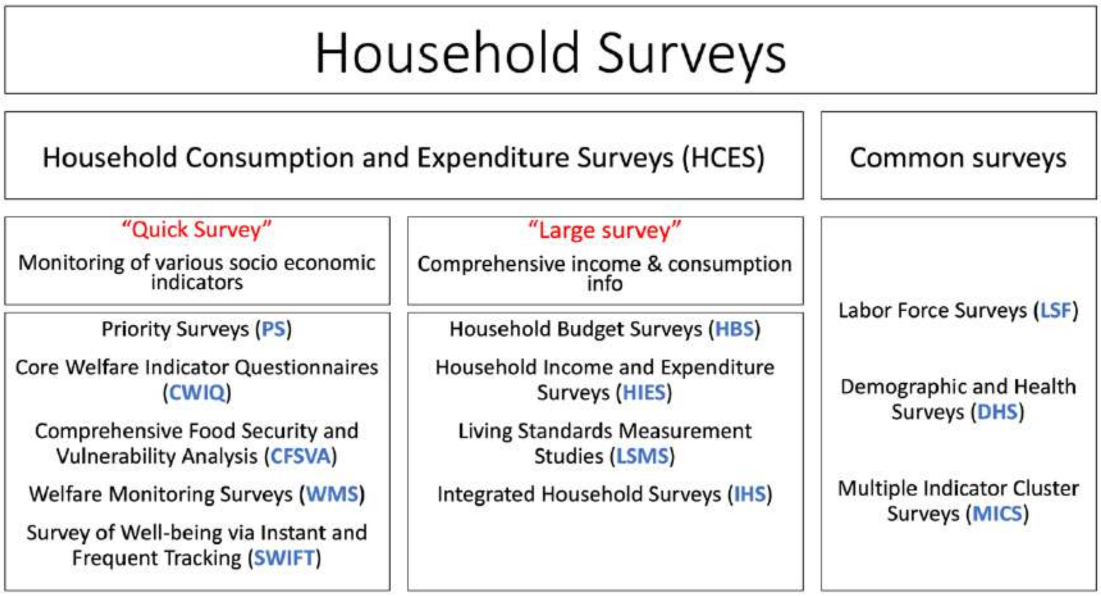


Figure 3.2 Diagram describing the various categories of household surveys. (Reference: World Bank 2019)

3.3.1 Household Consumption & Expenditure Surveys

Household Consumption & Expenditure Survey (HCES) is an umbrella term used to refer to a family of nationally representative cross-sectional surveys that aim to collect microdata that describes consumer behaviour and social welfare to some extent within a country. Based on the World Bank categorisations (Figure 3.2), this thesis will focus on "large HCES surveys", since "quick HCES surveys" have less relevance for the collection of food consumption data.

At minimum, HCES collect information on household food consumption, food and non-food expenditures, income, and household member demographics. HCES can be further categorised based on their purpose, which further describe the additional data they collect. First, household budget surveys (also known as household income and expenditure surveys) are conducted primarily to complement macroeconomic indicators by providing inputs for the calculation of consumer price indices or the compilation of national accounts (e.g., gross domestic product)[60]. Second, living standards surveys (also known as integrated household surveys, socioeconomic surveys, Living Standards Measurement Studies) are conducted to measure poverty in addition to studying household behaviour, determinants of outcomes, and linkages between asset ownership, household characteristics, livelihood source, government interventions, and welfare[61]. This category of HCES often contain several additional modules within the questionnaire to characterize a wide array of other socioeconomic conditions.

While every country has full agency over the type of HCES they conduct, the food consumption data collected through HCES have enough similarities that make their analysis relatively generalisable regardless of these differences. Questionnaire design and survey implementation is ultimately led by national government statistics offices, but recent published guidelines[59,60] and trainings[61] aim to provide harmonised guidance on best practices for measuring food consumption. In general, HCES food consumption data are semi-quantitative (i.e., quantified through respondent estimation rather than enumerator measurement), where enumerators interview a single respondent from the household using a multi-day household-level retrospective dietary recall guided by a predefined list of commonly consumed foods specific to the country (Figure 3.3). Commonly, the quantities of each food item consumed is reported using country-specific non-standard measurement units (e.g., buckets, tins, bunches), which require conversion into standard units (e.g., grams, millilitres) using conversion factors generated from concurrent market surveys and photo aids (Figure 3.4). While HCES generally from before 2010 tended to only collect information on food expenditures, more recent HCES collect food consumption data, where foods consumed are further modified by where each food was sourced (i.e., from own production, purchased from market, received as gift/from social protection programmes/other).

These standardised methods in collecting household food consumption data facilitate the integration of these food consumption modules into large household surveys. Similar to individual-level quantitative intake surveys, HCES are also expensive to implement, but nutritionists seeking to repurpose HCES generally do not need to assume the cost as they use the HCES as repurposed secondary data. The trade-off is a less bespoke survey designed primarily for purposes other than assessing micronutrient intake and accompanying limitations in accuracy.

HCES food consumption data is a central focus of this thesis, and further description of their opportunities and limits for dietary assessment will continue in subsequent chapters.

HCES food consumption data is a central focus of this thesis, and further description of their opportunities and limits for dietary assessment will continue in subsequent chapters.

Malawi Fourth Integrated Household Survey - Household Questionnaire - Page 32

MODULE G: FOOD CONSUMPTION OVER PAST ONE WEEK (CONTINUED)

DE LINE NUMBER	Over the past one week (7 days), did you or others in your household consume any [. . .]? INCLUDE FOOD BOTH EATEN COMMUNALLY IN THE HOUSEHOLD AND THAT EATEN SEPARATELY BY INDIVIDUAL HOUSEHOLD MEMBERS.	G01 YES. . 1 NO. . . 2>> NEXT ITEM	G02 ITEM CODE	G03 How much in total did your household consume in the past week?		G04 How much came from purchases?		G05 How much did you spend?	G06 How much came from own-production?		G07 How much came from gifts and other sources?		DE LINE NUMBER
				QUANTITY	UNIT	QUANTITY	UNIT	MK	QUANTITY	UNIT	QUANTITY	UNIT	
40	**Vegetables**												40
41	Onion *		401										41
42	Cabbage *		402										42
43	*Tanaposi* /Rape *		403										43
44	*Nkhwani* *		404										44
45	Chinese cabbage		405										45
46	Other cultivated green leafy vegetables		406										46
47	Gathered wild green leaves		407										47
48	Tomato *		408										48
49	Cucumber		409										49
50	Pumpkin *		410										50
51	Okra / *Therere* *		411										51
52	Tinned vegetables (specify)		412										52
53	Mushroom		413										53
54	Other vegetables (specify)		414										54
55	**Meat, Fish and Animal products**												55
56	Eggs		501										56
57	Dried fish *		502										57
58	Fresh fish *		503										58
59	Beef		504										59
60	Goat		505										60

CODES FOR UNIT:
KILOGRAMME 1
50 KG. BAG 2
PAIL (SMALL) . . . 4
PAIL (LARGE) . . . 5
No. 10 PLATE . . . 6
No. 12 PLATE . . . 7
BUNCH. 8
PIECE. 9
HEAP 10
BALE 11
OX-CART (UNSHELLED) . . 14
LITRE. 15
GRAM 16
MILLILITRE 19
TEASPOON. 20
SATCHET/TUBE. . . 22
OTHER (SPECIFY) . 23

* ENUMERATOR: PLEASE SPECIFY SUB-UNIT CODE FOR ITEM. REFER TO PHOTO AID

Figure 3.3 An example of a food consumption module section of a Household Consumption & Expenditure Survey

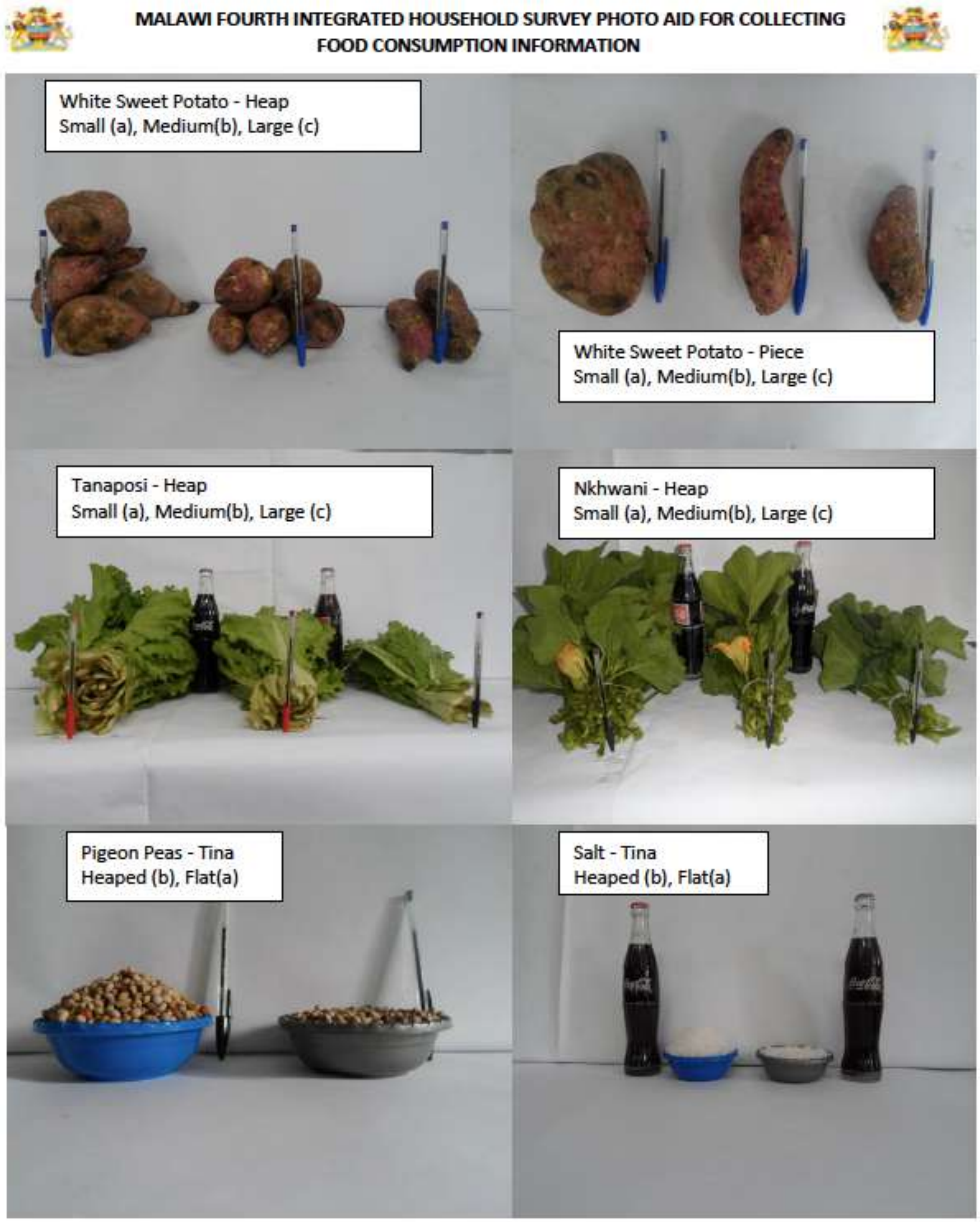


Figure 3.4 An example of a photo guide from a market survey conducted alongside a Household Consumption & Expenditure Survey to guide the conversion of non-standard measurement units.

3.3.2 Common Household Surveys

Common household survey is a term used to describe nationally implemented one-off or periodic household surveys that collect retrospective data on core indicators characterising population development and well-being[62]. The data relevant to micronutrient assessment of diets depends on the core objectives of the survey, where in LMICs two common household surveys stand-out as the largest, most frequently conducted, and most available to use for public policy.

First, the USAID-supported Demographic and Health Surveys (DHS) was established in 1984 and aims to generate a wide range of self-reported data on social and demographic characteristics combined with health and fertility data[63]. The DHS uses a vast questionnaire standardised across all countries, a repeated cross-sectional design, and large nationally representative survey samples when capturing information on a country's population. This supports a variety of epidemiological analyses to monitor public health trends between countries, across survey years, and within sub-populations of interest in surveyed countries. There are some variables included in the standard DHS questionnaire that are relevant to the assessment of micronutrient adequacy of diets[64]. In terms of diet, the women's questionnaire includes dichotomous questions about the recent consumption (within the last 24 hours) of vitamin A- and iron-rich foods or food groups for infants from 6-23 months and women aged 15-49 years. For access to micronutrient interventions, the women's questionnaire also asks questions about access to high-dose vitamin A supplementation within the past 6 months for infants and children between 6-59 months and access to iron supplementation for pregnant women and children.

Second, the UNICEF-supported Multiple Indicator Cluster Surveys (MICS) was established in 1995 in response to the World Summit for Children's call to collect more population data to monitor international targets for women and children[62]. MICS include six different questionnaires designed to collect data for women (15-49 years), men (15-49 years), children (5-17 years), infants and children (under 5 years), households, and health facilities. The only questions relevant to diets are found in the infant and children's questionnaire (under 5 years). The dietary data are similar those that are available on the DHS questionnaires, where mothers are asked to answer binary questions about the recent consumption (within the last 24 hours) of vitamin A- and iron-rich foods or food groups for their children within the age range[65].

The dietary data for both DHS and MICS are simply worded, feasible to scale-up, and provide enough information about a limited list of recently consumed foods to rapidly generate rather simple indices describing diet quality[66,67]. However, few food items probed, no quantitative or semi-quantitative measures on food consumption, and limiting sampling only to young children and women limits any understanding on whether the micronutrient intake is adequate to meet needs and the potential contributions of micronutrient interventions. I will explore what kinds of analyses these dietary data can contribute to dietary micronutrient assessment in Chapter 7 of this thesis.

The Global Diet Quality Project is an initiative that aims to collect dietary quality data in the general adult population across countries worldwide, and to provide the tools for valid and feasible diet quality monitoring within countries[68]. It is currently exploring the possibility for an internationally standardised method to rapidly assess diet quality in multiple countries using harmonised (but country-specific) instruments for data collection and validated metrics to assess diet quality.

For instruments, the project has developed the Diet Quality Questionnaire, a low burden tool that gathers dichotomous data on the recent individual consumption of 29 different food groups[69]. The instrument uses sentinel foods that are tailored specifically to foods available in local context to probe consumption from broader food groups. Compared to food groups defined by previous common household surveys, these food groups were defined to be more directly consistent with food groups that are more micronutrient dense and reduce some ambiguity when defining metrics assessing access to micronutrient dense foods (e.g., vitamin A-rich orange vegetables, vitamin A-rich fruits, dark green leafy vegetables, citrus, whole grains, legumes). Rapid administration coupled with these improved data quality refinements make the instrument appealing for integration into existing survey systems for large scale diet quality data collection, including the DHS, MICS, Gallup World Polls, and other surveys.

Several validated indicators can be generated from these data to assess various dimensions of diet quality. This includes measures of dietary diversity (e.g., Minimum Dietary Diversity Score for Women, Food Group Diversity Score), protection against non-communicable disease (e.g., NCD-Risk, NCD-Protect, GDR Score), and access to food items/groups of public health interest (e.g., zero vegetable or fruit, sugar-sweetened beverage)[67]. Questionnaires have been developed for adult women, adult men, and infants/young children in more than 90 countries and the data from 40 countries is intended to be made publicly available.

3.4 Food composition data

Food composition data are used to estimate the nutritional value of the foods consumed by individuals and populations. The nutrient values of different food items can be generated using various methods (e.g., laboratory analysis of food samples, imputation, calculation using recipes, literature review), and substantial efforts from prior research has compiled the results of this work into accessible databases to use for various purposes, including dietary assessment[70]. Several groups have compiled food composition databases and tables where each is specific to a nation or region of the world in both LMICs[71,72] as well as high-income countries[73]. When assessing the micronutrient adequacy of diets in a specific context, using food composition data that is as locally representative as possible is important for several reasons. First, while there have been efforts to standardise food item nomenclature within food composition tables[74], there may be some foods or varieties of foods that are very specific to individual geographies, so access to a food composition database that includes locally specific food items is essential. Second, the nutrient values of crops in particular can vary substantially based on a variety of factors characterising the environmental conditions of where the crop was grown (e.g., soil quality, rainfall, temperature), so using nutrient composition values that best represent the food items coming from these conditions should also be considered[75,76]. Even if local food composition databases are used, all food composition databases have limitations when used for dietary micronutrient assessment including borrowing values from other contexts, low sample sizes for laboratory analyses, low capacity of local laboratories limiting number of micronutrients analysed, and overly generalised food item descriptions[70]. While improving the quality of food composition data falls outside the scope of this thesis, maintaining transparency in the food composition data used for all analyses requiring their use remained a priority throughout this work.

3.5 Nutrient intake reference values

Nutrient intake reference values (NRV) are the lowest and highest continuing intake levels of a nutrient that between which, will maintain a defined level of nutriture in an individual without posing risks for excessive intake[3]. NRVs may be used to assess the micronutrient adequacy of a diet for individuals and populations, where different values are intended for different purposes. NRVs have been developed using data specific to sex and age group as well as for pregnant and lactating women due to substantial variation in requirements between groups[77,78]. Additional variation occurs due to other factors (e.g., physical activity levels, environment, lifestyle, genetic predisposition) forming a normally distributed (for all nutrients except iron) range of NRV values valid for a defined level of nutritional adequacy specific to each demographic group[3] (Figure 3.5). Average requirements (AR) are defined as the mean value of this distribution and used to estimate the prevalence of inadequacy for populations. Recommended daily allowances (RDA) are derived as two standard deviations above the AR and only used as the NRV for individuals as they yield overestimates of inadequacy when applied to populations[79]. Tolerable upper intake levels (UL) are the highest usual daily intake levels likely to pose no risk of adverse health effects and used as the NRV to estimate the prevalence of a population at risk for being excessive. While different NRVs have been published by different institutions, Allen et al. published a harmonised approach consolidating existing NRVs intended to be applied globally to assess population intakes, especially for estimating nutrient gaps that to inform public health programmes[79].

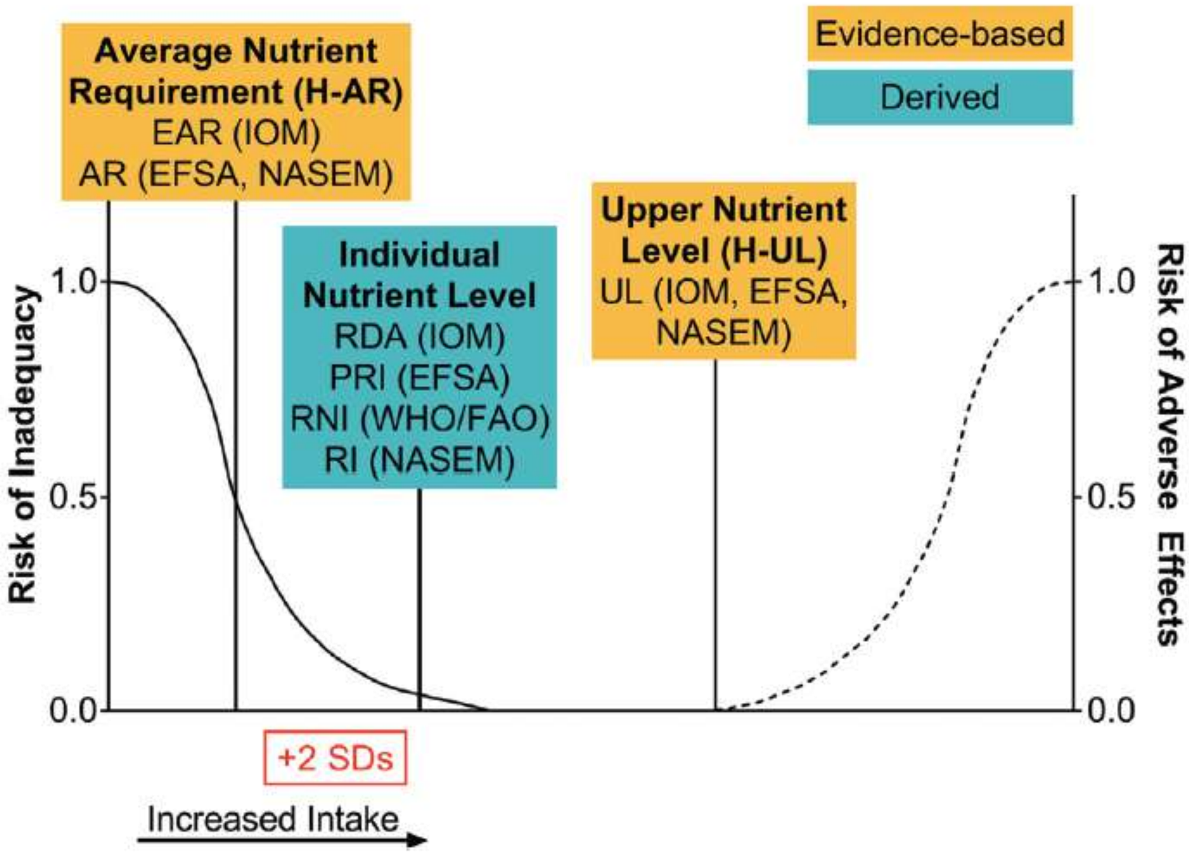


Figure 3.5 Nutrient intake reference value assumed distribution (for all nutrients except iron) and derivations for classification cut-offs. (Reference: Allen et al. 2020)

3.6 National-level food supply accounts

The Food and Agriculture Organization (FAO)-supported Food Balance Sheets (FBS) have been operating continuously since 1961 and generate annual national-level aggregated data describing a country's total production, import, and export of agricultural commodities as well as total food supply quantity, measured in kg/capita/year and kcal/capita/day[80]. Available for 181 countries in the most recent round, these data are gathered in a standardised manner though the analysis of secondary data, review of national accounts, and key stakeholder interviews from in-country experts. If combined with micronutrient content data from food composition databases and national population estimates from the United Nations (UN), FBS can be used to produce a rough estimate of the national micronutrient supply of a country per capita (Figure 3.6). While the availability of standardised, annual, longitudinal food availability data for a majority of countries has clear advantages, there are very distinct limits to which this data should be used to understand the micronutrient adequacy of diets. First, food supply data aggregated at the national level cannot be used to explore variation within a country's population, which is essential for equitable programme design. Second, FBS provide data on food availability, but not on actual food consumption. Therefore, it is important to use caution when interpreting these data, as the relationship between food availability and consumption can be influenced by a range of social and cultural factors. Third, per capita estimates rely on UN population estimates, which have high uncertainties in contexts that have no recent national census data[81] or where there is disagreement between the UN and governments (e.g., Uganda). Despite these limitations, research exploring the use of FBS as the foundation for a nation's micronutrient supply estimates and models built off of these data have been widely explored in previous research[23,80,82], and therefore will not have a strong focus in this thesis.

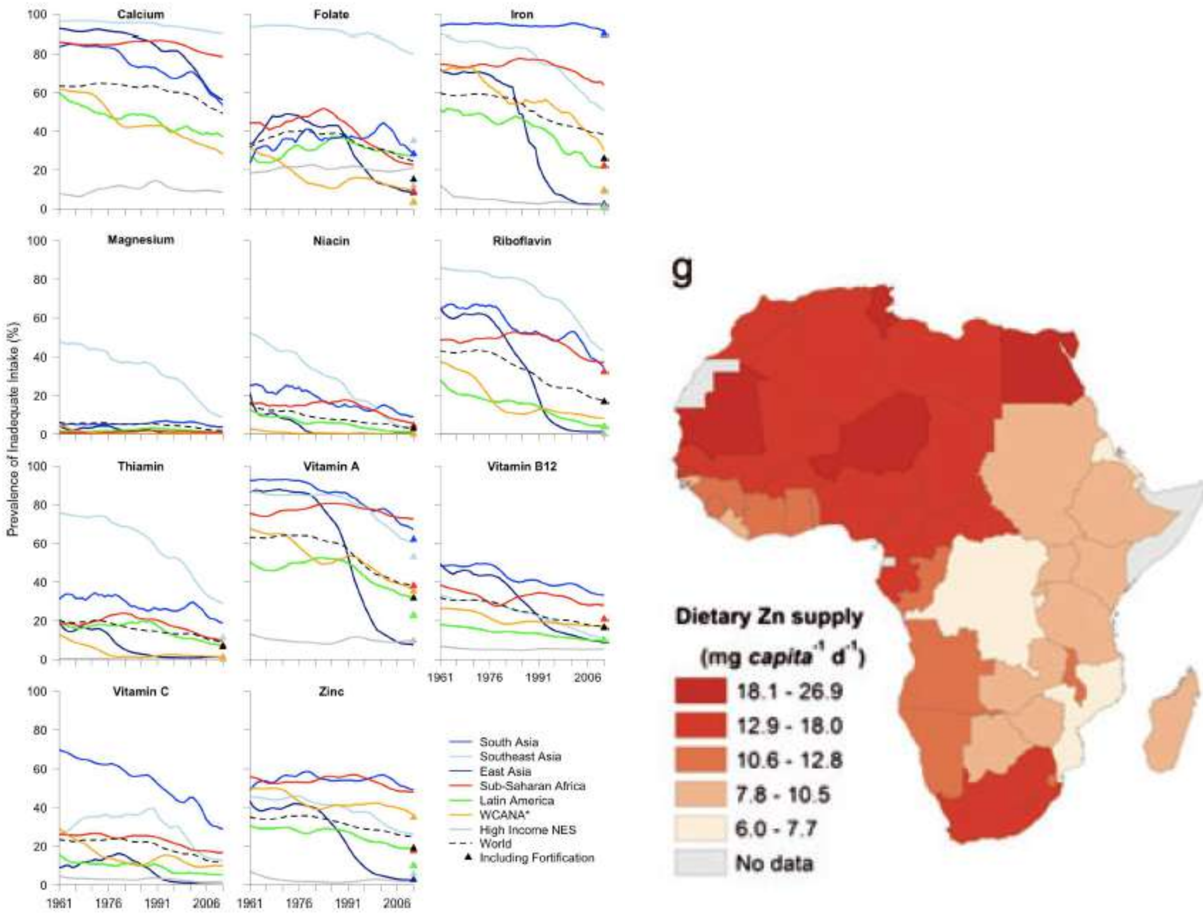


Figure 3.6 Examples on analyses using Food Balance Sheets to estimate micronutrient supplies in a national food system, presented by year (Reference: Beal et al. 2017) and by country (Reference: Joy et al. 2014).

3.7 Discussion

This chapter illustrates that a diverse range of dietary data are available to contribute insights into the micronutrient adequacy of diets across populations. Depending on the data source, the micronutrient adequacy of diets or the food supply can be assessed at individual, household, or national levels, where nuances at each level have important consequences on how each kind of data should be interpreted and communicated[3]. Different dietary assessment data collected at each level provide different opportunities and limitations when assessing micronutrient adequacy of diets or the food supply, often presenting a trade-off between size/resolution of the dataset against quality/completeness of the collected data. In data-abundant country contexts (e.g., when a county has nationally representative individual-level 24-hr dietary recall data for target groups of interest, a local food composition table, and recent HCES data), several sources of dietary data will be available, which allows for a comprehensive approach that combines the information from all data sources, each yielding different but complementary information. In these contexts, it is critical to scrutinise the representativeness of each type of data, which varies on the population sampled, time periods, geographic regions, and level of granularity. Interpretation of these data independently and when combined must consider these characteristics when interpreting results from the various data sources. In contrast, a data-constrained country will require a different approach, necessitating a focus on where and how data gaps obscure our understanding of a country context. In these contexts (e.g., when a country only has Food Balance Sheet data and/or outdated HCES data), data-constrained refers to a combination of lower frequency of surveys, less granularity in the sampling strategy, and poorer representativeness of the population and the context.

A global dearth in individual-level dietary data relevant for national policy places a heavy emphasis on novel applications of secondary data to generate insights about diets within countries. As a step forward, recent investments that focus on new and improved individual-level dietary data generation mark exciting advancements in improved population data systems relevant for assessing the micronutrient adequacy of diets. However, these data systems will take time to develop in all contexts, and even when they are in place, will not provide all details necessary to understand the dietary complexities of a population. For example, individual-level intake surveys are rarely seasonally representative and may miss key marginalised populations who may not be captured in the sampling frame (e.g., poorest populations).

Given these data constraints, a pragmatic approach would be to first describe the relevant information that can be extracted from secondary household survey data that are currently accessible, identify where these data leave gaps in knowledge, and strategize whether data systems in development or new data investments can be used to fulfil these gaps in knowledge. As there is substantial heterogeneity in the design of household surveys between different countries, especially HCES, this thesis will contribute to the broader body of evidence that questions whether consistencies between surveys are sufficient to warrant a standardised approach when developing models that use these data to assess micronutrient adequacy. From there, this thesis will continue this foundational work with examples of how these proxy dietary data can be best used to inform policies and programmes given their constraints. Part II of this thesis will be dedicated to doing this using household survey data from several country settings.

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PART II

Evidence

CHAPTER 4

Systematic review of metrics used to characterise dietary nutrient supply from Household Consumption and Expenditure Surveys

CHAPTER SUMMARY

This chapter presents a peer-reviewed published review article that identified previous studies using HCES food consumption data to characterise household dietary nutrient supply. The outputs of this review article include an overview of past applications of HCES food consumption data as a proxy for dietary assessment, a consolidation of the metrics used in prior literature to characterise household nutrient supply, a summary of comparisons between estimates of household-level micronutrient apparent intake and individual-level micronutrient intake as reported by prior literature, and techniques for comparing differences in results between sub-groups of interest. By collating all prior research by systematically searching for studies using HCES food consumption data to estimate household nutrient supply, this chapter provides an overview of the best practices for preparing and analysing HCES food consumption data for micronutrient assessment. This process highlighted potential opportunities and considerations when using HCES food consumption data for micronutrient assessment and their potential role when establishing systems to monitor sub-national risks for inadequate micronutrient intake.

The published review article is subsequently included in this chapter and supplementary material referenced in this work can be found in Appendix III.

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed for each research paper included within a thesis.

SECTION A – Student Details

Student ID Number	1600604	Title	Mr.
First Name(s)	Kevin Michael		
Surname/Family Name	Tang		
Thesis Title	Micronutrient adequacy of diets and contributions of large-scale interventions: secondary analyses of household surveys		
Primary Supervisor	Dr. Edward Joy		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Public Health Nutrition		
When was the work published?	10 January 2022		
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Have you retained the copyright for the work?*	Yes	Was the work subject to academic peer review?	Yes

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For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	K.T., M.R.B., E.L.A., and E.J.M.J. contributed to the conception and design of the study. K.T., K.P.A., E.L.F., M.R.B., and E.J.M.J. contributed to the development of the original study protocol. All authors participated in the analysis and deductions of paper. K.T. identified existing literature via the online database search and snowballing. K.T. and E.J.M.J. reviewed literature to evaluate for inclusion. K.T. extracted the data from the original manuscripts and prepared the tables and figures. All authors contributed to the interpretation of the data, critically reviewed the manuscript for important intellectual content and approved the final manuscript.

SECTION E

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Review Article

Systematic review of metrics used to characterise dietary nutrient supply from household consumption and expenditure surveys

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Abstract
Objective: To review existing publications using Household Consumption and Expenditure Survey (HCES) data to estimate household dietary nutrient supply to (1) describe scope of available literature, (2) identify the metrics reported and parameters used to construct these metrics, (3) summarise comparisons between estimates derived from HCES and individual dietary assessment data and (4) explore the demographic and socio-economic sub-groups used to characterise risks of nutrient inadequacy.
Design: This study is a systematic review of publications identified from online databases published between 2000 to 2019 that used HCES food consumption data to estimate household dietary nutrient supply. Further publications were identified by 'snowballing' the references of included database-identified publications.
Setting: Publications using data from low- and lower-middle income countries.
Results: In total, fifty-eight publications were included. Three metrics were reported that characterised household dietary nutrient supply: apparent nutrient intake per adult-male equivalent per day (*n* 35), apparent nutrient intake per capita per day (*n* 24) and nutrient density (*n* 5). Nutrient intakes were generally overestimated using HCES food consumption data, with several studies finding sizeable discrepancies compared with intake estimates based on individual dietary assessment methods. Sub-group analyses predominantly focused on measuring variation in household dietary nutrient supply according to socio-economic position and geography.
Conclusion: HCES data are increasingly being used to assess diets across populations. More research is needed to inform the development of a framework to guide the use of and qualified interpretation of dietary assessments based on these data.

Keywords
Dietary assessment
Metrics
Nutrients
Household Consumption and Expenditure Survey
Equity

Vitamins and minerals, also known as micronutrients, are required in small quantities in the diet and are essential for human health[1]. Micronutrient deficiencies continue to burden billions of people worldwide, disproportionately affecting the world's poorest populations[2]. Poor-quality diets, among other interconnected risk factors, are a main cause of micronutrient deficiencies because individuals do not consume adequate quantities of bioavailable nutrients

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to meet their physiological requirements[3]. Diet-related risk factors are compounded by other systemic social issues common in poor populations, such as inadequate healthcare, high rates of infection and poor sanitation[4,5] and a lack of education[6–8]. As highlighted in the 2020 Global Nutrition Report, reducing micronutrient deficiencies will require a coordinated effort between governments, businesses and civil society to address deep inequities that arise from unjust systems and processes, particularly for the world's most nutritionally vulnerable groups[9].

Quantifying and characterising national burdens of micronutrient deficiencies require a combination of data types. These include biomarker assessment in micronutrient surveys[6,10], estimates of national micronutrient supply in food systems[11] and individual micronutrient intake estimates from food consumption surveys[12]. However, in many contexts, these data require significant time, capacity, expertise and specialist equipment to collect and analyse, meaning few countries routinely collect these data at scale. Household Consumption and Expenditure Surveys (HCESs) can contribute a unique source of nationally representative food acquisition data that are regularly collected in low- and lower-middle income countries[13]. Questions about households' food consumption and expenditures using a country-specific food item list are commonly integrated into HCESs, and these data can be used to estimate the acquisition and apparent consumption of foods by members of the household[14].

HCES is a term used to refer to a family of nationally and sub-nationally representative, multicomponent surveys (e.g. Household Income and Expenditure Surveys, Socioeconomic Surveys, Living Standards Measurement Surveys, etc.), which are primarily designed to provide data to characterise an array of socio-economic conditions. National HCESs are implemented by national statistical agencies, often with technical assistance from the World Bank's Living Standards Measurement Study group. In most countries, bar a few exceptions, these data are publicly accessible and can be used for a variety of rapid analyses, for instance, to monitor poverty, measure economic inequality, characterise vulnerability to economic shock, estimate agricultural production, calculate macroeconomic aggregate indicators (e.g. gross domestic product) and construct consumer price indices[15–17]. While HCES data in some countries have been publicly available since the 1980s, only more recently have data from the household food supply modules of these surveys been used to estimate individual-level micronutrient intake and to inform public health research and decision making[18]. Alongside increased use of HCES food acquisition data have come an interest in assessing the how well these data can proxy for individual dietary assessment data[19].

HCES data are subject to error when used to estimate individual-level food consumption, which raises challenges for their use in estimating nutrient intakes[19,20]. Due to this, the use of the terms 'nutrient supply' at the household level and 'apparent nutrient intake' at the individual level are used to reflect the sources of error and imprecision when estimating nutrient intake from HCES compared with other more direct nutritional assessment methods (Table 1). Sources of potential error include assumptions about the intrahousehold food allocation, shortcomings in HCES questionnaire design related to food consumption (e.g. missed foods in pre-defined list of food items/groups, capturing composite foods using recipes, food waste, foods consumed away from home, collecting data only on food acquisitions rather than acqusitions and consumption), recall bias due to longer recall periods and estimating quantities consumed[21]. While most HCESs collect both food consumption (total quantity of foods consumed) and food expenditures (total monetary amount spent on consumed foods), some HCESs only collect food expenditure data, which require conversion of monetary units into units of food mass (e.g. grams) before calculating household nutrient supply[13]. In addition, errors may be context specific, as HCES methods vary between countries, introducing a differential bias when making comparisons across populations. Recent reviews[13] and guidelines[22] have identified differences between HCES questionnaire designs from different countries, with the authors calling for analyses to evaluate the effect of these differences on dietary nutrient supply estimates. Subsequent analyses have reported potential effects due to the following: recall period length (7–30 d)[23], measuring foods consumed away from home[24], food acquisition compared with consumption[25] and length and composition of food item lists (50–300 items)[26].

Despite these potential limitations, HCESs remain a source of information on what people eat and there is an expanding literature of studies that use HCES to estimate dietary micronutrient supplies and risks of deficiency. Studies have employed a variety of different metrics to report estimates of dietary nutrient supply/apparent nutrient intake and the prevalence of inadequacy, each requiring specific interpretation. This systematic review aims to identify and describe existing publications using HCES data to estimate nutrient supply/apparent nutrient intake in order to document current practices as they relate to the analysis of HCES food consumption data, summarise results of publications that aimed to validate the use of HCES consumption data to estimate nutrient supply/apparent nutrient intake and provide insights into how these estimates can identify sub-groups at heightened risk for micronutrient deficiencies from dietary inadequacy. This analysis addresses the following questions:

1. What is the scope of the existing literature?
2. What metrics have been used to estimate nutrient and energy supply/apparent intake and nutrient adequacy from HCES data and how do those estimates compare across metrics?
3. How do HCES-derived estimates of apparent nutrient and energy intakes compare with those estimated

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Table 1 Definitions of terms

Term	Unit level	Nutritional assessment type	Definition
Apparent nutrient intake[17,55]	Population	Household consumption and expenditure surveys	Nutrient intake of a population estimated by assuming intrahousehold food consumption is based on proportional energy requirements.
Apparent nutrient intake inadequacy[17,55]	Population	Household consumption and expenditure surveys	Estimate to indicate when apparent nutrient intakes are below the estimated average requirement (EAR) for a population group depending on age-, sex- and specific physiological stage (e.g. pregnancy and lactation).
Food consumption[55]	Individual	Individual dietary assessment	Measure of the average food consumption by an individual during a period of time, usually expressed per day. Necessary to estimate nutrient intake.
Household food supply[55]	Household	Household consumption and expenditure surveys	Self-reported estimate of the total amount of food available for consumption in the household over a fixed time period (usually 7 to 30 d), generally excluding foods consumed away from home.
Nutrient deficiency[55]	Individual/population	Nutrient biomarker assessments	Biological measure defined by the range where clinical or functional manifestations of nutrient deficiencies present. May be caused by various factors, including inadequate nutrient intake.
Nutrient density[32]	Household	Household consumption and expenditure surveys	An indicator of dietary quality expressed as the ratio of the nutrient supply of the diet to the energy supply provided by the same diet.
Nutrient intake[55]	Individual	Individual dietary assessment	Estimate of the average intake of nutrients, mostly through foods consumed by an individual. Calculated from quantitative data on food consumption and nutrient content compiled in food composition databases or tables.
Nutrient intake inadequacy[55]	Individual/population	Individual dietary assessment	Estimate to indicate when nutrient intakes are below the recommended nutrient intake (RNI, which is replaced in some countries for Recommended Daily Allowance – RDA) for individuals, or below the estimated average requirement (EAR) for a population group depending on age-, sex and specific physiological stage (e.g. pregnancy and lactation).
Nutrient supply[55]	Household	Household consumption and expenditure surveys	Estimate of nutrients available for consumption through foods for the household. Calculated from quantitative data on household food supply and nutrient content compiled in food composition databases or tables.

using individual-level dietary assessment methods? Do results differ by age group (i.e. adults, adolescents, children and infants)?

4. What types of sub-group comparative analyses have been conducted using nutrient and energy supply/apparent intake estimates from HCES data?

Methods

We conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines[27]. The study protocol is provided in Appendix 1 and was registered with the PROSPERO international database for systematic reviews (ref. 223 928).

Identification and screening of literature

A two-step procedure was used to identify and screen the available literature. First, fourteen public databases were systematically searched by one author in the domains of public health (e.g. Global Health Database and PubMed), agriculture and food systems (e.g. AgEcon, AGRIS, GARDIAN CGIAR and IFPRI Publication Database), economics (e.g. EconLit) and general academia (e.g. Google Scholar, JSTOR, SCOPUS and Web of Science). The primary search terms were the different HCES name variations in both English and French as listed by Fiedler *et al.*[21]. Where HCES search terms returned a large number of results (> 1000), secondary search terms were used to describe the food consumption module of the HCES questionnaire (e.g. 'nutrition', 'consumption', 'food' and 'micronutrient'). The search terms for all databases used in this review are included in Appendix 2. Second, the reference list of all included publications identified through the database search were systematically searched to identify additional papers not identified by the database search[28]. Titles and abstracts of all returned literature were screened to identify analyses using the food consumption module of the HCES, where positive screens were included for full-text review.

Eligibility, inclusion and exclusion criteria

Literature selected by the identification and screening procedure underwent a full-text review for inclusion into this study independently by two authors. Literature was included if it: (1) used HCES data (or other household food consumption data using an HCES questionnaire format) from a low- or lower-middle-income country[29] and (2) estimated household nutrient supply or apparent intake of nutrients or energy using data from the HCES food consumption and/or expenditure module. Literature was excluded if it (1) was written in a language other than English or French or (2) was published before the year 2000. Any disagreements between the two co-authors about whether to include a publication were resolved through discussion. Data were managed using Mendeley Desktop (version 1.19.4; Elsevier, London, United Kingdom).

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Data extraction
Extraction of information from each publication was archived for comparison in Microsoft Excel (version 16.36; Microsoft Corp, Redmond, USA) by one author. A complete list of all categories and extracted information is provided in Appendix 3. In brief, for Question 1, extracted data included the country/year the HCES was implemented, the nutrients analysed, recall period, methods of processing the HCES data and food composition data used. For Question 2, key information included the reported nutrient metric, parameters used for estimating energy requirements and reference values used to define inadequacy. For Question 3, key information included the individual dietary assessment method used if HCES-derived apparent intake estimates were compared with individual-level nutrient intake estimates, differences in nutrient intake and apparent nutrient intake estimates and disaggregation by age group if reported. For Question 4, we used the PROGRESS+ framework to guide extraction of information describing stratification by social determinants of diets[30]. This framework, which captures place of residence, race/ethnicity/culture/language, occupation, gender/sex, religion, education, socioeconomic status and social capital, can be used to apply an equity lens when conducting public health research.

Results

Scope of existing literature
In total, fifty-eight publications were identified either by the database search (*n* 48) or by snowballing (*n* 10) (Fig. 1). A list of these publications, their data sources and reported metrics is provided in Supplementary Table 1. These publications included data collected from twenty-four different countries (Fig. 2(a)) where four publications focused on more than one country. The highest frequency of analyses was observed for data collected in Bangladesh (*n* 14 publications), Malawi (*n* 9 publications), India (*n* 6 publications) and Uganda (*n* 6 publications). Household dietary energy supply was reported by 83 % (*n* 48) of publications, where 33 % (*n* 19) reported only dietary energy supply without reporting nutrients. Of the publications that did report nutrient supply/apparent intake, estimates covered twenty different nutrients (Fig. 2(b)). The most common nutrients reported were Fe (*n* 32 publications), vitamin A (*n* 32 publications) and Zn (*n* 27 publications). The number of publications per year increased substantially after 2012 (Fig. 3).

Characteristics of food consumption data used in the included publications are provided in Supplemental Table 2. The term household food 'consumption' was reported in 60 % (*n* 35) of publications, whereas 41 % (*n* 24) used a number of other verbs to report the quantity of food in the survey questionnaire (e.g. 'acquired', 'purchased' and 'received'). More than half of the publications (*n* 36) used nationally specific food composition tables to estimate nutrient or energy content of foods. In countries where nationally specific food composition tables either did not exist or had missing values, data were drawn from food composition tables of neighbouring countries or for the broader region (26 %, *n* 15) or from food composition values of US food items compiled by the US Department of Agriculture or other international food composition databases (38 %, *n* 22). Steps taken to clean and process HCES data varied by country due to differences in survey design, but conversion of food item quantities from local units (e.g. plate, bucket and heap) into standard units (e.g. kilograms), adjustments for edible portions of foods, adjustment for cooking yields and adjustment of outliers were most frequently reported. However, many studies did not provide sufficiently detailed descriptions of methods to make the study independently repeatable.

Summary of Household Consumption and Expenditure Survey nutrient supply and adequacy metrics
Three nutrient supply metrics were identified in the included publications (Fig. 4). First, the adult male equivalent (AME) approach to estimate apparent nutrient intake was used in 57 % (33/58) of the publications. The AME approach assumes that nutrient supplies are distributed among household members in proportion to the energy requirements of each household member, which are standardised in relation to the energy requirement of an adult male[31]. All studies using the AME approach assumed all household members had moderate or moderate-high physical activity levels when estimating individual energy requirements. Second, daily apparent nutrient intake *per capita* was used in 41 % (24/58) of publications. *Per capita* adjustment assumes that nutrient supplies are equally distributed among all members within the household (e.g. an adult male and his young daughter are assumed to consume equal food portions). Third, the nutrient density of household diets, or nutrient supply *per* energy supply, was used in 9 % (5/58) of publications.

When evaluating inadequacy, *per capita* and AME metrics were used to estimate the population's adequacy of dietary nutrient or energy supply by comparing apparent intake to a reference nutrient intake (39/58; 67 %). Of these publications, twenty-seven focused on micronutrients, where apparent intake estimates were compared with the Estimated Average Requirement (23/27, 85 %), the Recommended Nutrient Intake (7/27; 26 %) and/or the Recommended Daily Allowance (1/27; 4 %) for each micronutrient of interest. Among the twenty-three publications that focused on dietary energy, 57 % (13/23) compared household energy supply to the household's total energy requirements calculated as the sum of the individual requirements of all household members, and 43 % (10/23) compared individual-level apparent energy intake to

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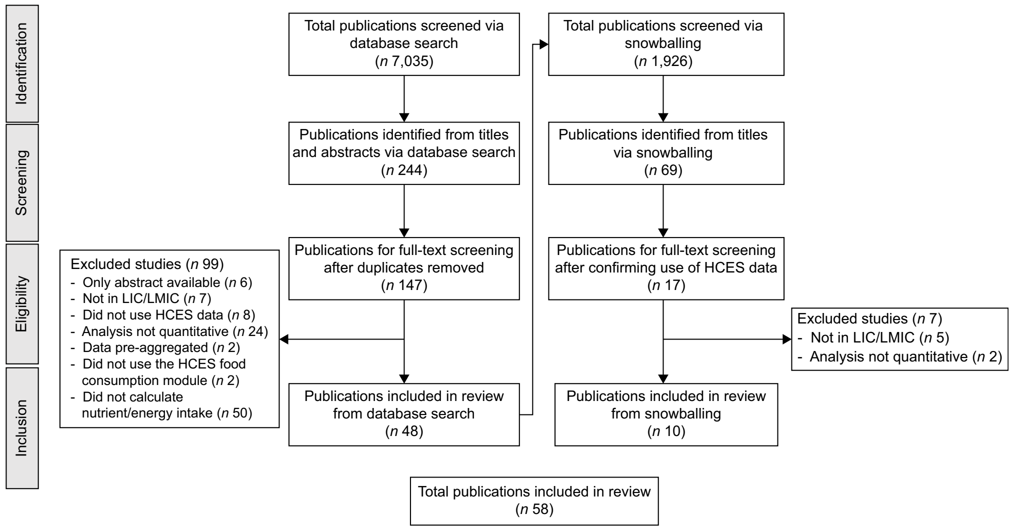

Fig. 1 Workflow for search, screening and inclusion for database-identified and snowballed publications

a pre-defined energy requirement threshold for an adult (e.g. 2100 kcal *per* day). No publications compared nutrient density estimates with nutrient density reference values, such as the critical nutrient density as defined by Vossenaar et al.[32]. Of all the publications comparing nutrient or energy supply to a dietary requirement to estimate dietary inadequacy, 13 % (5/39) included additional nutrient or energy requirements necessary for a pregnancy in the household and 23 % (9/39) included additional requirements necessary for women during lactation.

Comparison of Household Consumption and Expenditure Survey nutrient supply to individual-level dietary intake data

For publications reporting apparent nutrient intake using the AME approach, six compared their results to individual-level estimates based on a variety of different types of individual-level dietary intake data. This included individual 24-h dietary recalls of specific demographics within the household (e.g. children under 5 years, women of reproductive age)[33–35], 24-h dietary recall of all household members estimated by the meal preparer[19,36] or observed-weighed food records of specific demographics within the household[37]. Among these publications, four compared nutrient intake/apparent intake estimates from the same households or individuals within these households[19,33,36] and two compared nutrient intake/apparent intake estimates using different survey populations from the same country[34,35]. Two publications used the same data from the Bangladesh Integrated Household Survey[19,36].

For AME apparent intake estimates, four publications estimated apparent intake per AME using household-level food consumption data recalled over time horizons of 7–30 d and compared those to estimates based on individual-level dietary intake data recalled[19,33,36] or collected prospectively[37] over 24 h (Table 2). These studies allow for a true inter-comparison of how well HCES-style nutrient assessments perform compared with 24-h recalls, which are likely to have lower measurement error. In these studies, AME-based apparent intakes consistently overestimated individual nutrient and energy intakes, and the percentage point difference between the two methods varied according to nutrient or energy and across studies (Table 2: percentage point difference range = 12 % to 72 %).

Two publications reported sub-group analyses for children under five years of age (Table 2)[19,37]. The two publications that used the same household 24-h dietary recall data to assess intrahousehold food distribution found the largest differences for children under 2 years of age, suggesting greater uncertainty in apparent intake assumptions for infants when compared with other age groups. However, none of the studies incorporated the contributions of energy or nutrient intakes from breast-milk, potentially affecting apparent intake estimates for infant demographics.

One publication compared differences in the nutrient density metric when applied to HCES data *v.* corresponding 24-h dietary recall data in Uganda and found no statistically significant difference in median nutrient density for the fourteen nutrients assessed with the exception of folate

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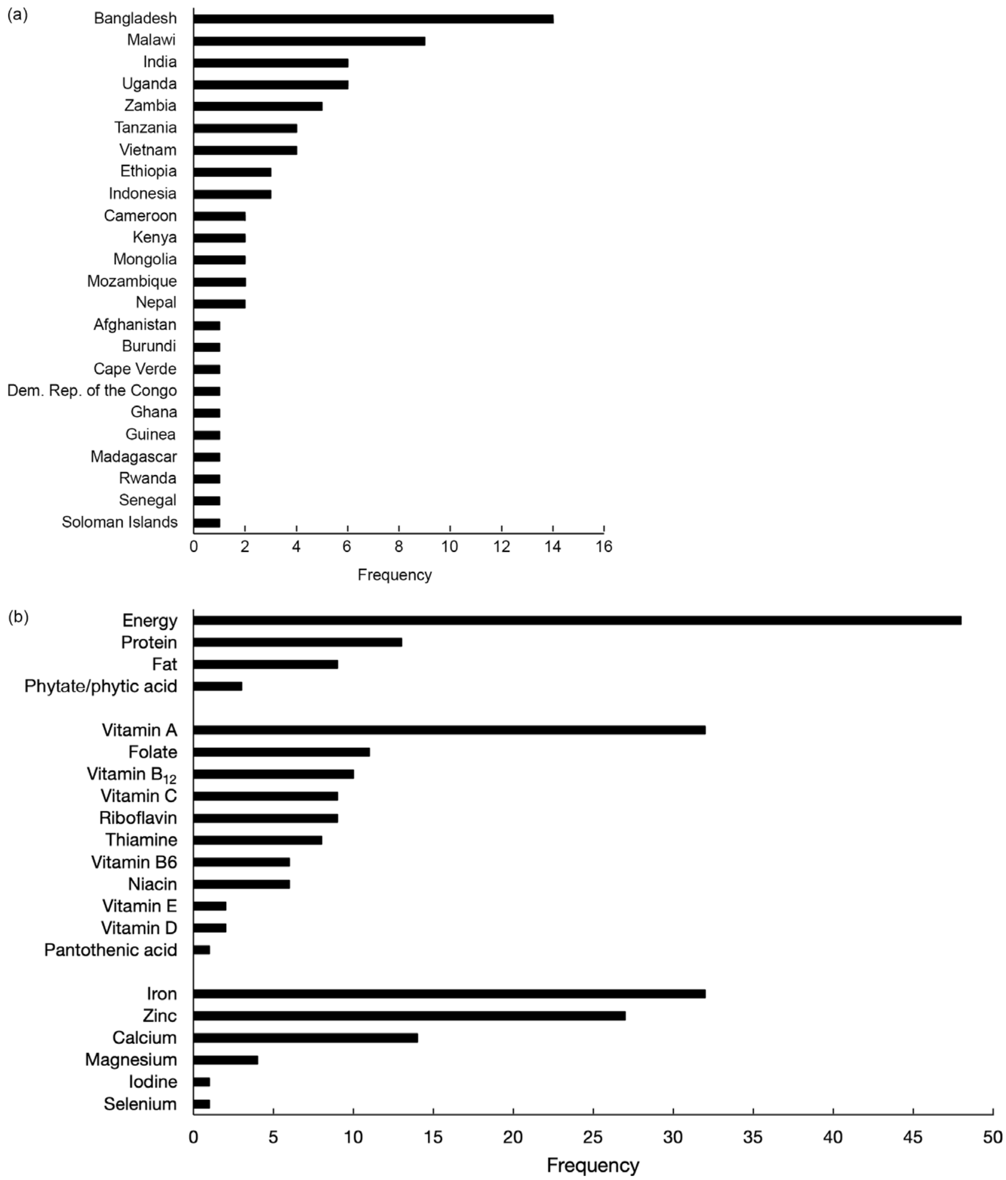

Fig. 2 Frequency of included publications (*n* 58) by (a) country and (b) nutrient measured

(8 % to 26 % difference, depending on region), vitamin B_{12} (10 % to 93 % difference) and vitamin C (19 % to 30 % difference)[38]. In this analysis, nutrient densities estimated from HCES data were consistently lower than nutrient densities estimated from corresponding 24-h dietary recall data for almost all nutrients.

Sub-group nutrient supply and inadequacy comparative analyses

Most publications included in this review stratified nutrient supply estimates by one or more sub-groups of interest. The stratification of nutrient supply by sub-group characteristics was more frequent for indicators of socio-economic

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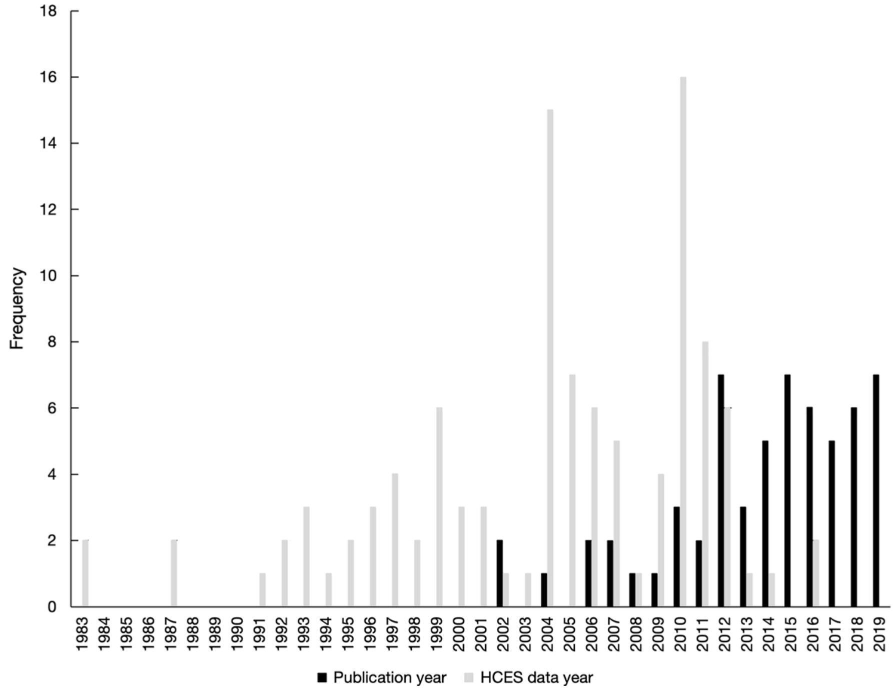

Fig. 3 Frequency of publications included and household consumption and expenditure survey (HCES) datasets used by year

position and geography than for socio-cultural demographic or intra-household characteristics (Fig. 5). Indicators of socio-economic position, as defined by Howe *et al.*[39], included total household income, household expenditure, durable asset ownership, level of educational attainment and occupation. Geographic characteristics generally reflected HCES sampling methodology, where HCESs are designed to be representative of geopolitical administrative regions (*n* 30) and urban *v.* rural settings (*n* 29). A number of publications stratified nutrient supply estimates by individual-level characteristics of members within the household including sex (*n* 21) and age (*n* 21); however; the definition of age and sex of the household varied. For instance, analyses using only household-level data either used individual characteristics of the 'head of household' as a proxy for the entire household ($n_{sex} = 10$; $n_{age} = 6$) or divided household nutrients according to energy requirements of individuals as a proxy for apparent individual intake of household members ($n_{sex} = 9$; $n_{age} = 6$). Some HCES data included individual-level food consumption data of household members which enabled the calculation of nutrient intake specific to the sex (*n* 2) and age group (*n* 1).

Discussion

This systematic review found that the use of HCES data to quantify, characterise and evaluate the adequacy of household nutrient supply across populations is being increasingly represented in published literature. Three primary metrics have been used to report dietary nutrient supply. These are (1) apparent nutrient intake using the AME approach to allocate household nutrient supply among constituent members, (2) apparent nutrient intake using the *per capita* approach where household nutrient supply is divided evenly among constituent members and (3) nutrient density of household diets. Each of these metrics has strengths and limitations when estimating the adequacy of nutrient supply and identifying vulnerable populations at risk of deficiency. While other reviews have analysed applications of HCES data for broader food security indicators[40], this is the first review to summarise the use of HCES data to estimate nutrient supply and evaluate adequacy, an increasingly common practice accepted by the nutrition community.

Households differ in size and composition across and within countries and regions, so the majority of publications attempted to convert nutrient supply estimated at the household level to estimates of individual-level apparent intake[41] using one of two approaches: *per capita* or AME. While the use of the *per capita* approach is simpler, it does not account for any difference in nutrient intakes between household members, which will skew estimates between households of different composition, especially

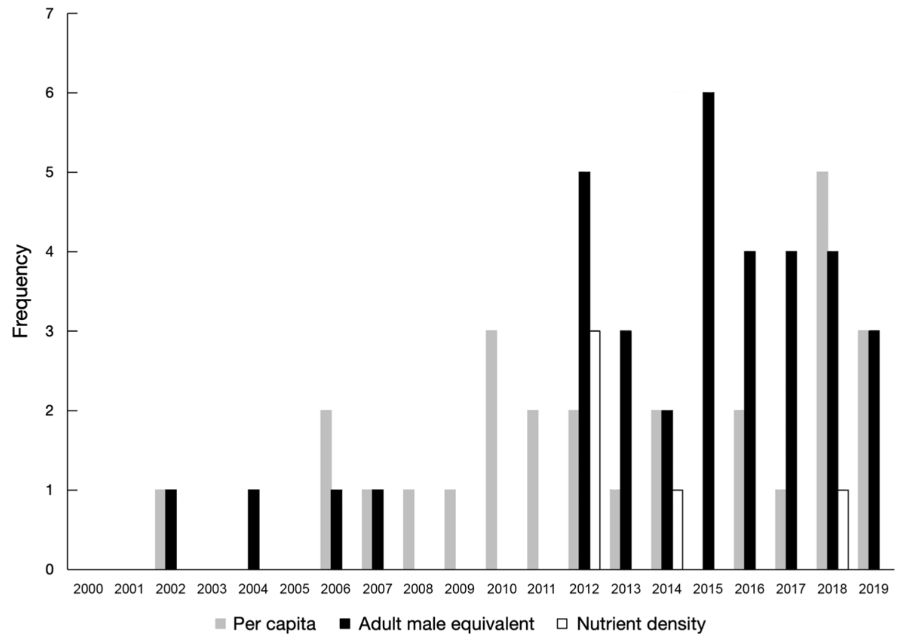

Fig. 4 Frequency of metrics used to characterise household nutrient supply by year of publication

those with large families. Following the publication of a paper series in 2012[3,31] that described the methods to distribute nutrients according to AME energy requirement and its application to household micronutrient supply, an increasing number of publications have estimated dietary supply using the AME approach. The major assumption underlying this approach is that foods consumed by the household are distributed among all household members in proportion to each member's energy requirements, but the method requires data describing individual household members' age, sex, weight, physical activity level, pregnancy status and lactation status[31]. HCESs often collect data on individual household members' age and sex, but data on other parameters affecting individual energy requirements are often not available and require simplifying assumptions to calculate the AME factors (e.g. assume a moderate physical activity level for all members of all households). With 57 % of publications identified in this review estimating apparent nutrient intake using the AME approach, despite a dependency on these assumptions, the AME approach is becoming standard practice.

Differences between estimates of apparent nutrient intake (using HCES data with the AME approach) and nutrient intakes (using individual dietary data) reported in the literature ranged between 12 % and 72 % and were greater for young children based on results by Karageorgou et al.[19]. Poor agreement for young children was likely influenced by the inability of HCES to capture the nutrient contributions of breastmilk and the distribution of nutrients from foods consumed only by young children to the entire household (e.g. infant formula milk, feeding cereals); none of the publications identified by this review made adjustments for these nutrient contributions for young children. Both household- and individual-level recalls are subject to measurement error, but the size of the difference for young children compared with other age groups suggests that HCES food consumption data are often not particularly accurate for young children. Using HCES may lead to systematic overestimation of nutrient intakes for infants and young children when adjustments are not made for breastmilk intakes and subsequent estimates of apparent micronutrient intake and inadequacy should be interpreted with caution. These differences, coupled with the increasing availability and use of HCES data for describing and assessing the micronutrient adequacy of diets across populations, suggest that more research is necessary to inform the development of a structured framework to guide the use and nuanced interpretation of HCES nutrient supply data that reflect its limitations.

The use of HCESs for nutrient analysis has a number of strengths. The HCES food consumption module is considerably less laborious and less expensive to conduct than national scale individual-level dietary surveys[42]. HCESs are conducted regularly, and data are typically made publicly available. HCESs are typically based on 7- to 30-d recall

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Table 2 Publications comparing estimates of apparent nutrient and energy intake using household consumption and expenditure survey (HCES) adult male equivalent (AME) method to individual-level dietary assessment data for total populations and child populations

Reference; country; summary metric	Individual dietary assessment data (*n*)	HCES-AME dietary data (*n* households)	Study sample population (*n*)	Nutrient	Individual intake	HCES-AME apparent intake	Percentage point difference
Bromage *et al.* (2018)[33]; Mongolia; means	24 h individual recall (*n* 4070)	7- to 30-d recall of household meals (*n* 1012)	Total population (*n* 4070)	Energy, kcal	1863	2951	58
				Folate, µg	132	208	58
				Fe, mg	10	16	60
				Vitamin A, µg	448	621	39
				Zn, mg	11	19	72
D'Souza & Tandon (2015); Bangladesh; means	24-h recall of household meals and proportions consumed by individuals (*n* 21 795)	7-d recall of household meals (*n* 5319)	Total population (*n* 21 795)	Energy, kcal	2436	2718	12
Karageorgou *et al.* (2018)[19]; Bangladesh; means	24-h recall of household meals and proportions consumed by individuals (*n* 22 173)	7-d recall of household meals (*n* 5503)	Total population (*n* 22 173)	Energy, kcal	2065	2322	12
				Folate, µg	121	157	31
				Fe, mg	9·9	12	21
				Vitamin A RAE, µg	214	323	50
				Zn, mg	8·6	9·8	14
			Children (< 5 years) (*n* 2807)	Energy, kcal	880	1130	28
				Folate, µg	55	76	40
				Fe, mg	4·2	5·8	38
				Vitamin A RAE, µg	108	158	47
				Zn, mg	3·6	4·8	31
Lividini *et al.* (2013)[37]; Rajshahi, Bangladesh; medians	2 non-consecutive days of 12-h observed weighed food records and 12-h dietary recall (*n* 477)	14-d recall of households containing children age 2–3 (*n* 513)	Children (2–3 years) (*n* 237)	Energy, kcal	905	1098	18
Lividini *et al.* (2013)[37]; Dhaka, Bangladesh; medians	2 non-consecutive days of 12-h observed weighed food records and 12-h dietary recall (*n* 464)	14-d recall of households containing children age 2–3 (*n* 678)	Children (2–3 years) (*n* 226)	Energy, kcal	868	1104	21

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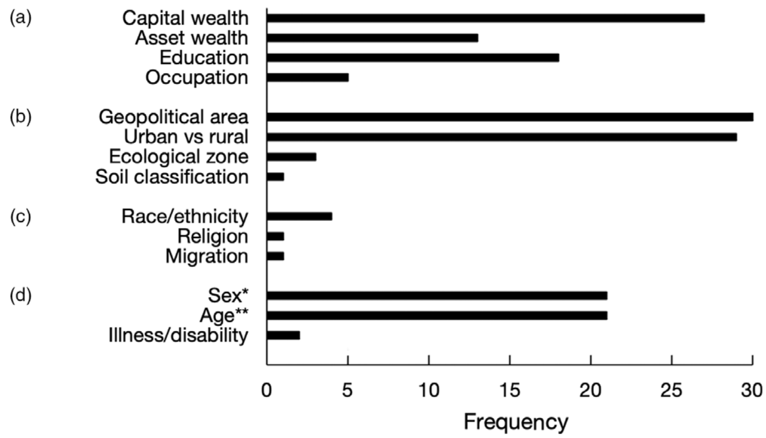

Fig. 5 Frequencies of publications included in this review that stratified results by (a) socio-economic position, (b) geography, (c) socio-cultural demographics and (d) intra-household characteristic. *Methods for sex stratification: empirical measure using individual-level 24-h dietary recall data (*n* 2), distribution according to adult-male equivalent factors (*n* 9), sex of household head (*n* 10). **Methods for age stratification: empirical measure using individual-level 24-h dietary recall data (*n* 1), distribution according to adult-male equivalent factors (*n* 6), distribution according to age group (*n* 8), age of household head (*n* 6)

periods that pose some advantages compared with a single 24-h dietary recall estimates when examining associations between food consumption and determinants affecting diets as HCESs account for day-to-day variation that may attenuate associations(43). In addition, large-scale individual-level dietary intake data are not routinely collected or available in many settings, meaning that the alternative to HCES are national-level Food Balance Sheets(11), which, among other limitations, lack sub-national resolution.

While HCES data can be used to estimate household-level nutrient supply, HCES data do not provide information about the distribution of foods consumed among household members. A majority of studies used the AME approach to convert from household-level to individual-level estimates; however, the following points are important to consider. First, the literature demonstrated differences between nutrient intake/apparent intake estimated using individual-level dietary data *v.* HCES with the AME approach, potentially driven by numerous factors including food consumption patterns(19,33,35) and differences in diet between sex and age groups(37,44). This presents challenges when conducting individual-level sub-group analyses using HCES data and isolating certain sub-groups for analysis may pose problems when using HCES data, considering food consumption is reported at the household level by one member, generally the head female. Foods regularly consumed away from home by other family members may be systematically under-reported, although the collection of household food supply data is evolving to adjust for foods consumed away from home, especially in urban contexts(13,24). Second, it is unknown how individual model parameters used in the AME approach, such as physical activity level and body weights, might affect apparent nutrient intake estimates, as few publications reported sensitivity analyses evaluating this. Additional research exploring the sensitivity of AME factors to individual parameter assumptions would improve general understanding of how much these broad population assumptions impact inadequacy estimates. Third, HCES data quality can vary between countries due to differences in HCES questionnaire design, leading to varying availability of important demographic variables, such as pregnancy status. These data are important to characterise household member's nutrient requirements, and the lack of these data increases uncertainty in estimates of apparent intake and inadequacy.

Uncertainty in how food is allocated within households and if intrahousehold allocation factors can be generalised across different contexts remains a key limitation in the use of HCES data to estimate individual-level apparent nutrient intake. Evidence from Bangladesh suggests that household heads (generally adult males) received proportionally more dietary energy compared with their spouses and children than equitable intra-household food allocation using the AME approach would suggest(36). Yet contrasting results were found in Ethiopia, where groups hypothesised to be more 'vulnerable' (i.e. women and children) were found using 24-h dietary recall data to consume a greater share of energy and protein in relation to their dietary requirements than their male and adult counterparts (although children under 5 years old were excluded from the regression analysis)(45). While differences in these results may be due to cultural differences between countries, understanding general uncertainty in intrahousehold allocation of food is important for sub-groups who are often the focus of nutrition policy(46), such as pregnant or lactating

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women, women of reproductive age, infants and children. Due to this, individual-level surveys (including micronutrient biomarker assessments and individual dietary assessments) will remain important when characterising the micronutrient status of these sub-groups. HCES data do, however, serve as a potential resource to identify dietary nutrient shortfalls putting populations at risk of deficiency, and this information may guide the design of individual-level surveys. For example, HCES data can be used to highlight regional and socio-economic variation and seasonal fluctuations in dietary nutrient supply, which can be useful when developing sampling units for future individual-level surveys.

Diets in low- and lower-middle income countries are affected by a myriad of social determinants[47], which must be addressed by policies intended to improve equity in the broader food system[9]. This review demonstrates that estimating nutrient supply from HCES data may help identify populations at risk of nutrient deficiencies due to poor diets. The literature identified in this review used HCES data to disaggregate nutrient supply results by well-documented social factors affecting diets, such as wealth[41,48,49], education[50,51], geography[49,52] and ruralness[41,53,54]. HCESs collect microdata describing a wide range of socio-economic and geographic determinants of diets, which provides the opportunity to explore the mechanisms driving these associations in great depth. Considering the original intention of HCESs was to provide microdata to characterise poverty and social welfare in low- and lower-middle income countries, there exist a number of potential opportunities to combine other variables already collected in these surveys with nutrition metrics to identify vulnerable populations and integrate this information into the development of nutrition policies that promote equity. Additionally, characterising these high-risk groups from information provided by HCESs can help guide nutrition interventions (e.g. do high-risk populations routinely purchase staple foods or food vehicles suitable for fortification?). To better address equity in nutrition policy, there lies potential opportunities for using HCES data to identify and target vulnerable populations disproportionally affected by key socio-economic and geographic determinants affecting diets. Further research is required to identify indicators of social determinants of poor-quality diets from HCESs and their relation to the specific mechanisms that affect nutrient supply, to inform consistent applications to designing and monitoring nutrition programmes and policy.

The growing evidence base guiding the use of HCES data to estimate nutrient supply has highlighted the potential opportunities HCES data have in informing food systems interventions. As this practice becomes more common, consistency in processing HCES data and reporting results will be important for comparability between findings. While estimating nutrient supply from HCES data will always require time and effort, detailed standard operating procedures, repositories for processed data and descriptive methods, access to standard weight/measure conversions and open-sourced data processing scripts could encourage further analyses, improve consistency between studies and facilitate research collaboration. In addition, to further understand what insights and to what degree of certainty HCES dietary analyses can contribute to understanding the adequacy of diets across populations, more research is needed to compare HCES estimates of nutrient adequacy derived from nutrient density compared with the AME approach, as well as to adequacy estimates from individual 24-h dietary recall data in various country contexts.

This systematic review had a number of strengths. The screening procedure was exhaustive, including a broad database search and snowballing. This resulted in a wide range of publications from peer-reviewed journals, working papers from multi-national institutions and other grey literature. Our study also extracted data describing the process of transforming HCES data to estimate nutrient supply and social determinants that may affect diets. The current study, however, had limitations. There were very few publications that applied the nutrient density approach, making it difficult to draw conclusions regarding potential variation in assumptions and applications of the metric. In addition, while the screening of results from the database search was independently undertaken by two individuals, the review of identified publications during screening was only conducted by one.

Estimates of nutrient supply and dietary quality using HCES data can play an important role in micronutrient surveillance and the design of interventions to tackle micronutrient deficiencies. However, HCES remain under-exploited for the identification of vulnerable populations at greatest risk of micronutrient deficiencies and for the design of effective and equitable micronutrient interventions. Further research is required to understand the implications of key methodological decisions when building models using HCES data in an effort to inform national nutrition policy.

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Supplementary material

For supplementary material/s referred to in this article, please visit https://doi.org/10.1017/S1368980022000118

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CHAPTER 5

Characterizing populations at-risk for micronutrient inadequacy from Household Consumption and Expenditure Surveys using apparent intake and nutrient density

CHAPTER SUMMARY

Based on the metrics and best practices identified in Chapter 4, this chapter presents an original research article that compares two dietary micronutrient assessment metrics identified in the prior chapter's systematic review (apparent intake and nutrient density) and describes the interpretation, considerations, strengths, and limitations of each metric. Chapter 5 will start with an Addendum to Chapter 4 presenting a result from Table 4.2, which is important for understanding potential bias that may be inherent to the use of these metrics. The outputs of this original research article include a comparison of the two metrics using HCES data from two different countries (exploring model dynamics from sub-group stratification and modelling of micronutrient programmes), analysis of food groups consumed, and a sensitivity analysis of key assumptions present in these models. This original research article contributes evidence on the types of micronutrient information each HCES metric can and cannot provide and how to translate the information from HCES to understand the apparent micronutrient adequacy of diets across populations.

This original research article has been prepared for submission to a peer-reviewed publication.

Addendum to Chapter 4

Differences in mean bias between apparent intake of micronutrients and energy

Table 4.2 presents the results of publications which compared intake using individual-level quantitative intake data and apparent intake using household-level data for energy, vitamin A, folate, iron, and zinc (when reported). The mean bias is defined as the percentage point differences between the two methods. Where reported by these publications, the magnitude of the mean bias was lower for estimates of energy intake (n = 4; 24-point difference) compared to the micronutrients estimated: vitamin A (n = 3; 45-point difference), folate (n=3; 43-point difference), iron (n=3; 40-point difference), and zinc (n = 3; 39-point difference). The direction of the mean bias was the same for energy and all micronutrients observed, where HCES apparent intake overestimated measures of energy and nutrient intakes compared to individual level measures; however, the magnitude of bias was different and suggests that nutrient density generally will be over-estimated in HCES.

The magnitude and direction of this mean bias may affect the interpretation of the nutrient density metric. For instance, based on the mean biases presented here, a larger mean bias overestimation in micronutrients compared to energy suggests that the nutrient densities may appear higher due to the higher imprecision for micronutrient supply estimates compared to energy supply estimates. Considering that nutrient density functions as an energy-adjusted measure of apparent micronutrient intake, there are potential risks in the use of nutrient density if there are differences in precision between the components of the nutrient density metric. Further research is needed to compare nutrient density and apparent intake estimated using HCES data to consider how these differences in precision will affect the nutrient density metric.

There are some aspects of these results that should be considered when interpreting these results. First, all but one of these studies used a single 24-hour recall to estimate mean intake and while adjustments were made to account for within-person variance, it is not well known how differences in single versus multiple recalls will compare against household level estimates (which may better approximate usual intake due to the longer recall period). While mean intake is an appropriate metric for use in dietary assessment, comparison of mean intake to apparent intake is not straightforward due to the varying approaches to account for within-person variance in individual 24-hour recall or weighed food records. Additional research is necessary comparing various individual quantitative intake data with household level estimates. Second, these studies were only conducted in two country settings (i.e., Bangladesh, Mongolia), which limits the generalisability of how individual intake and household apparent intake estimates compare. This is important in terms of dietary differences between countries and methodological differences between how HCES food consumption modules are designed between country settings (e.g., length of recall period, length of food item list). Similarly, additional research is necessary comparing individual quantitative intake data with household level estimates from various country settings.

This chapter aims to further explore the construction, interpretation, and limitations of the apparent intake and the nutrient density metrics.

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed <u>for each</u> research paper included within a thesis.

<u>SECTION A – Student Details</u>

Student ID Number	1600604	Title	Mr
First Name(s)	Kevin Michael		
Surname/Family Name	Tang		
Thesis Title	Micronutrient adequacy of diets and contributions of large-scale interventions: secondary analyses of household surveys		
Primary Supervisor	Dr. Edward Joy		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

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Where is the work intended to be published?	Nature Food

Please list the paper's authors in the intended authorship order:	Kevin Tang, Elaine Ferguson, Katherine P Adams, Lucia Segovia De La Revilla, Monica Woldt, Dawd Gashu, Gareth Osman, Binyam G Sisay, Folake Samuel, Jennifer Yourkavitch, Sarah Pedersen, Omar Dary, E Louise Anders, Edward JM Joy
Stage of publication	Not yet submitted

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	KT, MW, OD, ELA, and EJMJ set up the collaborative network. KT, OD, and EJMJ designed the study. KT, GO, KPA cleaned and transformed the food consumption data. ELF, DG, FS, and LSDLA compiled the food composition data matches. KT and OD developed the food fortification scenarios. KT, KPA, ELF, MW, JY, OD, SP, ELA, and EJMJ determined the adult female equivalent factor parameters. KT conducted the statistical analysis. KT, ELF, MW, JY developed the communication framework. KT, ELF, and KPA conducted the sensitivity analysis. KT, KPA and EJMJ led the interpretation of the results and drafting the manuscript. All authors critically reviewed and approved the final manuscript.

SECTION E

Student Signature	Kevin M Tang
Date	23/09/2022

Supervisor Signature	Edward JM Joy
Date	23/09/2022

FULL TITLE: Characterizing populations at-risk for micronutrient inadequacy and understanding biases using apparent intake and nutrient density from Household Consumption and Expenditure Surveys

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KEYWORDS

Household consumption and expenditure survey, HCES, micronutrients, apparent intake, nutrient density

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necessarily reflect the views of USAID, the U.S. Government, or the Bill & Melinda Gates Foundation.

ABSTRACT

Characterizing populations at-risk for micronutrient inadequate diets is challenging due to a global dearth of dietary data. Household food consumption data from Household Consumption and Expenditure Surveys in Malawi and Nigeria were used as proxies for dietary data to demonstrate how two metrics generated from these data, apparent intake and nutrient density, can be interpreted when characterizing sub-populations within countries at-risk for inadequate vitamin A and zinc intake, and potential risks implicit to the use of these metrics. In both countries, apparent intake provided insights into intake quantities, where nutrient density described the micronutrient quality of the diet. However, bias assessments and sensitivity analyses indicated that error in the underlying HCES data pose potential risks when interpreting the two metrics. In the absence of nationally representative, individual level dietary intake data, this study demonstrated the potential uses and risks of alternative sources of widely available data to generate insights about the micronutrient adequacy of diets.

5.1 Introduction

Micronutrient deficiencies are common globally, contributing to poor growth and development in early life and increased morbidity and mortality throughout life [1]. A poor- quality diet is a prominent risk factor for micronutrient deficiencies, as it increases risks of inadequate micronutrient intakes [2]. Food fortification and biofortification can improve the micronutrient content of diets by enriching poor-quality diets with vitamins and minerals without substantially altering the quantity or composition of the diet [3,4]. The assessment of current interventions and the choice of new interventions relies on several factors, including the micronutrients to be delivered, the target population, and the structure of the local food system [5]. Evaluating the potential contributions of a micronutrient-supplying intervention, for reducing risks of inadequate micronutrient intakes in vulnerable populations, requires population level dietary data. Various sources of dietary data exist, each having their own strengths and limitations [6–8].

Household Consumption and Expenditure Surveys (HCES) have been used as one source of data, for providing insights into the micronutrient adequacy and/or quality of diets within a country. Originally designed as national surveys to characterize an array of socio-economic conditions, data from the HCES food consumption module has also been used as proxy dietary data to assess the adequacy of household diets for meeting micronutrient needs [7]. The food consumption or acquisition data are collected via standardized methods unique to each HCES [9]. All HCES use a multi-day recall at the household level by a single respondent based on a list of commonly consumed foods. Compared to individual-level dietary assessment methods (e.g., 24-hour quantitative dietary recalls), household-level food consumption data collected via HCESs are regularly collected, in many countries, at a national scale, facilitating greater accessibility to data to inform national micronutrient policies and programs. However, certain methodological characteristics, such as the exclusion of foods from the food item list, not accounting for food waste or the consumption of foods away from home, and not quantifying foods actually eaten by individual household members versus acquired for the household, could affect the precision of estimates and may limit the use of HCES data for micronutrient policy or programmatic purposes [9].

Estimating micronutrient adequacy from household level data requires the construction of different metrics to assess a population's risk of inadequate micronutrient intakes given dietary practices. Two metrics have been used, in the published literature, to characterize populations at risk for inadequate micronutrient intake from HCES data [10]. The first, apparent intake, is the household's total micronutrient supply expressed per reference household member, such as adult female or male equivalents. This metric attempts to estimate intake quantity for an individual, assuming foods are proportionately distributed across household members based on their estimated average energy requirements [11,12]. The second, nutrient density, is the ratio of the household's total micronutrient supply to the household's total energy supply [13]. This metric attempts to estimate the micronutrient quality of the overall diet, and adjusts the micronutrient quantity per unit of energy provided by the same diet. The interpretation of these metrics must be clear and specific to a specific policy or program decision, especially since the information each metric provides and the assumptions implicit to each are inherently different. Additionally, a differential bias between energy intake estimates and micronutrient intake estimates may affect the nutrient density metric which requires their combination into a single metric, thus complicating their interpretation and increasing risk for unidentifiable bias.

National guidance informed by these metrics to characterize populations at-risk for inadequate micronutrient intake and to model the potential contribution of micronutrient interventions requires an understanding of the assumptions inherent to each metric to strengthen interpretations, recognizing the imprecisions inherent in HCES dietary data and the potential differences in bias between micronutrient and energy. This study aims to compare the two metrics, describe how they may be used together when characterizing and comparing populations at-risk for inadequate micronutrient intake, and identify any potential risks for bias in the uses of these metrics.

5.2 Methods

Household Consumption and Expenditure Surveys

The models in this study were based on data from two Household Consumption and Expenditure Surveys: the 2016/17 Fourth Integrated Household Survey of Malawi [14] and the 2018/19 Living Standards Survey of Nigeria [15]. Each HCES was conducted by their respective country's national statistics agency with support from the World Bank's Living Standards Measurement Study (LSMS). The survey design for these HCES was consistent with standard HCES methods: two-stage sampling (i.e., randomly selected households within randomly selected enumeration areas) and a single-visit interviewer administered multiple-module questionnaire with a respondent from the household (generally the individual responsible for preparing the household's meals). All HCES data were de-identified at source, downloaded from the World Bank LSMS data portal (accessed 28 September 2020 for Malawi, 4 October 2021 for Nigeria), and used in compliance with the data access policy.

There were several differences between the HCES data from the three countries including the total sample size (i.e., n = 22,587 and 12,447 in Nigeria/Malawi, respectively), the length of their food item lists (n = 136 and 99 in Malawi/Nigeria, respectively) and coverage of major food groups. The last two named differences might influence household micronutrient supply estimates [16]. Details about each survey are presented in Table 5.1.

Table 5.1. *Descriptive characteristics of Household Consumption & Expenditure Surveys (HCES) included in this study*

Characteristic	*Malawi*	*Nigeria*
Name of HCES	Fourth Integrated Household Survey (IHS4)	Living Standards Survey (NLSS)
Time horizon	15 April 2016 – 30 April 2017	28 September 2018 – 28 September 2019
Enumeration areas, n	780	2300
Households, n	12,447	22,587
Food items, n	136	99
Pregnancy data	Yes	No

Food consumption, micronutrient composition & fortification scenario

HCES data from each country included a food consumption module, where a household member recalled the quantity of foods consumed by the entire household in the past seven days using a standardized list of commonly consumed food items. Detailed descriptions of the data cleaning, transformation, and matching procedures are published elsewhere [17]. In summary, consumption quantities of each food item were converted from reported non-standard units to kilograms [18], adjusted to account for non-edible portions of the food item [19], and the replacement of outliers in individual food consumption quantities with the population median value for that food item. Outliers were defined in this study as households consuming any food item at a quantity greater than five standard deviations from the lognormal mean consumption quantity for each food item.

Food items were matched in raw form to an equivalent item from available food composition data to estimate each food item's vitamin A, zinc, and energy contents. Food item matches prioritized food composition data that satisfied data quality criteria and that were geographically closest to the country included in this study. In Nigeria, we assumed all palm oil was unrefined/red retaining 20% of its vitamin A contents based on consultations with nutrition researchers from Nigeria who considered differences in the preparation of unrefined red palm oil between regions. While it is possible that vitamin A retention in unrefined red palm oil is higher than 20%, we selected a conservative palm oil retention parameter to demonstrate the potential contributions of other vitamin A fortified food vehicles more intentionally. All food item matches are presented in the Supplementary Material.

Potential contributions from each country's large-scale food fortification program were modelled, which in this study included vitamin A-fortified edible oil, vitamin A-fortified sugar, and vitamin A- and zinc-fortified wheat flour. Large-scale fortification of maize flour and rice were not included in the analysis because of a low proportion of industrial-scale production or the absence of a large-scale food fortification policy for the food item in the included countries [20]. The fortification scenario assumed that all refined oil and wheat flour consumed were centrally processed/fortified and that fortification vehicles were fully compliant with each countries' national fortification policy [20]. While these assumptions are hypothetical, they provide an upper-bound estimate of the potential contribution of fortification at currently mandated fortification levels. Fortification scenarios are presented per country in Table 5.2.

Metrics to characterize populations at-risk for inadequate micronutrient intake

Two metrics were generated to characterize populations at-risk of inadequate vitamin A and zinc intake. All parameters, data, and assumptions necessary to define each parameter are presented in Table 5.3.

__Table 5.2__ Scenario representing additional vitamin A and zinc added to food vehicles from large-scale food fortification

		Vitamin A			Zinc		
Country	Fortification vehicle	Standard (mg/kg)	Legislation type	Reference	Standard (mg/kg)	Legislation type	Reference
Malawi	Oil	21	Mandatory	[1]	-	-	[1]
	Sugar	10.5	Mandatory	[1]	-	-	[1]
	Wheat flour & products	1.8	Mandatory	[1]	30	Mandatory	[1]
Nigeria	Oil	6	Mandatory	[2]	-	-	-
	Sugar	7.5	Mandatory	[2]	-	-	-
	Wheat flour & products	2	Mandatory	[3]	50	Mandatory	[3]

[1] Malawi Bureau of Standards. 2017. Catalogue of Malawi Standards. Blantyre.; Makhumula & Dary. 2020. Personal communication

[2] Global Alliance for Improved Nutrition & Oxford Policy Management. 2018. Fortification assessment coverage toolkit (FACT) survey in two Nigerian states: Ebonyi and Sokoto. Geneva.

[3] Food Fortification Initiative, Global Alliance for Improved Nutrition, Iodine Global Network & Micronutrient Forum. 2018. Global Fortification Data Exchange. https://fortificationdata.org/.

Table 5.3. *Base data and model parameters with base case values and ranges used in one-way sensitivity analysis*

Parameters		Data & assumptions	Sensitivity analysis range	Reference(s)
Adult female equivalent factors				
Energy requirement for reference adult female (kcal)		2100	–	[1]
Energy requirement for reference adult male (kcal)		2650	–	[1]
Sex of household members		Roster	–	[2–4]
Age of household members		Roster	–	[2–4]
Adult male body weight (kg)		65	55 – 75	Assumption
Adult female body weight (kg)		55	45 – 65	Assumption
Energy expenditure factor from physical activity (per basal metabolic rate)		1.6	1.45 – 1.75	[1]
Additional daily energy requirement for pregnancy (kcals)		452	0 – 565	[5]
Additional daily energy requirement for lactation in first 6 months (kcals)		330	0 – 500	[5]
Additional daily energy requirement for lactation between 6-23 months (kcals)		400	0 – 500	[5]
Energy intake from breastmilk, age 3-5 months (kcals)		434	338 – 530	[6]
Energy intake from breastmilk, age 6-8 months (kcals)		413	315 – 511	[6]
Energy intake from breastmilk, age 9-11 months (kcals)		379	269 – 490	[6]
Energy intake from breastmilk, age 12-23 months (kcals)		346	218 – 474	[6]
Nutrient density and apparent intake thresholds				
Vitamin A (μg RAE)	Harmonized Average Requirement *(female 18-50 years)*	490	–	[7]
	Critical nutrient density (per 1000 kcal)	233	192 – 297	[1,7]
Zinc (mg)	Harmonized Average Requirement *(female 18-50 years)*	10.2	–	[7]
	Critical nutrient density (per 1000 kcal)	4.9	4.0 – 6.2	[1,7]

1 FAO/WHO/UNU. Human energy requirements. Report of a Joint FAO/WHO/UNU Expert Consultation: Rome, 17–24 October 2001. *AO food Nutr Tech Rep Ser* 2004.

2 National Statistical Office, The World Bank. Fourth Integrated Household Survey of Malawi. Lilongwe: 2017. https://microdata.worldbank.org/index.php/catalog/2936/study-description#metadata-data_access (accessed 28 Sep 2020).

4 National Bureau of Statistics, The World Bank. Living Standards Survey of Nigeria 2018-2019. Abuja: 2019. https://microdata.worldbank.org/index.php/catalog/3827

5 U.S. Department of Agriculture, U.S. Department of Health and Human Services. Dietary Guidelines for Americans, 2020–2025. Washington, D.C.: 2020. https://dietaryguidelines.gov

6 World Health Organization. Complementary feeding of young children in developing countries: a review of current scientific knowledge. Geneva: 1998. https://apps.who.int/iris/handle/10665/65932

7 Allen LH, Carriquiry AL, Murphy SP. Proposed Harmonized Nutrient Reference Values for Populations. *Adv Nutr* 2020;**11**:469–83. doi:10.1093/advances/nmz096

First, apparent intake was defined as the daily household micronutrient supply divided by the Adult Female Equivalents (AFE) in the household. This metric assumes that the distribution of food consumed across members of a household is in proportion to each member's estimated mean daily energy requirement (MDER) [11]. We selected the adult female as the reference group as this demographic group is at higher risk of inadequate nutrient intakes than adult males, most households will have an adult female member in it, and in many contexts their intake is assumed to be closer to the household average intake than that of adult males. A household (j) at-risk of inadequate micronutrient intake using the apparent intake approach is represented by the following equation:

$$\left(\frac{Daily\ micronutrient_x\ supply_j\ (units)}{AFE_j\ = \sum_{i=1}^{n} \frac{R_i}{k}}\right) < H - AR_{Adult\ females}$$

Where apparent intake numerators (i.e., Daily micronutrient$_x$ supply$_j$) is the daily micronutrient supply of household for a micronutrient (*x)*. Apparent intake denominators (i.e., AFEs) were calculated for i=1-n household members as the sum of each household member's daily energy requirement (R_i) divided by an AFE constant (k), or the energy requirement of a non-pregnant, non-lactating, 18- to 29-year-old woman [11]. The energy requirements for each household member (R_i) were estimated using the joint FAO/WHO/UNU Human Energy Requirements accounting for variation in age, sex, and pregnancy status, if available, using the household roster data from each HCES [21]. Additional assumptions were made to consider variations in energy requirements due to differences in household members' body weight, physical activity level, additional energy required for lactating women, and energy contributions from breastmilk for children under two years old. Households at-risk were defined as those with an apparent intake that falls below the non-pregnant, non-lactating, 18 – 29-year-old woman's Harmonized-Average Requirement (H-AR) [22].

Second, nutrient density, for each micronutrient, was defined as the ratio of the household's total supply, for that micronutrient to the household total energy supply, expressed per 1000 kcal. A household (j) was defined as having a low nutrient dense diet, for a micronutrient (*x)*, when its nutrient density fell below the critical nutrient density threshold for that micronutrient [22,23], represented by the following equation:

$$\left(\frac{Micronutrient_x\ supply_j\ (units)}{Energy\ supply_j\ (kcals)}\right) * 1000 < Critical\ nutrient\ density$$

A micronutrient's critical nutrient density threshold was defined as the ratio of its daily H-AR [24] to the mean daily energy requirements [21] for a non-pregnant, non-lactating, 18 – 29-year-old woman, expressed per 1000 kcal. We chose the critical nutrient density for the adult female to represent the at-risk threshold for the household, as the critical nutrient densities were higher than their male counterparts (Table 5.4) and therefore a more sensitive group for detecting low density diets for the household.

Table 5.4 *Variations in Critical Nutrient Density values between demographic groups for vitamin A and zinc*

Age group (years)/ demographic	*Vitamin A*		*Zinc*	
	Male	*Female*	*Male*	*Female*
1	216	241	3.8	4.2
2	182	195	3.2	3.4
3	164	178	2.9	3.1
4	181	196	3.4	3.7
5	166	185	3.1	3.5
6	156	172	2.9	3.2
7	188	206	3.6	4.0
8	175	188	3.4	3.6
9	162	173	3.1	3.4
10	149	160	2.9	3.1
11	204	223	3.8	4.1
12	188	211	3.5	3.9
13	173	202	3.2	3.7
14	160	196	3.0	3.6
15	183	196	3.7	4.0
16	174	196	3.5	4.0
17	171	196	3.5	4.0
18 – 29	215	233	4.8	4.9
30 – 59	219	239	4.9	5.0
60+	265	265	5.9	5.5
14 (pregnant)	-	186	-	4.0
15-17 (pregnant)	-	183	-	3.9
18-29 (pregnant)	-	212	-	4.5
30-59 (pregnant)	-	216	-	4.6
14 (lactating, first 6m)	-	367	-	4.9
15-17 (lactating, first 6m)	-	360	-	4.8
18-29 (lactating, first 6m)	-	420	-	5.6
30-59 (lactating, first 6m)	-	429	-	5.8
14 (lactating, 7-23m)	-	358	-	4.8
15-17 (lactating, 7-23m)	-	352	-	4.7
18-29 (lactating, 7-23m)	-	408	-	5.5
30-59 (lactating, 7-23m)	-	416	-	5.6

Assessment of risk for bias

To help identify potential drivers of bias in the calculation of the nutrient density metric, two analyses will be conducted to understand the face validity of these metrics.

First, the nutrient density metric's median numerator (vitamin A or zinc supply expressed per AFE) and denominator (energy supply expressed per AFE) will be presented for each subpopulation. Numerators will be compared between subpopulations and relation to energy supply. Denominators will be compared between subpopulations and in relation to a 2100 kcal MDER (18- to 24-year-old non-pregnant, non-lactating woman) to assess potential bias due to over- or under-estimation.

Second, to assess the potential drivers of bias in energy and micronutrient supply estimates, the median consumption per AFE of six food groups (i.e., cereals/grains, roots/tubers, nuts/pulses, vegetables, fruits, animal-sourced foods) were presented and compared across subpopulations.

Data analysis

Prevalence of the population with inadequate apparent intake or who did not consume a nutrient dense diet was estimated at national levels. Prevalence estimates were further stratified within each country by urban versus rural residence, and then further stratified within their residence groups into socioeconomic quintiles based on the total annual inflation-adjusted household expenditure per capita [25]. The percentage of households with an apparent micronutrient intake less than the H-AR and with a nutrient density less than the critical nutrient density was estimated, for each nutrient, at the national level. Finally, these prevalence estimates were categorized into one of five wide categories (i.e., between 0 – 19%, 20 – 39%, 40 – 59%, 60 – 79%, and 80 – 100%).

Data analysis was conducted in RStudio (version 3.6.1, R Foundation for Statistical Computing). Survey weight adjustments and statistical analyses were conducted using the functions available on the *srvyr* package [26] and additional data cleaning and management used a variety of functions from the *tidyverse* package [27].

Sensitivity analysis

A one-way deterministic sensitivity analysis using parameter lower and upper bounds was used to evaluate the impact of individual parameter assumptions on the prevalence at-risk of inadequate vitamin A and zinc intakes for both metrics. The base case for all sensitivity analyses was defined as the prevalence at-risk for inadequate vitamin A and zinc intakes estimated at national levels under the fortification scenario. For the apparent intake approach, each energy requirement assumption for household members' AFE factors (e.g., MDER for assumed body weight, MDER for physical activity level, additional kcals for pregnant women, additional kcals for women lactating, proportion of kcals from breastmilk for children breastfeeding) were each assigned lower and upper bound values one at a time based on the range of probable values presented in published literature or $\pm$25% of the base case where these values were not available. In addition, all apparent intake per AFE parameters were simultaneously varied to their lower and upper bound values to estimate the potential combined effect of all parameters together on the prevalence at-risk for inadequate micronutrient intake. For the nutrient density approach, the critical nutrient density threshold was varied according to the non-pregnant, non-lactating, 18 – 29-year-old woman's daily energy requirement lower (1650 kcal) and upper (2550 kcal) bounds [21]. The lower and upper bound range for all sensitivity analysis parameters are presented in Table 5.3. A one-way deterministic sensitivity analysis also evaluated the sensitivity of the model to vitamin A contributions from unrefined red palm oil in Nigeria, assuming 0% and 100% retinol retention as lower and upper bounds.

5.3 Results

Metrics to define populations at-risk for inadequate micronutrient intake

Populations at-risk for inadequate vitamin A and zinc intake for the two metrics are presented for Malawi (Table 5.5) and Nigeria (Table 5.6). At national levels in each country, assuming no fortification, the estimated prevalence of the population at-risk for inadequate intakes of vitamin A comparing the two metrics, were similar, ranging from a 2 to a 5-percentage point difference (Tables 1-3). In all countries, a relatively high percentage of the population was at risk of inadequate vitamin A intakes (i.e., > 55%). For zinc, the prevalence of the population at-risk for inadequate intake varied more between the two metrics, where the range of prevalence estimates assuming no fortification was 73% vs 67% in Malawi and 65% vs 60% in Nigeria.

Assuming no fortification, trends in sub-national prevalence of the population at-risk for inadequate intake between socioeconomic positions were different when using the apparent intake approach versus the nutrient density approach. For apparent intake, consistently across all three countries, the estimated percentages of the populations at-risk for inadequate intakes of vitamin A and zinc was highest in the poorest populations, and as socioeconomic position improved, these estimated percentages decreased (Tables 5.5-5.7). The socio-economic differences were particularly high for vitamin A, ranging from a 36- to 67-point difference, depending on the country. In contrast, the percentage at-risk estimated using the nutrient density approach was relatively similar across socioeconomic positions, ranging from a 7- to a 34-point difference for vitamin A, depending on the country (Tables 5.5-5.7). The narrower range of prevalence estimates between socioeconomic positions for the nutrient density approach shows similar increasing patterns in both household micronutrient supply and energy supply as socioeconomic position increases, resulting in similar prevalence estimates between socioeconomic positions when calculating the ratio between micronutrient and energy supply to calculate nutrient density.

When modelling the potential contributions of large-scale food fortification, both metrics identified the same subpopulations that would likely benefit the most from the intervention. For vitamin A fortification, when compared to the no fortification scenario, both metrics showed the percentage point difference comparing the lowest to highest socio-economic groups increased across all countries, ranging from a 63- to 85-point difference, for apparent intakes and a 33- to 65-point difference for nutrient density. Widening ranges suggest an inequitable benefit, in other words, the micronutrient intervention would benefit subpopulations with lower risks for inadequate intake more than those with higher risks. Narrowing ranges suggest more equitable interventions capable of closing gaps between sub-populations.

For zinc, potential wheat flour fortification program contributions varied by country. Both metrics indicated, for Malawi, a wheat flour fortification would lead to low or marginal improvements (3- and 4-point improvement in Malawi for the apparent intake and nutrient density metrics). In Nigeria, however, the predicted benefit from a wheat flour fortification varied, depending on the metric used, where the nutrient density metric predicted a 34-point prevalence improvement and the adequate apparent zinc metric predicted a 13-point prevalence improvement. Both metrics indicated that populations of high socioeconomic position would disproportionally benefit more from a wheat zinc fortification program compared to populations of lower socioeconomic position in Malawi and Nigeria.

Table 5.5 *Prevalence of population in Malawi at-risk for inadequate vitamin A (retinol activity equivalent) and zinc intake using the nutrient density approach and the apparent intake approach per adult female equivalent (AFE) by place of residence and socioeconomic position (SEP).*

0-19%	20-39%	40-59%	60-79%	80-100%

			No fortification		Fortification	
	Population	Households, n	Nutrient density, %	Apparent intake, %	Nutrient density, %	Apparent intake, %
Vitamin A	**National total**	**12,447**	**77**	**75**	**38**	**41**
	Rural	**10,175**	**76**	**77**	**45**	**48**
	Lowest SEP	2035	76	91	66	86
	Lower Middle SEP	2035	73	84	55	67
	Middle SEP	2035	79	78	48	49
	Higher Middle SEP	2035	78	70	36	29
	Highest SEP	2035	80	60	20	10
	Urban	**2272**	**77**	**67**	**10**	**11**
	Lowest SEP	455	79	82	26	37
	Lower Middle SEP	454	78	70	12	10
	Middle SEP	455	77	72	6	1
	Higher Middle SEP	454	74	61	4	1
	Highest SEP	454	73	48	1	1
Zinc	**National total**	**12,447**	**73**	**67**	**69**	**64**
	Rural	**10,175**	**70**	**68**	**68**	**67**
	Lowest SEP	2035	54	94	53	93
	Lower Middle SEP	2035	65	80	63	80
	Middle SEP	2035	71	67	69	66
	Higher Middle SEP	2035	78	59	75	56
	Highest SEP	2035	82	42	78	37
	Urban	**2272**	**84**	**62**	**75**	**53**
	Lowest SEP	455	71	85	64	84
	Lower Middle SEP	454	84	72	75	67
	Middle SEP	455	86	62	77	52
	Higher Middle SEP	454	90	51	79	35
	Highest SEP	454	91	31	78	17

Table 5.6 Prevalence of population in Nigeria at-risk for inadequate vitamin A (retinol activity equivalent) and zinc intake using the nutrient density approach and the apparent intake approach per adult female equivalent (AFE) by place of residence and socioeconomic position (SEP).

0-19%	20-39%	40-59%	60-79%	80-100%

			No Fortification		Fortification	
	Population	Households, n	Nutrient density, %	Apparent intake, %	Nutrient density, %	Apparent intake, %
Vitamin A	**National total**	**22,123**	**57**	**63**	**31**	**41**
	Rural	**15,302**	**61**	**66**	**40**	**46**
	Lowest SEP	3061	74	95	58	90
	Lower Middle SEP	3061	71	85	53	67
	Middle SEP	3060	64	74	43	47
	Higher Middle SEP	3060	58	55	34	28
	Highest SEP	3060	43	31	20	14
	Urban	**6808**	**50**	**60**	**17**	**33**
	Lowest SEP	1362	67	90	35	73
	Lower Middle SEP	1362	57	77	24	45
	Middle SEP	1362	50	63	15	31
	Higher Middle SEP	1361	42	49	9	18
	Highest SEP	1361	41	35	9	14
Zinc	**National total**	**22,123**	**65**	**60**	**31**	**47**
	Rural	**15,302**	**56**	**53**	**32**	**45**
	Lowest SEP	3061	46	74	37	72
	Lower Middle SEP	3061	50	57	34	53
	Middle SEP	3060	55	54	35	47
	Higher Middle SEP	3060	58	49	32	38
	Highest SEP	3060	67	39	26	25
	Urban	**6808**	**80**	**70**	**30**	**51**
	Lowest SEP	1362	68	82	39	76
	Lower Middle SEP	1362	77	77	37	64
	Middle SEP	1362	80	75	31	53
	Higher Middle SEP	1361	82	66	24	43
	Highest SEP	1361	87	55	25	30

Assessment of risk for bias

Table 5.7 presents per capita energy, vitamin A, and zinc supply (per AFE per day) at national levels, between rural and urban populations, and for all socioeconomic subpopulations.

When in reference to the 2100 kcal MDER reference, the Malawi national median apparent energy intake was higher at 2112 kcals/AFE/day. In Malawi, when comparing per capita energy supply by socioeconomic positions, wealthy and wealthiest subpopulations had the highest median per capita energy supply (2436 to 3591 kcals/AFE/day) with greater variation within subpopulations (IQR: 1334 to 1538 kcals/AFE/day) compared to other subpopulations, presenting risks of overestimation. This is confirmed when assessing the median grams consumed of cereals/AFE/day (Table 5.8), where in Malawi, wealthier wealth quintiles reported apparently consuming between 495 – 588 g of cereals/grains per capita per day (equivalent to approximately 5 servings of staple grains). In Nigeria, the national median per capita energy supply was lower than the 2100 kcal MDER reference estimated at 1985 kcals/AFE/day, where median per capita energy supply was lower in the urban subpopulation (1935 kcals/AFE/day) compared to rural subpopulations (2014 kcals/AFE/day). One likely factor, amongst many, that may contribute to this possible underestimation in per capita energy supply is recall omission due to consumption of foods away from home (FAFH), which is more common in urban subpopulations. While variation in per capita energy supply was highest in wealthier populations in both countries, all populations and subpopulations demonstrated large variations in per capita energy supply (SEP IQR range: 759 to 1538 kcals/AFE/day in Malawi and 770 to 1643 kcal/AFE/day in Nigeria).

In both countries, apparent energy intake estimates for the populations of the poorest socioeconomic positions were very low when compared to MDER references. In Malawi, the median apparent energy intake for the poorest socioeconomic position was 1721 kcals/AFE/day in urban residences, and 1240 kcals/AFE/day in rural residences. In Nigeria, the median apparent energy intake for the poorest socioeconomic position was 1456 kcals/AFE/day in urban residences and 1327 kcals/AFE/day in rural residences. These low energy intake estimates are not plausible considering that they are far below the minimum quantities necessary for human survival, which suggests that there may be a bias leading to underestimation for these poorest populations. Potential sources of this bias for these poorest populations are numerous, including respondent bias if respondents believe they will receive food or financial aid if reporting low intake, social desirability bias resulting in the omission of 'unhealthy' foods, or differential response bias resulting from fatigue from the time-consuming survey questionnaires (especially if these populations have lower educational attainment).

For per capita vitamin A supply, in both countries, estimates were higher in urban compared to rural residences, and increased incrementally as socioeconomic position increased. The median quantity consumed for the main sources for vitamin A in the diet (i.e., dark green leafy vegetables, orange-fleshed fruits/vegetables, animal-sourced foods) reflected a similar pattern between rural/urban residences and between socioeconomic positions (Table 5.8). Fruit consumption quantity median was zero in the poorest populations in both Malawi (urban and rural) and Nigeria (only rural), which calls to question whether there is an underlying bias that results in underestimating the consumption of fruits for poorest populations. This potential bias may have an impact on overall estimates of vitamin A apparent inadequacy, where the model estimated a high national level prevalence in Malawi (75%) and Nigeria (67%). Considering that sources of dietary vitamin A are concentrated in selected food items, an underestimation in one of these sources has the potential to bias overall apparent intake estimates.

For zinc, per capita zinc supply in Malawi was greater in urban residences compared to rural, where in Nigeria urban residences reported lower supply compared to rural. In both settings, cereals/grains are the largest dietary contributions to zinc supply, where Table 5.8 demonstrates lower quantities of cereals/grains consumed compared to rural residences (likely due to omission of FAFH for cereals/grains).

Table 5.7 Median (IQR) per capita energy (kcals/AFE/day), vitamin A (μg retinol activity equivalent/AFE/day), and zinc (mg/AFE/day) supply by different sub-populations in Malawi and Nigeria.

Population	Energy	Vitamin A	Zinc
Malawi (total)	**2112 (1367)**	**224 (402)**	**8.3 (5.9)**
Urban	**2544 (1499)**	**333 (422)**	**9.3 (5.7)**
Poorest	1721 (759)	190 (295)	7.1 (4.3)
Poor	2201 (983)	273 (417)	8.1 (5.1)
Neither	2597 (976)	307 (319)	9.2 (4.9)
Wealthy	3003 (1334)	387 (402)	10.3 (5.7)
Wealthiest	3591 (1485)	523 (448)	12.4 (6.2)
Rural	**2017 (1310)**	**200 (379)**	**8.0 (5.8)**
Poorest	1240 (667)	103 (187)	5.6 (3.7)
Poor	1718 (778)	151 (269)	7.2 (4.8)
Neither	2015 (965)	198 (349)	8.2 (5.4)
Wealthy	2463 (1136)	257 (462)	9.2 (6.3)
Wealthiest	3086 (1538)	363 (588)	11.3 (7.6)
Nigeria (total)	**1985 (1286)**	**659 (543)**	**9.1 (7.5)**
Urban	**1935 (1170)**	**727 (569)**	**8.3 (6.0)**
Poorest	1456 (770)	487 (327)	6.5 (4.5)
Poor	1770 (887)	643 (390)	7.6 (5.0)
Neither	1984 (997)	748 (485)	8.3 (5.1)
Wealthy	2151 (1162)	858 (590)	9.4 (6.0)
Wealthiest	2518 (1590)	1068 (911)	10.4 (7.4)
Rural	**2014 (1343)**	**631 (528)**	**9.6 (8.3)**
Poorest	1327 (806)	373 (290)	6.6 (5.6)
Poor	1811 (1045)	524 (331)	9.1 (7.5)
Neither	2037 (1108)	639 (398)	10.0 (7.9)
Wealthy	2294 (1281)	777 (489)	10.9 (8.8)
Wealthiest	2774 (1643)	1093 (891)	12.3 (9.6)

Table 5.8. Median (IQR) apparent consumption in grams/AFE/day of food groups (i.e., cereals/grains, roots/tubers, nuts/pulses, vegetables, fruits, animal sourced foods) by different sub-populations in Malawi and Nigeria.

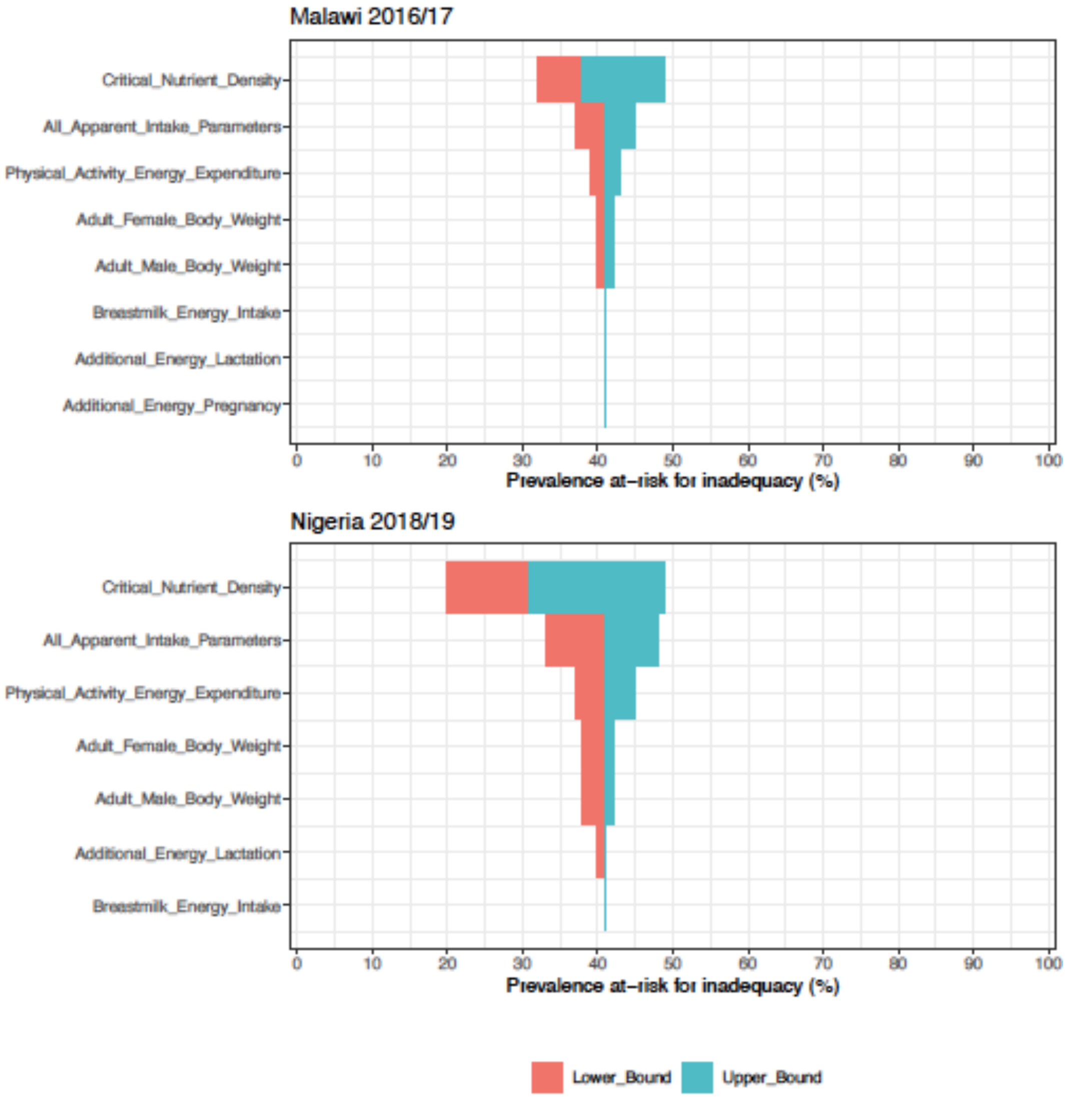
Population	Cereals/grains	Roots/tubers	Nuts/ pulses	Vegetables	Fruits	Animal sourced foods
Malawi (total)	**422 (302)**	**37 (114)**	**25 (50)**	**94 (128)**	**7 (46)**	**15 (43)**
Urban	**447 (292)**	**90 (135)**	**30 (43)**	**134 (125)**	**31 (71)**	**53 (80)**
Poorest	346 (194)	38 (90)	17 (28)	84 (80)	0 (28)	15 (24)
Poor	412 (248)	75 (104)	28 (34)	115 (94)	23 (52)	32 (40)
Neither	448 (260)	93 (115)	31 (41)	131 (112)	34 (52)	55 (52)
Wealthy	515 (295)	115 (139)	40 (54)	163 (125)	39 (62)	86 (68)
Wealthiest	579 (359)	147 (178)	41 (58)	194 (155)	77 (91)	132 (97)
Rural	**416 (303)**	**21 (97)**	**24 (52)**	**85 (123)**	**0 (39)**	**10 (32)**
Poorest	287 (184)	0 (29)	6 (24)	48 (53)	0 (11)	2 (6)
Poor	375 (227)	0 (62)	20 (39)	67 (82)	0 (25)	5 (14)
Neither	425 (273)	20 (85)	26 (46)	86 (112)	0 (35)	9 (23)
Wealthy	495 (325)	48 (128)	35 (58)	109 (141)	11 (47)	20 (38)
Wealthiest	588 (369)	85 (181)	47 (73)	143 (180)	28 (78)	53 (71)
Nigeria (total)	**219 (245)**	**210 (381)**	**40 (46)**	**81 (84)**	**64 (148)**	**47 (65)**
Urban	**195 (178)**	**224 (302)**	**43 (44)**	**100 (92)**	**84 (143)**	**58 (64)**
Poorest	197 (214)	103 (217)	29 (30)	60 (48)	35 (85)	25 (30)
Poor	190 (176)	217 (275)	40 (36)	87 (61)	64 (99)	44 (39)
Neither	182 (163)	250 (282)	46 (39)	105 (72)	83 (122)	61 (47)
Wealthy	198 (160)	269 (307)	50 (50)	130 (97)	115 (149)	80 (58)
Wealthiest	217 (185)	292 (325)	55 (67)	158 (136)	173 (247)	109 (101)
Rural	**233 (281)**	**201 (422)**	**39 (46)**	**74 (41)**	**55 (138)**	**43 (24)**
Poorest	234 (245)	28 (179)	20 (31)	38 (38)	0 (37)	14 (29)
Poor	275 (337)	120 (302)	33 (34)	57 (46)	35 (86)	29 (38)
Neither	250 (330)	214 (382)	40 (40)	76 (59)	59 (117)	42 (46)
Wealthy	208 (269)	302 (465)	50 (48)	95 (71)	93 (143)	59 (55)
Wealthiest	214 (217)	390 (522)	66 (69)	142 (122)	152 (221)	101 (100)

One-way sensitivity analysis

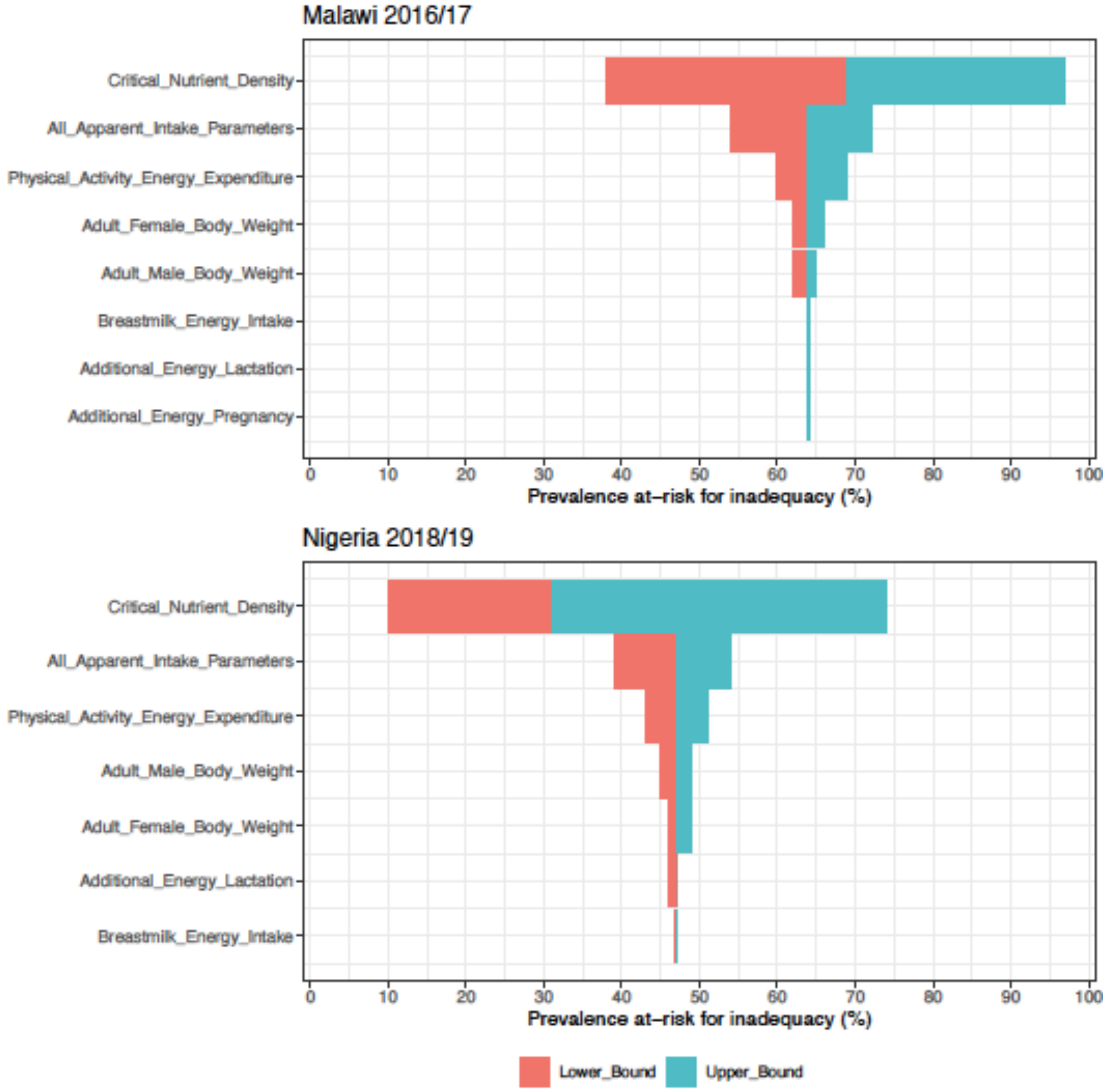
The results of the one-way sensitivity analysis for each metric's parameter assumptions are presented for vitamin A (Figure 5.1A) and zinc (Figure 5.1B). In all countries and for both micronutrients, the nutrient density metric was most sensitive to the assumed estimated daily energy requirements. Estimates of the prevalence of the population at-risk was more stable to parameter variations using the apparent intake metric compared to the nutrient density metric. Prevalence estimates using the apparent intake approach were not sensitive to variations in male/female body weight, energy contributions from breastmilk for children under two years old, and additional energy requirements for lactating or pregnant women. Sensitivity of vitamin A estimates from unfortified red palm oil contributions are presented for lower bound estimates in Table 5.9 and upper bound estimates in Table 5.10.

Figure 5.1 *One-way sensitivity analysis tornado diagrams of prevalence of population at-risk for inadequate (A) vitamin A and (B) zinc intake in Malawi and Nigeria.*

A.



B.



Malawi 2016/17
Critical_Nutrient_Density
All_Apparent_Intake_Parameters
Physical_Activity_Energy_Expenditure
Adult_Female_Body_Weight
Adult_Male_Body_Weight
Breastmilk_Energy_Intake
Additional_Energy_Lactation
Additional_Energy_Pregnancy
0 10 20 30 40 50 60 70 80 90 100
Prevalence at–risk for inadequacy (%)
Nigeria 2018/19
Critical_Nutrient_Density
All_Apparent_Intake_Parameters
Physical_Activity_Energy_Expenditure
Adult_Male_Body_Weight
Adult_Female_Body_Weight
Additional_Energy_Lactation
Breastmilk_Energy_Intake
0 10 20 30 40 50 60 70 80 90 100
Prevalence at–risk for inadequacy (%)
Lower_Bound
Upper_Bound

Table 5.9 *Prevalence of population in Nigeria at-risk for inadequate vitamin A (retinol activity equivalent) intake assuming all palm oil is unrefined red oil with 0% vitamin A retention using the nutrient density approach and the apparent intake approach per adult female equivalent (AFE) by place of residence and socioeconomic position (SEP).*

0-19%	20-39%	40-59%	60-79%	80-100%

Population	Households, n	No fortification		Fortification	
		Nutrient density	Apparent intake (AFE)	Nutrient density	Apparent intake (AFE)
National total (Vitamin A)	**22,110**	**88**	**88**	**64**	**68**
Rural	**15,302**	**87**	**87**	**71**	**73**
Lowest SEP	3061	93	99	87	98
Lower Middle SEP	3061	90	97	81	92
Middle SEP	3060	89	94	75	82
Higher Middle SEP	3060	86	86	69	66
Highest SEP	3060	80	66	50	37
Urban	**6808**	**89**	**88**	**54**	**62**
Lowest SEP	1362	93	99	76	94
Lower Middle SEP	1362	91	97	68	82
Middle SEP	1362	89	92	55	67
Higher Middle SEP	1361	88	87	47	53
Highest SEP	1361	86	74	34	31

Table 5.10 *Prevalence of population in Nigeria at-risk for inadequate vitamin A (retinol activity equivalent) intake assuming all palm oil is unrefined red oil with 100% vitamin A retention using the nutrient density approach and the apparent intake approach per adult female equivalent (AFE) by place of residence and socioeconomic position (SEP).*

0-19%	20-39%	40-59%	60-79%	80-100%

Population	Households, n	No fortification		Fortification	
		Nutrient density	Apparent intake (AFE)	Nutrient density	Apparent intake (AFE)
National total (Vitamin A)	**22,110**	**8**	**10**	**5**	**7**
Rural	**15,302**	**9**	**11**	**6**	**8**
Lowest SEP	3061	19	29	16	23
Lower Middle SEP	3061	11	11	7	8
Middle SEP	3060	8	7	5	5
Higher Middle SEP	3060	6	5	4	3
Highest SEP	3060	7	6	3	5
Urban	**6808**	**7**	**9**	**2**	**6**
Lowest SEP	1362	8	17	5	11
Lower Middle SEP	1362	4	7	1	3
Middle SEP	1362	5	6	1	3
Higher Middle SEP	1361	3	4	1	2
Highest SEP	1361	12	14	3	9

5.4 Discussion

Policies and programs that leverage existing food systems to deliver additional micronutrients through the diet require careful design, monitoring, and evaluation at sub-national scales to ensure equitable benefit to populations with the greatest risks for inadequate micronutrient intakes. This study suggests that when using HCES data to estimate prevalence of the population at-risk for inadequate micronutrient intake, the nutrient density and apparent intake metrics contribute different kinds of information to characterize and compare dietary risks between sub-populations. These metrics pose opportunities but present risks due to bias from the underlying data, so this information must be used carefully and critiqued frequently for responsible translation into policy guidance.

Nutrient density is used to evaluate diet quality, expressed as the ratio between micronutrients and energy provided by the diet [23]. A diet that meets the Critical Nutrient Density, depending on the nutrient reference value used, can help monitor whether the requisite amount of a nutrient of interest is met when energy needs are met [13]. Representing micronutrient supply per unit energy poses advantages as estimates are maintained at the household level (avoiding intrahousehold distribution assumptions in calculation) and provides unique insights about the micronutrient quality of the diet. However, when using HCES to assess nutrient density, this study found that nutrient density posed risks due to compounding bias from household micronutrient supply error and energy supply error. This is important as the differential bias for micronutrient supply estimates may differ in magnitude compared to the bias when estimating energy supply[10], so interpreting household nutrient density in relation to these differential biases becomes challenging. Also, this risk for bias is notable because our sensitivity analyses indicated that prevalence at-risk is sensitive to the position of the critical nutrient density threshold, so variability in nutrient density measures due to bias may affect the prevalence at-risk.

Nutrient density should be carefully interpreted since it assumes that populations at low risk for inadequate micronutrient intakes have adequate energy intake, which may not be the case for some populations. Our analysis found that prevalence of the population that lacked a vitamin A or zinc dense diet was more similar between different socioeconomic positions compared to inadequate apparent intake, where apparent inadequacy was much higher in rural populations of low socioeconomic position due to lower per capita energy intake in these populations [17]. These populations of lower socioeconomic positions had very low apparent energy intakes (~1400 kcals/AFE/day) which suggests that food consumption may have been underestimated. For the model in Nigeria, where the poorest urban regions had the lowest apparent energy intakes, underestimates may be due to omitted FAFH where consumption from restaurants and vendors may be more common[28]. While in some of these subpopulations low energy intake may actually be a problem due to food insecurity, further research is necessary to confirm these findings with other indicators of food insecurity (e.g., food consumption scores, reduced coping strategy index) or chronic hunger (e.g., wasting, low BMI).

Evaluating household diets only using the apparent intake approach is a more common method to identify populations at-risk for inadequate micronutrient intake using HCES [10]. While assumptions defining the intrahousehold distribution of foods to determine apparent intakes have not been consistent in published literature, this study found that variations in selected assumptions (e.g., defining body weights or pregnancy/lactation status for defining household member energy requirements) had little effect on the prevalence of apparent inadequacy. However, the greatest risk for bias in this approach is due to errors in the quantity of foods recalled and the ability to accurately match the predefined food items with nutrient components from food composition databases. For food quantities, the risk of bias assessment demonstrated that some food items for some populations were greatly overestimated (e.g., cereals/grains in wealthiest populations) where there were greater risks for underestimation in other populations (e.g., poorest populations reporting low overall apparent energy intake, zero fruit consumption, and zero root/tuber consumption). For food composition matching, there is potential for apparent intake underestimation, particularly micronutrients that are sourced from very few nutrient dense food items that are omitted due to methodological reasons (e.g., for vitamin A, animal liver are not explicitly included in the food list, unrefined red palm oil is not well defined, seasonal vitamin A-rich fruits may be omitted if consumed away from home). Some of these results are not plausible when compared to minimum requirements necessary for human survival, so results from derived using this approach will require a very critical assessment to ensure that these biases are integrated into the overall interpretation of results.

Other studies have also reported that HCES food consumption data are subject to error when recalling food quantities, including over- or under-estimating household food consumption or foods consumed episodically or in small quantities [12,29]. In addition, using HCES data to estimate food consumption and micronutrient apparent intake according to relative energy requirements may be particularly imprecise for young children [12,30] and underestimated for women [29] depending on the context. When using nutrient density, the effect of overestimates in the household micronutrient supply may be reduced by equal overestimates in the household energy supply, although further research is required to understand if micronutrient dense foods are equally overestimated as foods that contribute high proportions of energy to the diet (as the results in the risk for bias assessment suggests). In addition, while nutrient density may reduce the effect of recall error, the metric provides no insights into how nutrient density may vary between household members, especially if certain micronutrient dense food items and fortification vehicles are disproportionately distributed to some household members over others. Additional research that includes the collection of both household dietary data and individual dietary data of members within the same household could help users of HCES data understand whether there is variation in the consumption of different food items between household members, and how to better inform micronutrient interventions so that they can adequately increase micronutrient intakes for demographics with the greatest micronutrient needs.

Considering these factors, the use of these metrics must be interpreted with caution when evaluating the potential contributions of micronutrient interventions, especially for demographic groups with higher relative micronutrient needs. Micronutrient interventions, such as large-scale food fortification, should be equitably designed to fill nutrient gaps of populations with the greatest needs (i.e., selecting fortification vehicles that can benefit demographics who have higher micronutrient requirements and/or lower nutrient dense food consumption, such as women and children) [31]. Relying on apparent intake intrahousehold distribution assumptions when identifying potential food vehicles may obscure these equity considerations. Considering the aim of micronutrient interventions is often to enrich existing diets with additional vitamins and minerals without providing additional energy (e.g., food fortification, biofortification, agronomic biofortification), controlling for variations in energy intake using nutrient density could provide insights into whether or not these interventions can improve the quality of the diet if the quantity of food consumed remains constant. More research to understand variation in consumption of fortifiable food vehicles and nutrient-dense foods between sex and age in different geographic contexts is necessary to inform the equitable design of micronutrient policies and programs.

The availability, scope, and size of HCES data presents an opportunity to evaluate the micronutrient adequacy of diets and characterise vulnerable sub-populations within countries identified to have the greatest risks. While analyses of HCES data can be compelling when used to understand a particular policy question, this study suggests that there are risks for bias that must be taken into consideration when drawing conclusions from these data. Population micronutrient assessment involves using several types of data each providing different perspectives and each carrying their own risks for biases in their results (e.g., dietary assessment via HCES[7], dietary assessment via individual quantitative intake surveys[8], biological assessment via biomarkers[32], anthropometric assessment[33]). Due to the variety of different perspectives each type of data presents, coupled with the biases in these results that are unique to each approach, future research understanding how to harmonise various results from different types of data from the same setting is needed.

This study had several strengths. This analysis was conducted using HCES data from two different countries revealing potential variations when interpreting these HCES metrics in different contexts. In addition, the inclusion of a sensitivity analysis and risk for bias analysis in the study's design provides guidance for the interpretation of metrics and highlights vulnerabilities in uncertainties that are implicit in the metrics. This study also had limitations. First, when defining populations at-risk we dichotomously categorised populations based on whether they were above or below the adequacy threshold, where defining populations continuously based on their magnitude away from the adequacy threshold could have better characterised the scale of the vulnerability. Second, our understanding of the differential bias between apparent energy intake and apparent micronutrient intake was based off of a systematic review identifying very few studies which attempted to quantify this bias[10]. More research is necessary to quantify the bias between energy and micronutrient apparent intakes from diverse country contexts to better assess the validity of the nutrient density metric. Third, ambiguous classification of foods listed on the questionnaire required additional assumptions when matching to food composition data and the sensitivity of the model outputs to food composition data was not explored outside of the retention of vitamin A in red palm oil in Nigeria. Fourth, this analysis only used data from two countries in sub-Saharan Africa. Future research using HCES data from other contexts, especially in Asia and Latin America, is recommended.

In conclusion, HCES data have the potential to provide valuable insights about diets across populations, but metrics must be carefully constructed and interpreted to recognizes the specific nuances and limitations implicit in the underlying data and the metrics themselves. Due to the various kinds of micronutrient assessment data, each with their own limitations, evaluating the micronutrient status of populations remains a challenging, yet necessary exercise to help inform micronutrient policy and programs. This analysis provides guidance on the different HCES metrics that can be used when conducting micronutrient analyses, how they could complement one another, and what risks they present due to various uncertainties in the underlying data. While the role of HCES data for informing micronutrient policy and programs is becoming more clear, further research is necessary to understand how these results can be combined with results from other population micronutrient assessment data to most coherently guide decision-making for micronutrient policies and programs.

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CHAPTER 6

Modelling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys

CHAPTER SUMMARY

Drawing from the framework presented in Chapter 5 that was developed to guide the use of HCES data to assess apparent micronutrient adequacy of diets, this chapter presents an application of the proposed HCES metrics and models to inform pressing national micronutrient policy discussions in Malawi. In early 2020, the national government led discussions about the nation's overall micronutrient strategy considering recent evidence, where engaged stakeholders questioned the role of large-scale food fortification for meeting micronutrient requirements. The aim of this analysis was to estimate the potential contributions of industrially fortified oil, sugar, and wheat flour towards meeting dietary micronutrient requirements in Malawi using the HCES mathematical modelling framework. The outputs of this original research article include an assessment of the coverage and apparent consumption quantity of the three fortification vehicles, the combined potential contributions from these fortified vehicles for meeting requirements for nine micronutrients, and stratified analyses for sub-groups at increased risk for inadequate intake. This original research article demonstrates the practicality of using HCES data as a cheap, rapidly accessible resource to inform micronutrient policy decision-making in contexts where they are available. The published original research article is subsequently included in this chapter and supplementary material referenced in this work can be found in Appendix IV.

5.1 Chapter Preamble

From 18-19 February 2020 in Lilongwe, the Government of Malawi led the Policy Advisory Team Workshop on Vitamin A Programmes in Malawi chaired by the Director of Nutrition, HIV, and AIDS (Figure 6.0). The government invited an international team of technical advisors from the Global Alliance for Vitamin A (GAVA) and members of the MAPS team to present the most recent available vitamin A evidence from Malawi. The objectives of the workshop were (1) to review emerging evidence on vitamin A in Malawi, (2) to discuss implications of the current vitamin A evidence in Malawi, and (3) to understand the global decision-making framework for vitamin A programmes and implications for Malawi. Technical advisors presented emerging evidence on the vitamin A biomarker analysis from the Malawi Micronutrient Survey 2015-16 and vitamin A dietary supply analysis using previously prepared data from the Third Integrated Household Survey (IHS3) of Malawi. The presented evidence was contextualised using the GAVA decision-making framework to guide potential policy decision-making in response to this evidence. These discussions generated support for additional research that aimed to analyse the more recent Fourth Integrated Household Survey (IHS4) of Malawi and to model the potential contributions of Malawi's mandatory large-scale vitamin A food fortification programme.

This led to a collaboration between the MAPS project and partners at USAID and USAID-Advancing Nutrition to conduct a secondary data analysis of the Malawi Integrated Household Survey data and modelling the potential contributions from large-scale food fortification. The following original research article is a primary output of this collaboration.

Government of Malawi

POLICY ADVISORY TEAM WORKSHOP ON VITAMIN A PROGRAMS IN MALAWI

FEBRUARY 18 and 19, 2020

Chair: Theresa Banda

Workshop Objectives:

- Review emerging evidence on Vitamin A in Malawi
- To discuss implications of the current Vitamin A evidence in Malawi
- Understand the global decision- making framework for Vitamin A programs and implications for Malawi

Time	Activity	Presenter
Tuesday,18th February		
8:30 – 8:45	Registration	Secretary -DNHA
8.45 – 9.00	Welcome and introductions	DNHA
9:00 – 9:15	Objectives and Agenda for the work shop	DNHA
9:15-9:20	Global Alliance for Vitamin A (GAVA) background	Alison Greig- GAVA
9:20-9:50	Nutrition Landscape in Malawi and Historical overview of VAD, "enabling factors for change and challenges"	Alex Kalimbira
9:50-10:00	Overview of the Vitamin A Addendum	Maria Elena Jefferds-CDC
10:00-10:30	Health break	
10:30-11:00	WHO Guidance - Indicators for Assessing VAD	Susan Kambale- WHO
11:00-11:30	Vitamin A status indicators in Malawi	Nicole Ford- CDC
11:30-12:10	Vitamin A analysis results and interpretation including new results Q & A (10 mins)	Nicole Ford (CDC) & Sherry- University of Wisconsin
12:10 - 13:00	Plenary Discussion on biomarker data	Theresa Banda & Maria Elena Jefferds
13:00-14:00	Lunch Break	
14:00-14:30	Assessing Vitamin A intake data sources for decision making	Katie Adams -UC Davis
14:30-15:00	Vitamin A dietary supply estimates for Malawi	Louise Ander -MAPS Team
15:00-15:15	Health Break	
15:15-15:30	Conclusions of the dietary data	Omar Dary-USAID
15:30-16:15	Plenary discussion on Vitamin A intake	Theresa Banda & Omar Dary
16:15-16:30	Day 1 Wrap Up	

Day 2: Wednesday, 19th February		
8:30-9:00	Summary of Day 1	Kuda Chimanya-UNICEF
9:00-9:30	Applying data to the decision-making framework for Malawi context	Alison Greig-Nutrition International
9:30-10:00	Next Steps & Plenary	Theresa Banda & Omar Dary
10:00-10:30	Health Break	
10:30-10:45	GAVA /Key Considerations for next steps	Alison Greig-Nutrition International
10:45-11:45	What are the policy implications for Malawi and next steps	Director, DNHA/ Chair
11:45-12:00	Vote of thanks Meeting Close	DNHA
12:00	Lunch & Departure	

Figure 6.0 Agenda for the Policy Advisory Team workshop on vitamin A programmes in Malawi (18-19 February 2020)

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed for each research paper included within a thesis.

SECTION A – Student Details

Student ID Number	1600604	Title	Mr.
First Name(s)	Kevin Michael		
Surname/Family Name	Tang		
Thesis Title	Micronutrient adequacy of diets and contributions of large-scale interventions: secondary analyses of household surveys		
Primary Supervisor	Dr. Edward Joy		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Annals of the New York Academy of Sciences		
When was the work published?	28 September 2021		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	N/A		
Have you retained the copyright for the work?*	Yes	Was the work subject to academic peer review?	Yes

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	
Please list the paper's authors in the intended authorship order:	
Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	KT, MW, OD, ELA, and EJMJ set up the collaborative network. KT, OD, and EJMJ designed the study. KT, KPA, and BL cleaned and transformed the food consumption data. ELF and LSDLA compiled the food composition data matches. OD developed the food fortification scenarios. KT, KPA, ELF, MW, JY, OD, AAK, SP, ELA, and EJMJ determined the adult female equivalent factor parameters. KT and BC defined the analysis for subpopulations. KT conducted the statistical analysis. KT, KPA and EJMJ led the interpretation of the results and drafting the manuscript. All authors critically reviewed and approved the final manuscript. KT is responsible for the integrity of the data analysed.

SECTION E

Student Signature	Kevin M Tang
Date	23/09/2022

Supervisor Signature	Edward JM Joy
Date	23/09/2022

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Original Article

Modeling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys

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Large-scale food fortification may be a cost-effective intervention to increase micronutrient supplies in the food system when implemented under appropriate conditions, yet it is unclear if current strategies can equitably benefit populations with the greatest micronutrient needs. This study developed a mathematical modeling framework for comparing fortification scenarios across different contexts. It was applied to model the potential contributions of three fortification vehicles (oil, sugar, and wheat flour) toward meeting dietary micronutrient requirements in Malawi through secondary data analyses of a Household Consumption and Expenditure Survey. We estimated fortification vehicle coverage, micronutrient density of the diet, and apparent intake of nonpregnant, nonlactating women for nine different micronutrients, under three food fortification scenarios and stratified by subpopulations across seasons. Oil and sugar had high coverage and apparent consumption that, when combined, were predicted to improve the vitamin A adequacy of the diet. Wheat flour contributed little to estimated dietary micronutrient supplies due to low apparent consumption. Potential contributions of all fortification vehicles were low in rural populations of the lowest socioeconomic position. While the model predicted large-scale food fortification would contribute to reducing vitamin A inadequacies, other interventions are necessary to meet other micronutrient requirements, especially for the rural poor.

Keywords: large-scale food fortification; HCES; micronutrient; inadequacy; equity; Malawi

Introduction

Micronutrient undernutrition burdens billions of people worldwide, disproportionately affecting the world's poorest countries and populations.[1] Potential risks of micronutrient deficiencies can be characterized by estimating the prevalence of inadequate dietary intake, where individuals do not consume adequate quantities of bioavailable micronutrients to meet their physiological requirements.[2] The global approach to estimating and understanding burdens of micronutrient undernutrition requires a

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combination of data types,[3,4] and dietary data play an essential role in identifying interventions that could provide sufficient additional micronutrients to populations with the greatest needs.[5] The design of these interventions can be informed using mathematical models that combine food consumption data with food composition data to estimate total micronutrient contributions from the overall diet and the additional contribution of micronutrient interventions.[1,6,7]

One intervention that can increase dietary intake of micronutrients broadly across populations is large-scale food fortification, where micronutrients are added to industrially processed, commonly consumed food items (also referred to as "fortification vehicles") to increase each vehicle's micronutrient content.[8] Large-scale food fortification can be a cost-effective intervention to increase the dietary supply of micronutrients in the food system.[9] Mandatory fortification of food vehicles has been adopted into national policy by over 100 countries, with the national strategy depending on country context.[10] Well-implemented programs benefit from strong partnerships between the public and private sectors and guidance from the scientific community to maximize program contributions to improve micronutrient-inadequate diets.

Household Consumption and Expenditure Surveys (HCESs) are a family of multicomponent socioeconomic surveys that collect detailed food consumption data, which, when combined with food composition data, can be used to estimate the household dietary supply of micronutrients.[11] Before they can be used to assess the micronutrient adequacy of population diets, HCES food consumption data require transformation into usable metrics. One metric, the apparent intake approach, individualizes household micronutrient supplies by distributing micronutrients among household members in proportion to each individual's energy requirements.[12] Micronutrient apparent intake can be standardized in reference to any individual, most commonly to adult males expressed as *adult male equivalents* (AME), but other household members can be set as the standardized reference, including nonpregnant, nonlactating, and premenopausal women expressed as *adult female equivalents* (AFE). Another metric, the micronutrient density approach, assesses the quality of the overall diet by estimating the total household micronutrient supply per unit of energy.[13] Additional metrics, including fortification vehicle coverage and quantity of the vehicle consumed, can provide insights into the potential contribution of large-scale food fortification toward meeting country's micronutrient needs.[14]

In Malawi, the diets of its near 19 million inhabitants depend on cereals, roots/tubers, and vegetables to supply a large proportion of micronutrient needs.[15] Low consumption of micronutrient dense foods (e.g., animal-sourced foods) and seasonal variation in the availability of certain fruits, vegetables, and root/tubers suggest that risks for dietary micronutrient inadequacy may be high and fluctuate throughout the year.[6] The Malawian government has enacted the mandatory fortification of several fortification vehicles, which, when implemented together, are intended to fill micronutrient gaps throughout the population resulting from poor quality diets. This includes fortifying oil and sugar with vitamin A and wheat flour with vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12}, iron, and zinc, with fortification occurring at large-scale processing facilities.[16] Over the past two decades, in parallel to the implementation of the number of micronutrient interventions,[17] the prevalence of deficiencies of some micronutrients has substantially declined in Malawi.[18] However, it is unknown how much can be attributable to large-scale food fortification and the extent to which all populations are adequately served by current policies.

This study aimed to estimate the potential contributions of vitamin A–fortified oil and sugar and fortified wheat flour (with vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12}, iron, and zinc) toward meeting dietary micronutrient requirements in Malawi using a mathematical modeling framework. The potential contribution of the large-scale food fortification programs was measured according to the following objectives:

1. Coverage and apparent consumption quantity of each fortification vehicle;
2. The potential contribution of large-scale food fortification to the micronutrient density of diets (or micronutrient supply per 1000 kcal of the population's diet), to apparent micronutrient intakes (per adult-female equivalents), and to reduce the prevalence of dietary

inadequacy among nonpregnant, nonlactating, premenopausal women;
3. Subpopulation differences in the adequacy of micronutrient density and apparent intake in urban and rural residences and between socioeconomic positions (SEPs).

Because Malawi mandates the fortification of three food vehicles with vitamin A, we estimated the potential contribution of each of the three food vehicles individually and in combination, while the potential contribution of the additional micronutrients in Malawi's wheat flour fortification standards was modeled individually. This study demonstrates the application of a mathematical modeling framework, which can be used in other country contexts, to estimate potential contributions of large-scale food fortification, provided data are available. As the nutrition landscape in Malawi evolves, findings from this study can provide data-driven inputs into policy discussions around Malawi's strategy to alleviate the burdens of micronutrient deficiencies.

Materials and methods

Model framework

The foundation for this model's framework requires data from HCES. While HCES questionnaires vary substantially between countries, this model's framework was designed to consider consistencies between HCES questionnaires from different countries so that the model can be applied in multiple contexts where HCES data are available. These similarities in HCES questionnaires include foods consumption recalled by the household over a fixed period, basic demographic data collected on each household member, and the inclusion of multiple questions to characterize an array of socioeconomic conditions.

The model in this study was based on HCES data from the Fourth Integrated Household Survey of Malawi (IHS4),[19] conducted by the National Statistics Office of Malawi with support from the World Bank's Living Standards Measurement Study (LSMS). The IHS are used by the Government of Malawi to monitor the poverty and welfare of Malawian households. The IHS4 was implemented between April 2016 and April 2017, with a single-visit 24-module questionnaire collecting data on household living standards, expenditures, and other measures of social and economic welfare. The IHS4 sampling frame was based on the 2008 Malawi Population and Housing Census and was designed to be representative at national, urban/rural, regional, and district levels. Urban strata include the four major urban areas: Lilongwe City, Blantyre City, Mzuzu City, and the Municipality of Zomba, while rural strata include all 28 districts of Malawi (including the island district of Likoma). A stratified two-stage sampling design was employed in which enumeration areas ($n = 779$) were selected at random to represent districts, with the probability of enumeration area selection proportional to size (i.e., the number of households), and 16 households were selected with equal probability from the total listing for each selected enumeration area. The final sample size was 12,447 households.

For this study, the IHS4 data were downloaded from the World Bank LSMS data portal (accessed September 28, 2020) and are used in compliance with the data access policy.[19] The IHS4 data are deidentified at the source.

Food consumption

The IHS4 included a food consumption module, in which a household member was asked to recall the quantity of foods consumed by the entire household in 7 days preceding the interview using a standardized list of 136 commonly consumed food items. The consumption quantities of each food item were reported in nonstandard units (e.g., sachets, pails, and pieces) with the help of visual aids. For this study, consumption quantities were converted to metric units, that is, kilograms. Food consumption quantities were adjusted for the nonedible portions of foods, for example, banana skins. The outlying values of consumption quantity for each food item (likely due to foods acquired in bulk or recall error[20]) were identified and replaced with the food item's median consumption quantity from the entire population. This provides a metric we refer to as *apparent consumption*.

Micronutrient composition and large-scale food fortification scenarios

This study modeled the contribution of the existing program of food fortification in Malawi, which mandates the fortification of cooking oil and sugar with vitamin A, and wheat flour with vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12}, iron, and zinc. Food consumption data were matched with food composition data to

Table 1. Parameter values for food fortification modeling (composition per 100 g of a food item)

Micronutrient	Scenario	Cooking oil	Sugar	Wheat flour
Vitamin A (μg RAE)	No fortification	0	0	0
	Status quo[a]	1000	700	80
	Improved compliance[b]	2100	1050	180
Thiamine (mg)	No fortification	–	–	0.2
	Status quo	–	–	0.5
	Improved compliance	–	–	0.8
Riboflavin (mg)	No fortification	–	–	0.1
	Status quo	–	–	0.3
	Improved compliance	–	–	0.5
Niacin (mg)	No fortification	–	–	2.4
	Status quo	–	–	4.2
	Improved compliance	–	–	6.5
Vitamin B_6 (mg)	No fortification	–	–	0.5
	Status quo	–	–	0.7
	Improved compliance	–	–	0.9
Folate (μg)	No fortification	–	–	240
	Status quo	–	–	427
	Improved compliance	–	–	648
Vitamin B_{12} (μg)	No fortification	–	–	0
	Status quo	–	–	0.6
	Improved compliance	–	–	1.3
Iron (mg)	No fortification	–	–	2.0
	Status quo	–	–	3.0
	Improved compliance	–	–	6.0
Zinc (mg)	No fortification	–	–	0.5
	Status quo	–	–	1.8
	Improved compliance	–	–	3.5

[a] On the basis of food vehicle samples collected from sentinel sites in markets throughout Malawi.
[b] On the basis of assuming industry compliance at point of fortification to meet national standards and accounting for fortificant deterioration during the time between production at the factory and preparation for consumption at the household.

estimate the household micronutrient supply of vitamin A, thiamine, riboflavin, niacin, vitamin B_6, folate, vitamin B_{12}, iron, and zinc. All food items were matched to an equivalent item from available food composition data. Data from the 2019 Malawian Food Composition Table (FCT)[21] or from other food composition studies conducted in Malawi[22] were prioritized for matching. For food items where data from Malawian sources were not available, FCTs from other eastern African countries[23–25] were used as substitutes, and where data gaps remained, regional and international food composition databases[26–28] were used. Food composition matches and references for all micronutrients and energy are available in Table S1 (online only).

Three scenarios were modeled and compared with an estimate of the potential contributions of oil, sugar, and wheat flour fortification programs to meet vitamin A needs and of wheat flour fortification to meet dietary requirements for the other eight micronutrients included in Malawi's wheat flour fortification standard (Table 1). First, the "no fortification" scenario was modeled, which assumed the food vehicles were not fortified with any micronutrients. This scenario provided estimates of the baseline (i.e., without fortification) adequacy of diets and served as a comparator to understand the potential contribution of Malawi's fortification program to improving the micronutrient adequacy of diets. Second, the "status quo" fortification scenario modeled large-scale fortification at current levels of fortification, which are below the mandated standard levels. These levels, for each food fortification vehicle, were based on the analyzed micronutrient content of fortified food samples collected at sentinel sites in markets throughout

Malawi in 2020.[29] Third, the "improved compliance" scenario was modeled, which represented a hypothetical improvement in industry compliance to the national standards guidelines on average nutrient contents at the point of fortification, and adjusted for expected losses as summarized using the Food Fortification Formulator tool[30] before preparation for consumption at home. This scenario resulted in higher micronutrient contents of each food vehicle compared with those modeled in the status quo scenario. For the status quo and improved compliance scenarios, the micronutrient composition of oil, sugar, and wheat flour was adjusted to create fortified products. The micronutrient composition of products made with wheat flour (e.g., bread, scones, and mandasi) was adjusted based on the proportional contents of wheat flour to reflect the three fortification scenarios (recipes and proportions are reported in Table S2, online only).

Data analysis

For objective 1, coverage was estimated as the percentage of households apparently consuming any quantity of the food vehicle. Apparent consumption was estimated as the quantity of each food vehicle consumed by households in grams per day, then divided by the number of AFE in each household,[12] where expressing apparent consumption per AFE allows for comparison of apparent consumption across households of varying demographic composition. This method assumes that food consumed by the household is distributed within the household proportionally according to the energy requirements of each household member, standardized to a nonpregnant, nonlactating, 18- to 29-year-old female as the reference family member for reasons detailed in the following paragraph. The data and assumptions necessary to calculate the AFE factors are presented in Table S1 (online only). Coverage and apparent consumption estimates were calculated at the national level, then stratified by administrative regions and urban versus rural residences. Urban and rural subpopulations were further stratified into five SEPs on the basis of quintiles for total annual inflation–adjusted household expenditure per capita. These quintiles differed for urban and rural subpopulations.

For objective 2, the micronutrient density of the diet was estimated as a ratio of the household micronutrient supply to the total household energy supply and expressed per 1000 kcal for all three scenarios.[13] A diet of inadequate density was defined as a household with a micronutrient density that fell below the critical nutrient density (CND) threshold,[13] which is the ratio of an adult female's harmonized average requirement (H-AR) (i.e., the average daily micronutrient intake that is estimated to meet the requirements of half of the healthy individuals and used to estimate inadequacy for populations)[31] to an adult female's daily average energy requirement assuming moderate physical activity level.[32] The nonpregnant, nonlactating 18- to 29-year-old woman was selected as the household reference as she has high micronutrient requirements relative to energy requirements compared with other household members and represents the average energy intake for the family. Therefore, if the household nutrient density was adequate to meet the micronutrient density requirements of an adult female, it is expected to meet the needs of most other household members of varying demographics. Households with micronutrient densities that fell below the CND threshold were classified as having an inadequate dietary micronutrient density. For the apparent intake approach for each micronutrient, dietary inadequacy was defined as the apparent intake per AFE below the micronutrient's H-AR for an adult female.[31] Since nonpregnant, nonlactating 18- to 29-year-old women were selected as the household reference to define the CND threshold due to higher density requirements compared with other household members, apparent intakes were expressed per AFE (rather than per AME) in order to maintain the consistency between micronutrient density and apparent intake inadequacy thresholds. Table S3 (online only) shows the CNDs and H-AR thresholds for adult females for each micronutrient used to define these two dimensions of dietary inadequacy.

For objective 3, differences in dietary inadequacy assessed using the micronutrient density and apparent intake approaches were analyzed between SEPs in urban and rural residences under all three fortification scenarios. To visualize seasonal patterns in the household micronutrient supply over time, the micronutrient density and apparent intake estimates were assessed by survey date for each subpopulation for all micronutrients using a weighted least-squares local regression ("loess") to reduce the effect of outliers.[33] Loess smoothing used quadratic

Table 2. Descriptive summary of the survey population from the Fourth Integrated Household Survey of Malawi (2016/17)

Residence	Rural					Urban					
The socioeconomic position by quintile of total annual household expenditure	Lowest	Lower-middle	Middle	Upper-middle	Highest	Lowest	Lower-middle	Middle	Upper-middle	Highest	*P* value (urban/rural)[a]
Households, *n*	2035	2035	2035	2035	2035	455	454	455	454	454	–
Anyone in household's main occupation is…											
Wage employment, %	3	6	8	10	21	29	42	51	57	72	<0.001
Household business (nonagriculture), %	8	10	12	14	20	28	43	47	43	33	<0.001
Household agriculture/farming, %	89	90	87	84	72	49	36	27	24	13	<0.001
Distance (km) to the nearest:											
Road, mean	12.5	11.5	10.9	10.9	9.7	2.8	2.3	2.8	2.4	1.6	<0.001
Agricultural market, mean	24.1	24.7	26.2	27.2	26.9	8.4	7.4	7.6	7.3	5.4	<0.001
Population center, mean	41.8	41.2	40.7	41.0	41.1	14.7	11.6	11.3	10.6	9.5	<0.001
Highest educational qualification (males)											<0.001
None, %	69	63	54	51	39	52	36	24	17	8	
Primary school, %	15	18	23	23	24	31	33	30	20	11	
Secondary school +, %	2	3	6	8	18	12	24	36	53	64	
Highest educational qualification (females)											<0.001
None, %	80	72	67	60	44	64	44	31	17	8	
Primary school, %	10	15	18	22	23	25	41	40	34	14	
Secondary school +, %	1	2	2	3	10	4	8	20	37	55	
Participate in social safety net programs											
Cash transfers, %	6	6	5	5	4	3	2	1	0	0	<0.001
Nutrition programs, %	41	39	37	35	27	27	26	21	13	3	<0.001
At least one child under 5 in household, *n*	1270	1038	904	824	602	262	229	202	145	83	
Wasted (WHZ<−2) or edematous (apparent), %[b]	11	8	9	6	8	10	6	7	5	5	<0.001
Stunted (HAZ<−2), %[b]	32	31	32	30	27	29	27	25	23	17	<0.001
Underweight (WAZ<−2), %[b]	13	11	12	8	9	8	6	8	5	5	<0.001

[a] Urban/rural differences within variables tested using Pearson's Chi-squared test for factor variables and Student's *t*-test for numeric variables.
[b] Among households *with* at least one child under 5 years.
HAZ, height-for-age Z-score; WAZ, weight-for-age Z-score; WHZ, weight-for-height Z-score.

equations to fit within each "moving window," where $\alpha = 0.75$. Seasonality curves and 95% confidence intervals were presented for each of the fortification scenarios and compared in relation to the CND for the micronutrient density seasonality curves and the H-AR for the apparent intake seasonality curves.

Data analysis was conducted in RStudio® (version 3.6.1, the R Foundation for Statistical Computing), using a variety of elements in the *tidyverse* package,[34] including *dplyr* for data cleaning and transformation and *ggplot2* for visualization. Detailed descriptions of the data cleaning and transformation procedures are available in the file Supplementary Materials (online only), and, in addition, further analysis methods and code are available upon request.

Results

Description of the population

All 12,447 households surveyed in the IHS4 were included in the analysis, where 10,175 (82%) were rural, and 2272 (18%) were urban. Characteristics of the urban, rural, and SEP subpopulations are presented in Table 2. Compared with urban households, rural households were more likely to be farmers, less likely to be in wage employment, had lower completion rates of formal education for both men and women, were more likely to participate in cash transfer and nutrition social safety net programs, and were more likely to have at least one wasted, stunted, or underweight child in the household. Differences in these characteristics were even more pronounced between rural households of the lowest and highest SEPs.

Objective 1: Fortification vehicle coverage and apparent consumption

Table 3 presents the coverage of each fortification vehicle, or the percentage of households apparently consuming any quantity of the fortification vehicles during the 7-day recall period. Nationally, 76% of households reported consuming oil, and 56% reported consuming sugar. The percent-

Table 3. Percentage of households apparently consuming any or none of the food fortification vehicles and median consumption quantity among consumers (grams per adult female equivalents per day) from the Fourth Integrated Household Survey of Malawi

	Households	Oil		Sugar		Wheat flour and products		None consumed
Population	*n*	%	Median (IQR)	%	Median (IQR)	%	Median (IQR)	%
National (total)	12,447	76	12 (5, 23)	56	28 (19, 40)	52	9 (4, 28)	17
Geography by administrative region								
North	2491	79	14 (9, 24)	66	31 (22, 45)	50	13 (5, 33)	14
Center	4220	74	9 (3, 20)	55	28 (20, 40)	55	7 (3, 28)	17
South	5736	76	13 (5, 24)	52	26 (17, 38)	50	10 (4, 27)	18
Residence and socioeconomic position (SEP) by quintile of total annual household expenditure per capita								
Rural (total)	10,175	72	10 (4, 19)	48	25 (17, 37)	44	6 (3, 16)	20
Lowest SEP	2035	44	3 (1, 8)	17	11 (6, 19)	20	2 (2, 4)	45
Lower middle SEP	2035	66	6 (2, 12)	34	18 (10, 24)	33	3 (2, 6)	25
Middle SEP	2035	75	9 (3, 15)	47	21 (14, 29)	42	4 (3, 8)	16
Upper middle SEP	2035	83	11 (5, 20)	62	26 (19, 37)	53	6 (3, 15)	10
Highest SEP	2035	91	19 (11, 33)	80	36 (26, 51)	73	16 (6, 34)	3
Urban (total)	2272	96	21 (12, 34)	92	34 (25, 48)	86	29 (14, 53)	2
Lowest SEP	455	87	9 (4, 14)	76	23 (16, 30)	64	7 (3, 18)	6
Lower middle SEP	454	97	15 (9, 23)	92	28 (22, 39)	84	19 (9, 33)	1
Middle SEP	455	98	22 (15, 31)	97	36 (27, 48)	92	29 (15, 43)	0
Upper middle SEP	454	98	26 (18, 37)	98	40 (30, 51)	95	40 (23, 62)	0
Highest SEP	454	99	39 (27, 62)	97	45 (31, 67)	94	58 (34, 87)	0

IQR, interquartile range.

age of households consuming any quantity of wheat flour or wheat flour products was 52% and varied depending on the product: 35% consumed mandasi/doughnut, 22% consumed bread, and 14% consumed buns/scones. Coverage of all fortification vehicles was lower in rural populations compared with urban populations, and coverage of oil and sugar in urban areas was nearly universal (96% and 92% of households, respectively). Coverage decreased with SEP, with the lowest coverage observed in the poorest populations in both urban and rural residences for the three fortification vehicles. In rural populations, when comparing the lowest to highest SEPs, coverage of sugar was 17% of households in the lowest quintile compared with 80% in the highest quintile, and coverage of wheat flour was 20% in the lowest quintile compared with 73% in the highest quintile. Coverage between Malawi's three administrative regions was similar, ranging between 74% and 79% for oil, 52% and 66% for sugar, and 50% and 55% for wheat flour.

Table 3 also presents the median apparent consumption of each food vehicle. Nationally, the median apparent consumption was 12 g/day per AFE for oil, 28 g/day per AFE for sugar, and 9 g/day per AFE for wheat flour. For all three vehicles, the median apparent consumption was higher among urban households than rural households. For all three food vehicles in both rural and urban residences, apparent consumption increased as the SEP increased. In rural populations: from 3 to 19 g/day per AFE for oil, from 11 to 36 g/day per AFE for sugar, and 2–16 g/day per AFE for wheat flour. In urban populations: from 9 to 39 g/day per AFE for oil, from 23 to 45 g/day per AFE for sugar, and 7–58 g/day per AFE for wheat flour. Median apparent consumption between administrative regions ranged from 9 to 14 g/day per AFE for oil, 26–31 g/day per AFE for sugar, and 7–13 g/day per AFE for wheat flour.

Objective 2: Micronutrient inadequacy

Micronutrient density percentile curves modeling the three fortification scenarios are shown in Figure 1. Under the no fortification scenario, micronutrients with a high prevalence of inadequate density (more than 75%) were vitamin A, riboflavin, and vitamin B_{12}; the moderate prevalence of inadequate density (between 50% and 75%) were niacin, iron, and zinc; and low prevalence of inadequate density (between 25% and 50%) was folate. The inadequate density of thiamine and vitamin B_6 was very low (<25%).

Under the status quo fortification scenario, only the prevalence of the inadequate density of vitamin A and folate was reduced. A reduction in the inadequate density of vitamin A (Fig. 1A) was mainly due to the combined contributions from oil and

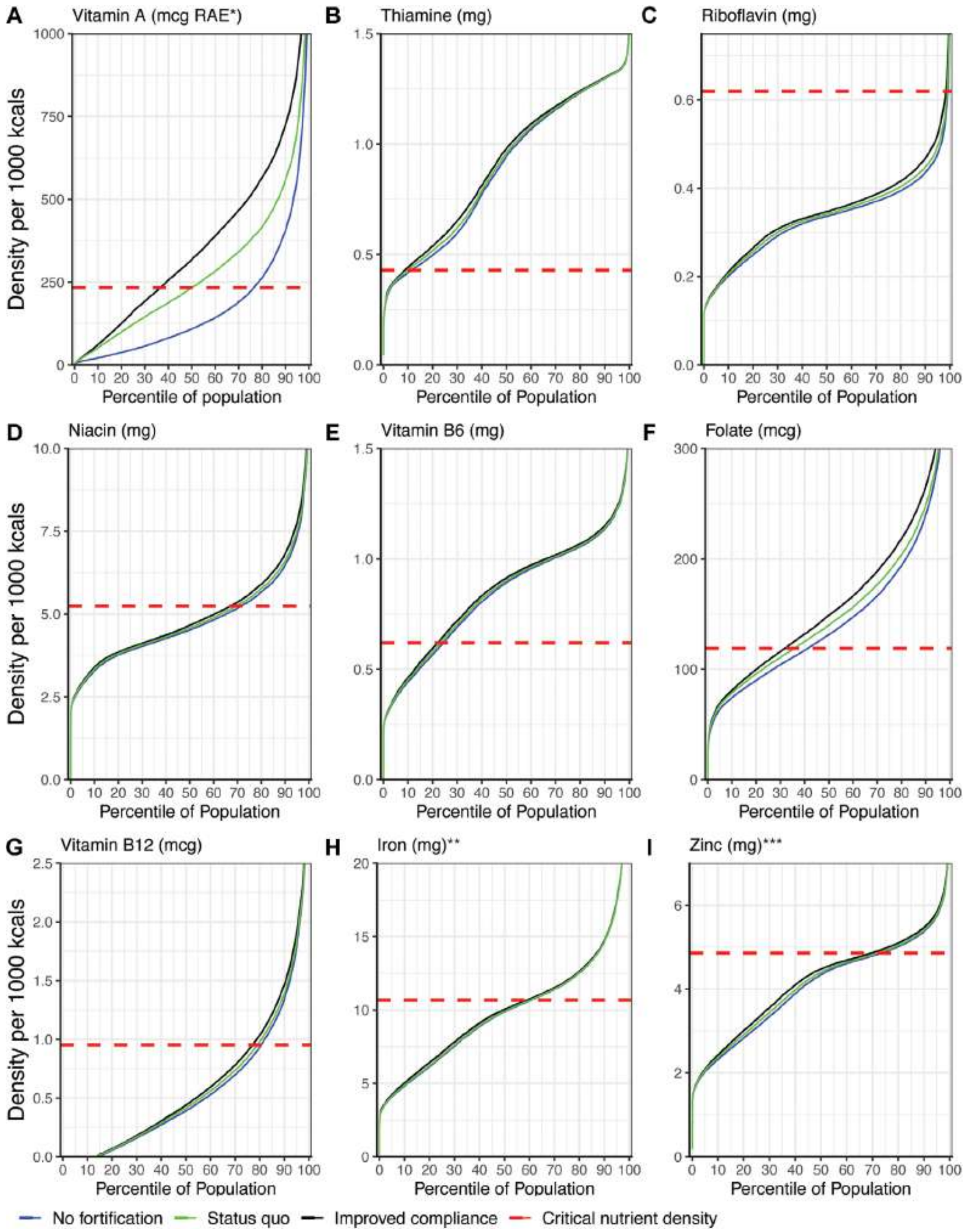

Figure 1. **Micronutrient density population percentile curves and estimates of dietary inadequacy for three fortification scenarios for (A) vitamin A, (B) thiamine, (C) riboflavin, (D) niacin, (E) vitamin B_6, (F) folate, (G) vitamin B_{12}, (H) iron, and (I) zinc. *RAE, retinol activity equivalents. **Iron inadequacy cannot be defined using the critical nutrient density cut-point method due to the nonnormal distribution of iron requirements. ***Zinc inadequacy thresholds assume low bioavailability because of a diet high in unrefined grains.**

sugar, where wheat flour also provided additional vitamin A but in negligible amounts. There was potential for further declines in the prevalence of inadequate density for vitamin A and folate if the average content of each food vehicle met the current Malawian regulations via improved compliance. Improved compliance of wheat flour fortification did not reduce the prevalence of inadequate density for all the other micronutrients due to the low consumption of wheat flour in Malawi. The results for micronutrient inadequacy estimated by apparent intake per AFE were similar to inadequate density estimates using the micronutrient density approach compared with the CND threshold, and the equivalent figures are shown in Figure 2.

Objective 3: Comparison between urban, rural, and socioeconomic strata

Figure 3 presents the vitamin A supply graphs comparing the no fortification, status quo, and improved compliance scenarios by season and disaggregated by urban, rural, and socioeconomic subpopulations. Deductions on seasonal contributions of vitamin A fortification between subpopulations were similar when comparing the micronutrient density approach (Fig. 3A) versus the apparent intake approach (Fig. 3B). Vitamin A–fortified oil and sugar had the potential to decrease vitamin A inadequacy in most strata, except rural populations of low SEP. However, populations of high SEP benefit the most from fortification because, in these populations, fortification increased the vitamin A density of the diet at greater margins compared with populations of low SEP (Fig. 3A), and fortification vehicles were consumed in higher quantities (Fig. 3B). Under the improved compliance scenario, rural populations of low SEP still had inadequate vitamin A density during seasons where vitamin A supply was the lowest despite higher fortification contents.

Apparent intake of vitamin A (Fig. 3B) under the no fortification scenario indicates that populations of low SEP in both rural and urban residences would be expected to have an inadequate apparent intake of vitamin A across seasons, mostly due to the lower apparent intakes of the fortification vehicles compared with populations of higher SEP rather than lower vitamin A density of their diets. Vitamin A contributions from oil, sugar, and, to a lesser degree, wheat flour remained consistent throughout the year, demonstrating little seasonal fluctuation. Consistent vitamin A supply across seasons from fortification vehicles contrasted the large seasonal fluctuation of vitamin A supply from the nonfortified diet, suggesting that fortified foods may be able to help fill gaps in seasonal inadequacy from natural food sources in the diet. In summary, total vitamin A apparent intake increased in all urban and rural populations of high SEP when compared with the no fortification scenario. Rural populations of low SEP saw minimal contributions from fortification under both the status quo and improved compliance scenarios.

Figure 4 shows seasonality in zinc micronutrient density (Fig. 4A) and apparent intake (Fig. 4B) in urban and rural populations across SEPs. Despite their low zinc concentration, cereals contributed the largest proportion of zinc to the total dietary supply, and micronutrient density of the diet decreased as the SEP increased. However, zinc apparent intake increased as the SEP increased, indicating that populations of higher SEP are consuming more food overall. Wheat flour was the sole fortification vehicle for zinc, and unlike the case with vitamin A, fortification did not lead to substantial changes in total dietary zinc supply, and inadequacy in the two fortification scenarios remained similar to the no fortification scenario in all groups with the exception of those of the highest SEP.

Figures S1 through S7 (online only) present seasonality plots disaggregated by urban, rural, and socioeconomic subpopulations for all other micronutrients provided via wheat flour fortification. For all micronutrients measured using both the micronutrient density and apparent intake, the no fortification, status quo, and improved compliance scenarios were similar in all subpopulations, with the exception of the urban populations of high SEP, which received marginal contributions from wheat flour fortification.

Discussion

In this paper, we present an application of a mathematical modeling framework using open-source HCES data to model the coverage, potential contributions, and equity dimensions of the fortification of oil, sugar, and wheat flour for a range of micronutrients in Malawi. Our analysis showed that oil and sugar had wide coverage (>50% of households), and fortification was predicted to reduce the prevalence of vitamin A inadequacy

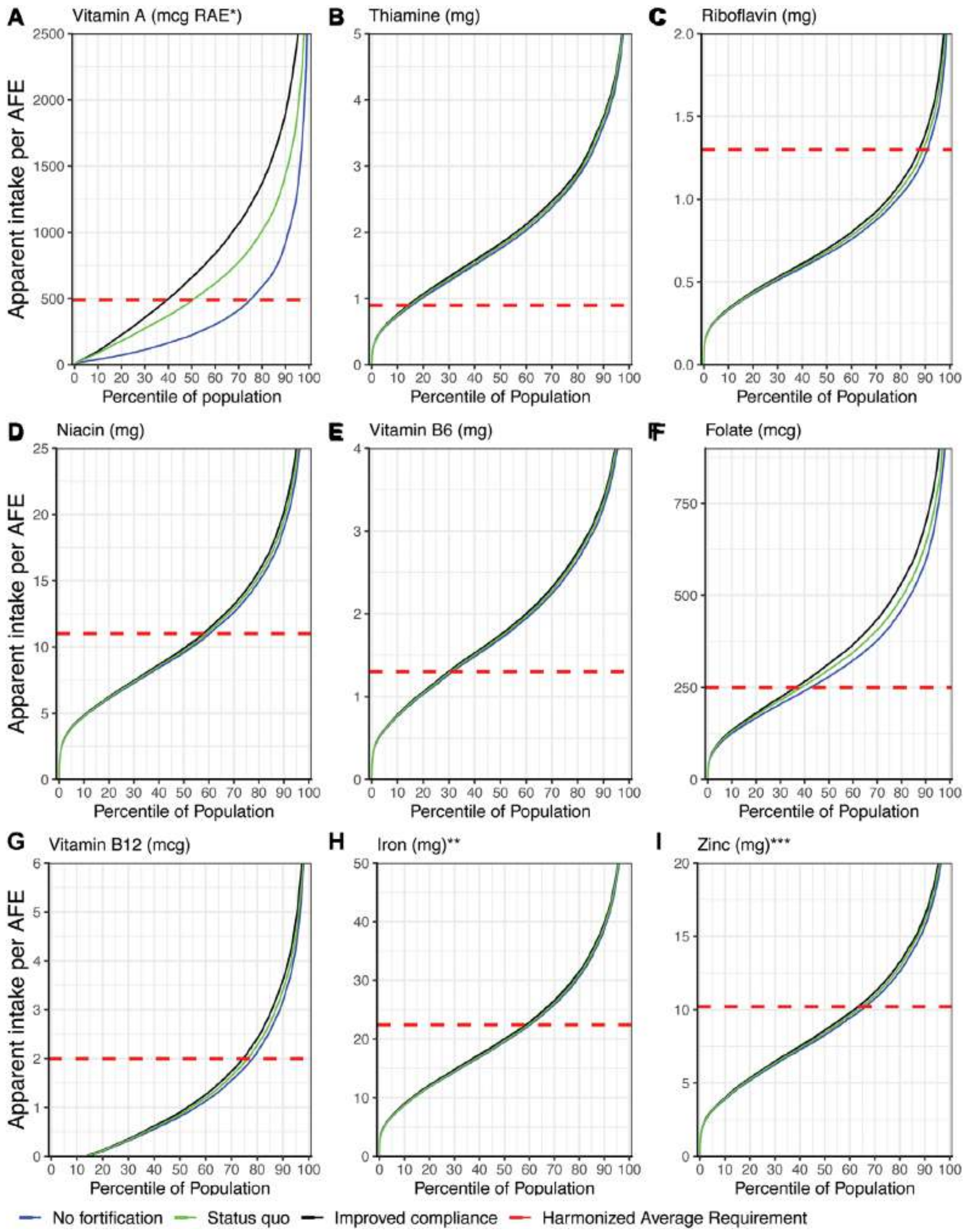

Figure 2. **Micronutrient apparent intake population percentile curves and estimates of dietary inadequacy for three fortification scenarios for (A) vitamin A, (B) thiamine, (C) riboflavin, (D) niacin, (E) vitamin B_6, (F) folate, (G) vitamin B_{12}, (H) iron, and (I) zinc. *RAE, retinol activity equivalents. **Iron inadequacy cannot be defined using the critical nutrient density cut-point method due to the nonnormal distribution of iron requirements. ***Zinc inadequacy thresholds assume low bioavailability due to a diet high in unrefined grains.**

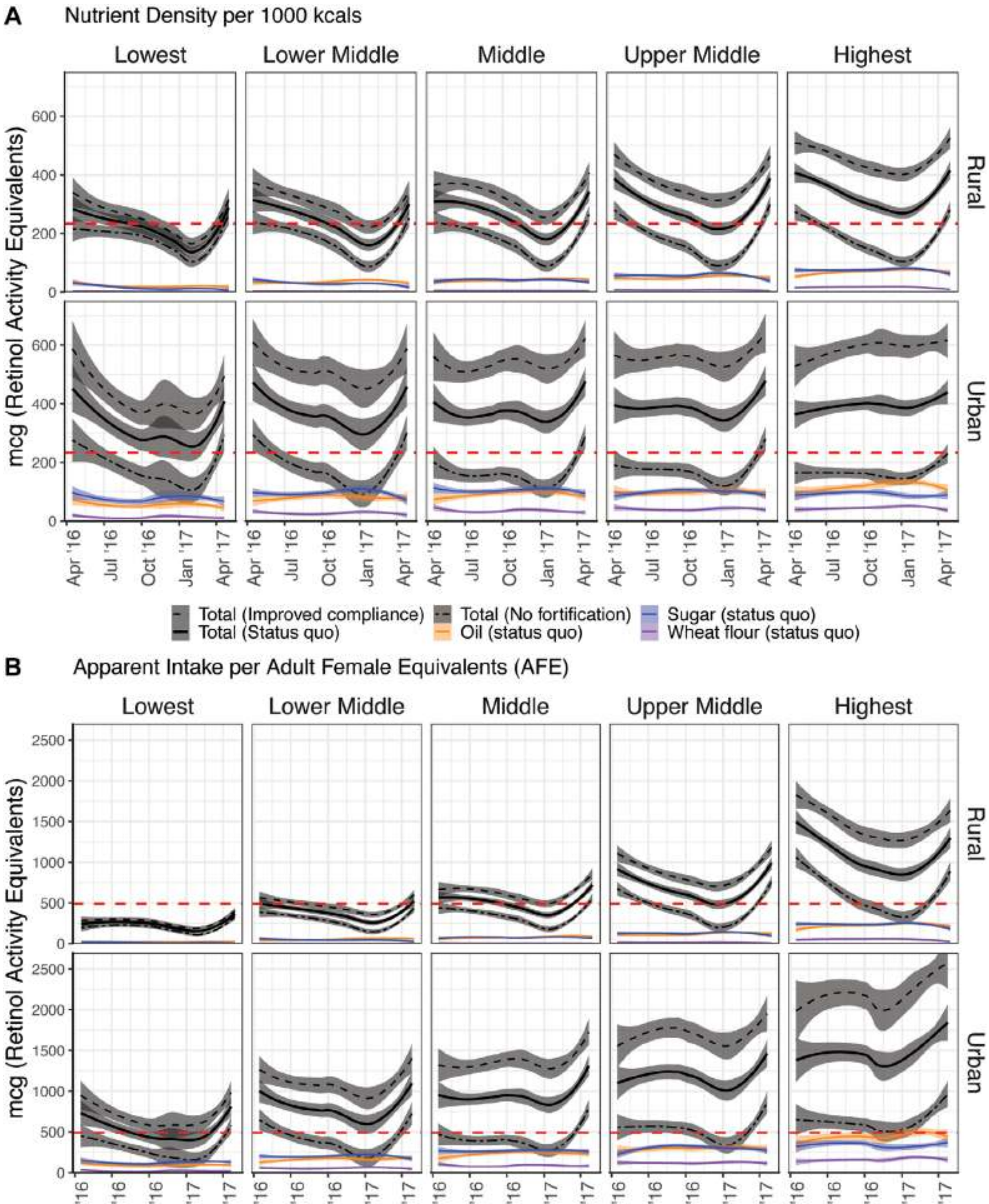

Figure 3. Seasonality in the (A) nutrient density and (B) apparent intake of vitamin A under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences. Panels of seven further micronutrients are available in Supplementary Figures S1–S7 (online only).

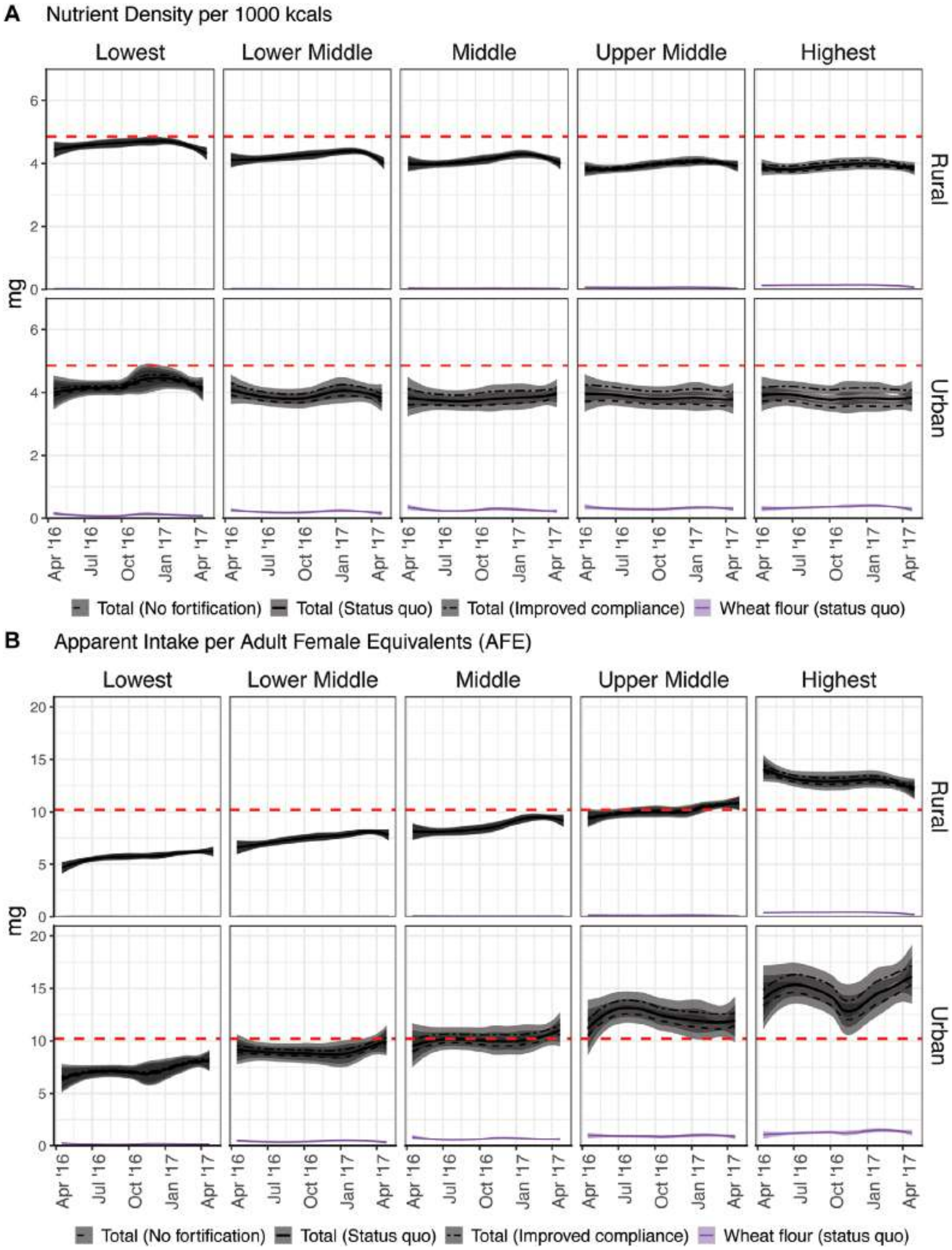

Figure 4. Seasonality in the (A) nutrient density and (B) apparent intake of zinc under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences. Panels of seven further micronutrients are available in Supplementary Figures S1–S7 (online only).

of diets (75% inadequate density under the no fortification scenario versus 50% under the status quo scenario, and 37% under the improved compliance scenario). Wheat flour also had wide coverage (52% at the national level, 44% in rural areas, and 86% in urban areas), but low apparent consumption across the population resulted in low potential contributions for all micronutrients, with little potential for improvement through improved industry compliance alone. All fortification vehicles demonstrated lower coverage and potential contributions in rural populations of the lowest SEP, suggesting that additional micronutrient interventions are necessary to meet the micronutrient needs of these most vulnerable groups.

Oil and sugar fortification

In Malawi, wide coverage and adequate consumption quantities make oil and sugar good candidates for vitamin A fortification vehicles. Vegetables and fruits contribute the largest proportion of vitamin A to the unfortified Malawian diet,[15] but the availability of these foods fluctuates seasonally (Fig. 3). This analysis found very little variation in oil and sugar consumption across seasons, suggesting that fortification of these products can provide a consistent source of vitamin A during times of the year when dietary supply is otherwise low. Vitamin A contributions from fortified oil and sugar can increase vitamin A density of diets to adequate levels in most urban and some rural populations, especially if compliance to industry standards at point of fortification is met. Strategies to improve compliance could include investment in improved government regulatory monitoring,[35] subsidies to producers for internal product quality control and reporting, and improved fortified product labeling to improve the feasibility of spot-checks throughout the food value chain.[36]

Rural populations of the lowest SEP do not consume enough oil and sugar to sufficiently benefit from industrial fortification, suggesting that the current fortification interventions alone are not sufficient to meet the vitamin A requirements for the entire population of Malawi. These findings suggest that to alleviate vitamin A inadequacies successfully and sustainably, additional micronutrient interventions are required that target these hard-to-reach populations who have the highest prevalence of vitamin A inadequacy. There are many other interventions with demonstrated success in improving vitamin A intake across populations. First, vitamin A–rich crop varieties through biofortification (i.e., orange-fleshed sweet potato, orange maize, and orange cassava prototypes) in combination with a comprehensive behavior change communication strategy to promote dietary diversification could increase vitamin A supply to these groups if programs are designed to reach vulnerable populations.[37] Second, for preschool children (PSC), Malawi's high-dose vitamin A supplementation program was reported to have high coverage (67% received a supplement in the past 6 months) with an equal reach between rural and urban populations and across all SEPs.[38] Recent evidence suggests that the combination of vitamin A fortification and supplementation interventions may be leading to excessive vitamin A intake among PSC in Malawi,[18] although caution is needed in interpreting these data and more research is needed before consideration of any policy changes.[39,40] We found a low risk of excessive vitamin A intakes under the status quo fortification scenario, although the risk of excessive apparent intake increases to 19% among wealthy, urban households under the improved compliance scenario (Table S5, online only). Further research is needed to model how additional micronutrient interventions can meet vitamin A needs unaddressed by oil and sugar fortification.

Wheat flour fortification

The fortification of wheat flour with nine micronutrients in Malawi is predicted to have minimal effect on reducing the prevalence of dietary micronutrient inadequacy. When consumed, wheat flour products are not consumed in high quantities in Malawi outside of urban populations of high SEP and increasing wheat flour fortification to meet regulatory standards was shown to have little effect on the estimated prevalence of inadequacy. Since this analysis indicates that micronutrient requirements are not being met through the diet alone (especially for riboflavin, niacin, vitamin B_{12}, iron, and zinc), additional micronutrient interventions are likely necessary to meet dietary requirements.

For example, agronomic biofortification (i.e., enriching mineral concentration of crops through the application of mineral fertilizers) could be effective in increasing the supply of minerals from staple crops and improving yields on infertile soils.[41,42] Other varieties of iron- and zinc-enriched biofortified cereals and legumes (e.g., beans and pearl millet) have the potential to increase micronutrient supplies from food items commonly consumed in Malawi.[43] For industrial fortification, maize flour has wider coverage and higher quantity consumption throughout Malawi,[6,38] but decentralized milling via thousands of small and medium enterprises posed significant mechanical, financial, and quality control challenges when a large community-level fortification program was implemented in Malawi from 1998 to 2009.[44] Further research is needed to assess the potential contribution of these alternative interventions to meeting micronutrient needs and the cost-effectiveness of Malawi's wheat flour fortification program relative to, and in combination with, other micronutrient programs.

Relevance for national nutrition strategies

While identifying micronutrient interventions that can reach vulnerable populations with the greatest micronutrient gaps is important, efforts to improve the micronutrient quality of the diet (estimated using the nutrient density metric) should be balanced with efforts to ensure that these populations have adequate quantities of micronutrients (estimated using the apparent intake metric), that is to ensure that households have both adequate supplies of energy and supplies of micronutrient dense foods. Similar micronutrient densities of the diet between subpopulations (assuming no fortification), yet lower apparent intake in the rural populations of the lowest SEP, suggest that the quality of the family diet does not vary greatly throughout the whole country, but rural populations of the lowest SEP have inadequate energy intakes. The apparent energy intake of the poorest 40% of rural populations was below 1636 kcal/day,[15] which is noticeably below the 2100 kcal/day recommended mean daily energy intake for an adult female with moderate physical activity levels.[32] While large-scale food fortification can fill some micronutrient gaps, a continued investment in improving the food security of these vulnerable populations is necessary.

The availability of multiple types of nutrition data requires careful integration when assessing the micronutrient status of a population. A variety of data types (e.g., micronutrient biomarker, household consumption and expenditure, individual intake, and anthropometric surveys) can be used to provide complementary insights into the nutritional profile of a population.[6,38,45] The national burdens of micronutrient deficiencies are classified using biomarker surveys, but operational and analytical challenges can pose difficulties when interpreting results.[40] Furthermore, some micronutrients that were indicated by this analysis to be of concern for dietary inadequacy are either not commonly assessed using biomarker analyses (e.g., riboflavin) or are challenging to measure using biomarkers, for example, owing to tight homeostatic control of concentrations in blood plasma/serum (e.g., zinc).[46] Using dietary data to assess inadequacies in micronutrient intake can provide information to guide the design of policies centered around food-based interventions. Additionally, dietary data can help to identify commonly consumed food items for future interventions[4] and can be used to help identify populations at risk of deficiency when planning biomarker surveys and build context around which biomarker results can be interpreted. Dietary data will continue to play an integral role when describing the micronutrient profile of a population.

Mathematical modeling tools are valuable resources for providing policymakers with information to help guide nutrition investments and identify potential improvements to current nutrition policies. While many tools have been independently developed for various purposes, combining insight from multiple tool outputs could be valuable for informing policy and programs and may lead to increased uptake by end-users.[47] The policy relevance from our model outputs would be strengthened if it was possible to compare with other mathematical modeling tool outputs that describe other factors that influence decision making. This includes the cost-effectiveness of current fortification policies and other micronutrient interventions,[48] how to prioritize and bundle multiple micronutrient interventions to meet needs,[49] and desirable food-based alternatives to fortification to reduce inadequacy at the lowest cost.[50] For many tools, mathematical models are dependent on up-to-date quality data, so while investment in advancing modeling techniques will remain important, parallel investment in survey design and data collection remains a priority.

Strengths, limitations, and conclusions

This study had a number of strengths. When evaluating the micronutrient supply across the population, results were disaggregated by subpopulations to provide insight into which populations have the highest prevalence of dietary micronutrient inadequacy and which populations are likely to benefit most from the fortification of the selected vehicles. A novel adjustment of apparent intakes per AFE allowed for comparison between the apparent intake and micronutrient density approach when estimating dietary inadequacy. Additionally, the predictive model was developed to conduct the analysis across multiple fortification scenarios to predict the potential impact of different fortification scenarios using the selected vehicles. For some micronutrients, the analysis revealed fluctuations in the micronutrient supply from the overall diet across seasons, providing a more nuanced picture of the potential contribution of large-scale food fortification.

There are several limitations in our study that should be noted. First, given that the food consumption data underpinning this study were at the household level, intrahousehold distribution of food between household members is unknown, and individual-level estimates rely on a number of assumptions. Confirmation of the micronutrient status of any subpopulation of members within the household (e.g., PSC and women of reproductive age) will require data from individual-level dietary and micronutrient biomarker assessments. For apparent intake, the assumptions adopted in this analysis focused exclusively on food distribution based on proportional energy requirements. However, the distribution of foods within the household is likely to be influenced by socioeconomic, gender, and cultural factors,[51] and, depending on the context and household factors, certain demographic groups may be at greater risk of inadequate micronutrient intake due to inequitable food distribution.[52] Alternative assumptions could be applied to explore scenarios that provided more or less energy than requirements for certain demographics to model the inequitable distribution of micronutrients between household members. While scenarios exploring additional research questions can be added to the current model framework, further research exploring the sensitivity of policy recommendations to the number of scenarios run is needed for clear model dissemination. Second, the micronutrient composition of food items, both naturally occurring and industrially processed, is assumed to be constant across all households, despite studies suggesting that the micronutrient composition of food items may vary due to numerous factors. In one study, Ulemu *et al.* found that vitamin A fortificant in oil deteriorates as the food product moves through the supply chain,[53] suggesting that vitamin A concentration in fortified products is sensitive to the sun and air exposure and is likely to vary depending on the length of time since production and packaging/storage conditions. In addition, subnational spatial variation in the mineral micronutrient composition of staple crops has been reported in Malawi, likely due to soil properties and other environmental factors.[22,54] The current analysis assumed constant micronutrient composition of each food item, and further research identifying subnational variation in the micronutrient composition of food items could be integrated into our models. Third, our status quo scenario assumed that all oil, sugar, and wheat flour consumed by households is equally fortified. Market data of vitamin A contents of oil, sugar, and wheat flour collected from sentinel sites indicated that some samples were not fortified at all,[29] despite our model applying the average from all sentinel sites equally. Finally, because we relied on HCES data to estimate the micronutrient intake and model the potential contributions of large-scale food fortification, measurement error may have reduced the precision or accuracy of these estimates given the limitations of using HCES data (e.g., recall error, micronutrient loss during cooking, foods consumed away from home, fixed-food item lists, and others).

In conclusion, this analysis demonstrated the use of HCES data and a novel mathematical modeling framework to estimate the coverage, potential contributions, and equity dimensions of large-scale food fortification in Malawi. While large-scale food fortification was predicted to have high potential contributions in reducing vitamin A inadequacies throughout most of Malawi, additional interventions are likely required to meet the needs of rural populations of low SEP. This information provides relevant insight for nutrition policy and programs when designing strategies to alleviate the overall burdens of micronutrient deficiencies, although further research is necessary to identify the optimal combination of interventions for future micronutrient investments.

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Author contributions

K.T., M.W., O.D., E.L.A., and E.J.M.J. set up the collaborative network. K.T., O.D., and E.J.M.J. designed the study. K.T., K.P.A., and B.L. cleaned and transformed the food consumption data. E.L.F. and L.S.D.L.R. compiled the food composition data matches. O.D. developed the food fortification scenarios. K.T., K.P.A., E.L.F., M.W., J.Y., O.D., A.A.K., S.P., E.L.A., and E.J.M.J. determined the adult female equivalent factor parameters. K.T. and B.C. defined the analysis for subpopulations. K.T. conducted the statistical analysis. K.T., K.P.A., and E.J.M.J. led the interpretation of the results and drafting of the manuscript. All authors critically reviewed and approved the final manuscript. K.T. is responsible for the integrity of the data analyzed.

Supporting information

Additional supporting information may be found in the online version of this article.

Table S1. Micronutrient composition for 100 g of food items from the IHS4 using food composition data from the Malawian (MWI),[1] Kenyan (KEN),[2] Lesothan (LSO),[3] Mozambican (MOZ),[4]FAO West African (WAF),[5] and the United Kingdom (UK)[6] food composition tables.

Table S2. Fortifiable food equivalent factors for wheat flour in wheat flour products.

Table S3. Base parameters defining daily dietary micronutrient and energy requirements.

Table S4. Standard and nonstandard food consumption units recorded in Malawi's Fourth Integrated Household Survey.

Table S5. Prevalence of households exceeding the daily harmonized upper limit for vitamin A apparent intake across large-scale food fortification scenarios by subpopulation.

Supplementary materials

Figure S1. Seasonality in the (A) nutrient density and (B) apparent intake of thiamine under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S2. Seasonality in the (A) nutrient density and (B) apparent intake of riboflavin under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S3. Seasonality in the (A) nutrient density and (B) apparent intake of niacin under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S4. Seasonality in the (A) nutrient density and (B) apparent intake of vitamin B_6 under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S5. Seasonality in the (A) nutrient density and (B) apparent intake of folate under the three fortification scenarios by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S6. Seasonality in the (A) nutrient density and (B) apparent intake of vitamin B_{12} under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S7. Seasonality in the (A) nutrient density and (B) apparent intake of iron under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residences.

Figure S8. Histogram of apparent vitamin A intake per adult female equivalent in relation to the harmonized upper limit for daily vitamin A intake (dotted red line) under the three large-scale food fortification scenarios.

Competing interests

The authors declare no competing interests.

Ethical standards disclosure

This study was approved by the London School of Hygiene and Tropical Medicine Observational Research Ethics Committee under the Micronutrient Action Policy Support (MAPS) project (ref. 21903; April 17, 2020).

Peer review

The peer review history for this article is available at https://publons.com/publon/10.1111/nyas.14697.

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6.7 Additional results

District-level maps of inadequacy

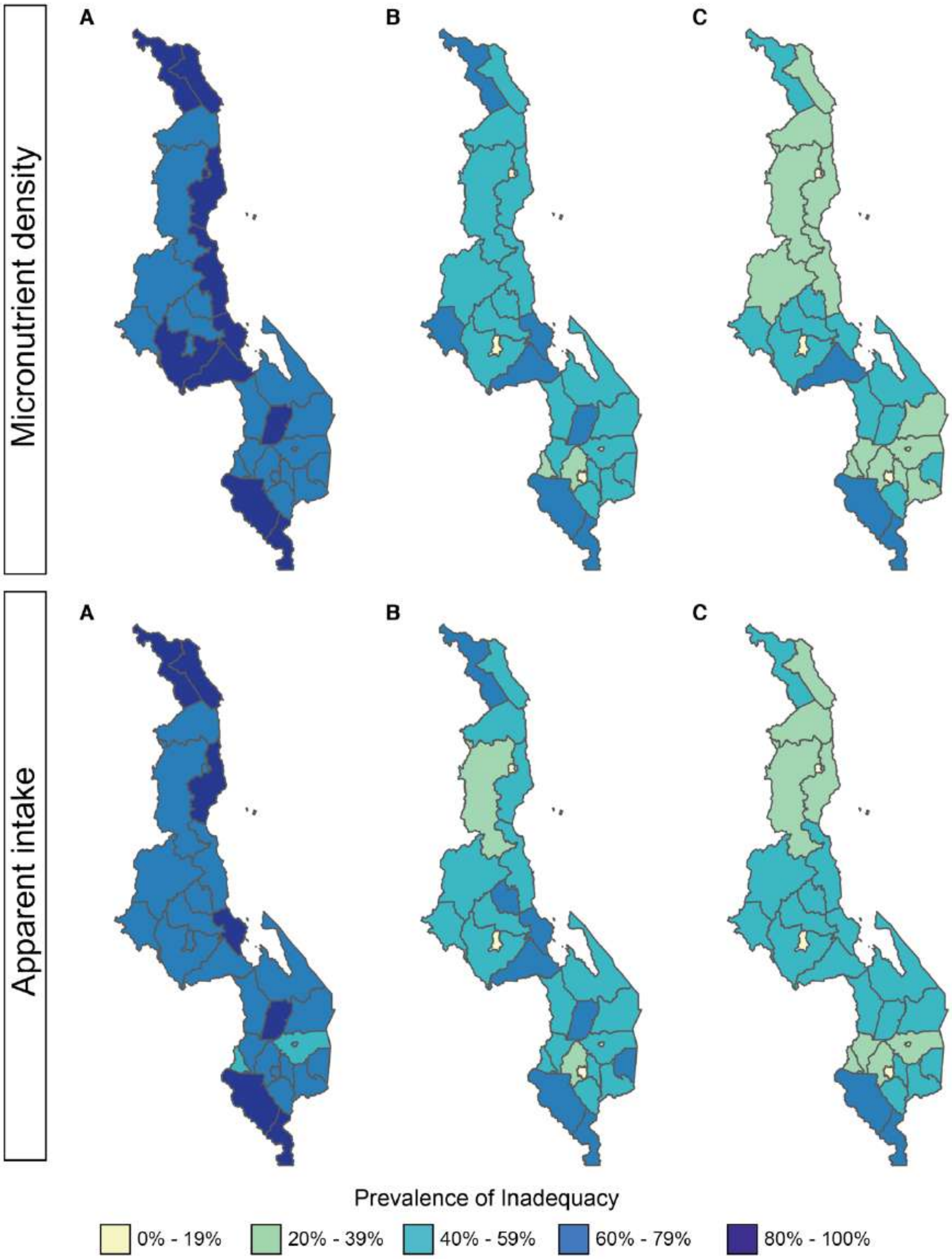

Figure 6.5 Vitamin A inadequacy by district in Malawi for under the (A) no fortification, (B) status quo fortification, and (C) improved compliance fortification scenarios.

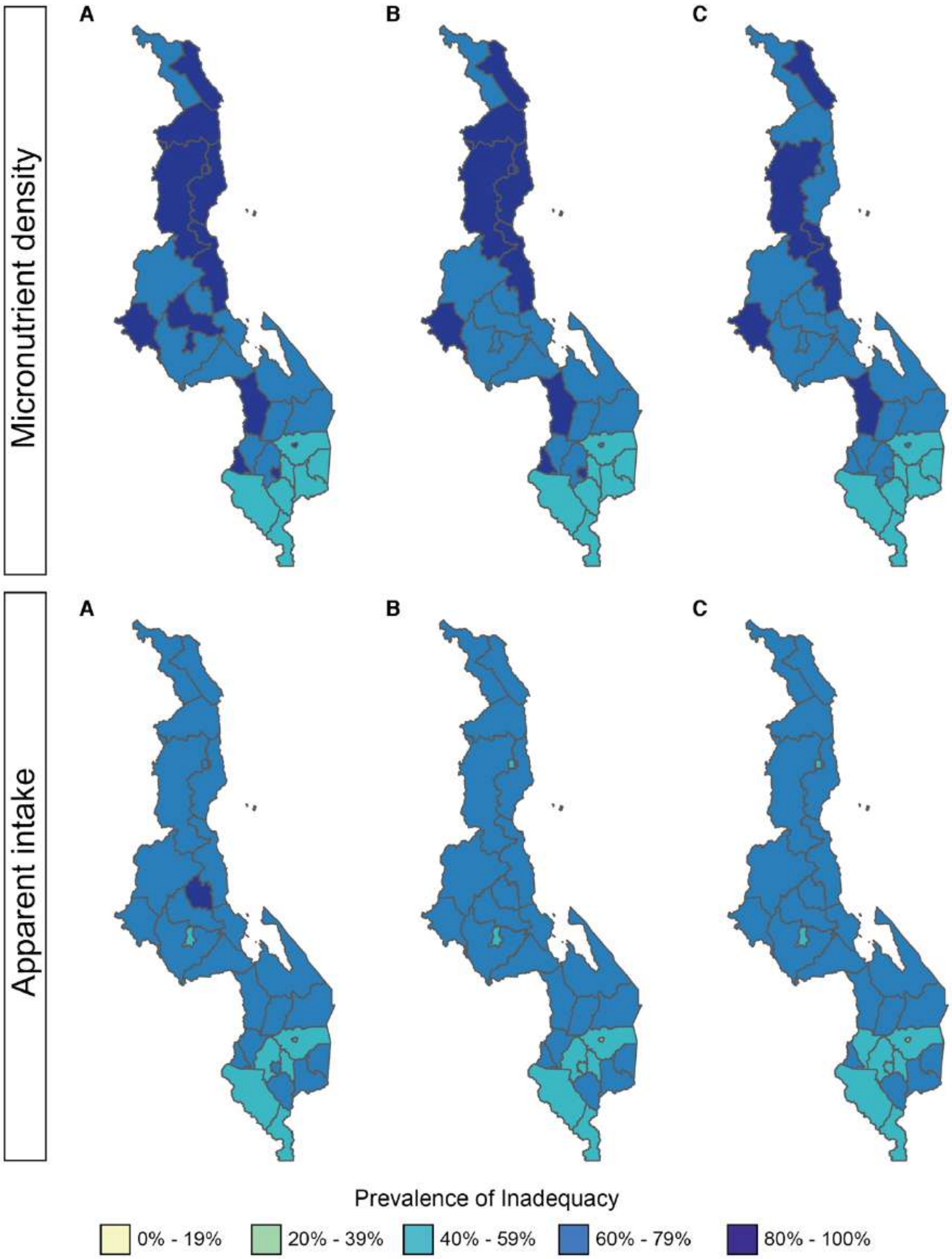

Figure 6.6 Zinc inadequacy by district in Malawi for under the (A) no fortification, (B) status quo fortification, and (C) improved compliance fortification scenarios.

Risk of excessive apparent intake

While not originally included in the first version of this manuscript, our analysis also estimated the prevalence of households with apparent vitamin A intake above the Harmonized-Upper Limit (H-UL) to estimate risk for excessive apparent intake. These results can be found in Table 6.4 below. For the 'No fortification' and 'Status quo' scenarios, the risk for excessive apparent intake for vitamin A is low for all subpopulations. Under the 'Improved compliance' scenario, prevalence of vitamin A excessive apparent intake increased in households of highest SEP (rural = 8%, urban = 19%). Vitamin A apparent intake demonstrates a right-skewed distribution (Figure 6.7) suggesting that the elevated prevalence of apparent excessive intake in the urban-highest SEP group under the improved compliance scenario may have been affected by imprecision in HCES dietary recall methods.

Table 6.4 Prevalence of households exceeding the daily Harmonized-Upper Tolerable Limit for vitamin A apparent intake across large-scale food fortification scenarios by sub-population.

Population	Households, *n*	Excessive apparent intake prevalence, %		
		No fortification	*Status quo*	*Improved compliance*
National (total)	**12,447**	**1**	**1**	**3**
Geography by administrative region				
North	2491	0	1	3
Center	4220	1	1	3
South	5736	1	1	3
Residence & socioeconomic position (SEP) by quintile of total annual household expenditure per capita				
Rural (total)	**10,175**	**1**	**1**	**2**
Lowest SEP	2035	0	0	0
Lower Middle SEP	2035	0	0	0
Middle SEP	2035	0	0	0
Upper Middle SEP	2035	1	1	1
Highest SEP	2035	1	3	8
Urban (total)	**2272**	**0**	**2**	**6**
Lowest SEP	455	0	0	0
Lower Middle SEP	454	1	1	2
Middle SEP	455	0	1	2
Upper Middle SEP	454	0	2	6
Highest SEP	454	1	5	19

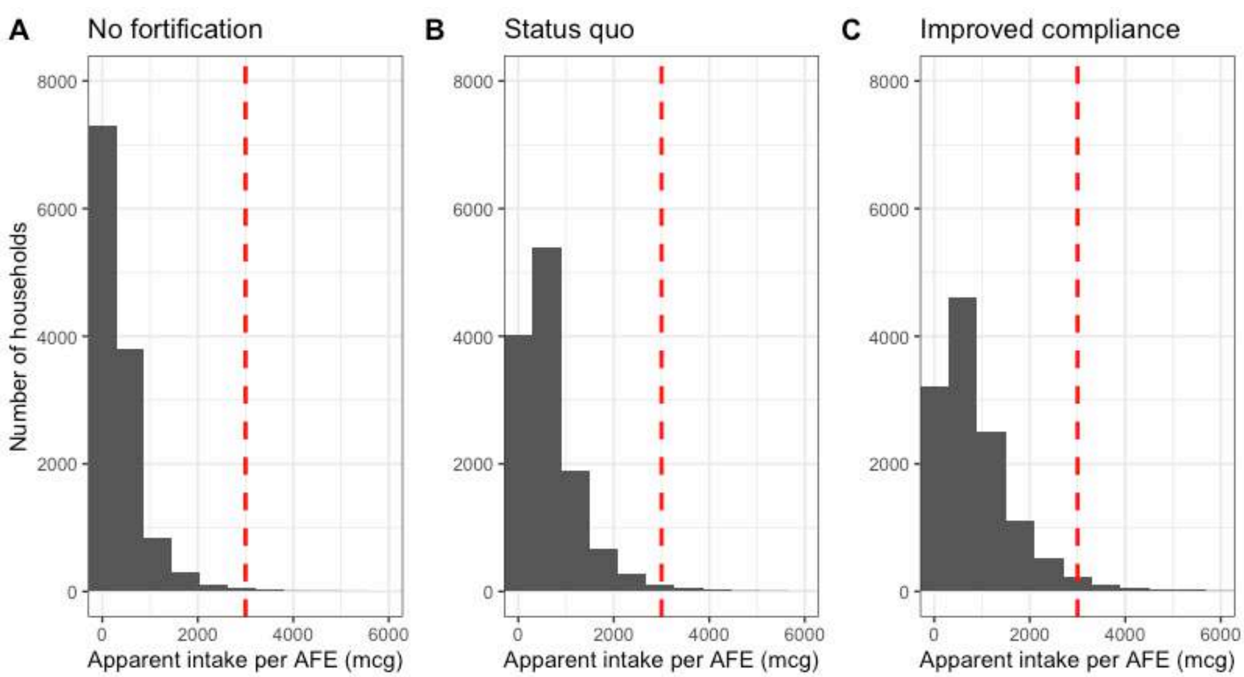

Figure 6.7 Histogram of apparent vitamin A intake per adult female equivalent in relation to the Harmonized-Upper Limit for daily vitamin A intake (dotted red line) under the three large-scale food fortification scenarios.

Modelling apparent protein intake

An additional analysis estimating protein supply and potential maximum contributions of a quality protein maize intervention applying the same approach demonstrates an additional application of this model framework. The full manuscript is available in Appendix V.

nutrients

MDPI

Article

Limited Supply of Protein and Lysine Is Prevalent among the Poorest Households in Malawi and Exacerbated by Low Protein Quality

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Abstract: We estimated dietary supplies of total and available protein and indispensable amino acids (IAAs) and predicted the risk of deficiency in Malawi using Household Consumption and Expenditure Survey data. More than half of dietary protein was derived from cereal crops, while animal products provided only 11%. The supply of IAAs followed similar patterns to that of total proteins. In general, median protein and IAA supplies were reduced by approximately 17% after accounting for digestibility, with higher losses evident among the poorest households. At population level, 20% of households were at risk of protein deficiency due to inadequate available protein supplies. Of concern was lysine supply, which was inadequate for 33% of households at the population level and for the majority of the poorest households. The adoption of quality protein maize (QPM) has the potential to reduce the risk of protein and lysine deficiency in the most vulnerable households by up to 12% and 21%, respectively.

Keywords: protein quality; amino acids; digestibility; protein deficiency; household survey

check for updates

Citation: Muleya, M.; Tang, K.; Broadley, M.R.; Salter, A.M.; Joy, E.J.M. Limited Supply of Protein and Lysine Is Prevalent among the Poorest Households in Malawi and Exacerbated by Low Protein Quality. *Nutrients* **2022**, *14*, 2430. https://doi.org/10.3390/nu14122430

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1. Introduction

Protein containing appropriate amounts of indispensable amino acids (IAAs) is an essential component of the human diet. Protein derived from animal products is generally regarded as high quality due to its IAA content and digestibility, and its consumption is projected to increase in low-income countries as socioeconomic status improves and the global population continues to rise [1] However, livestock production raises environmental issues due to high greenhouse gas (GHG) emissions, nitrogen pollution, and increased land degradation, mainly due to the production of crops required for animal feed [2–4]. In addition, excessive consumption of red meat is associated with an increased risk of developing cardiovascular diseases and some forms of cancer [5]. Thus, shifting diets towards more plant-based protein is often promoted on environmental sustainability and human health grounds [6]. However, in low-income countries where plant-based diets already predominate, greater consumption of animal-source foods may be required to help alleviate chronic malnutrition and micronutrient deficiencies [7,8], and associated GHG emissions may rise [9,10].

Animal and plant protein differ not only in their IAA composition but also in their digestibility, with the latter being of lower quality due to the presence of antinutrients such as phytates, tannins, trypsin, and protease inhibitors [8,11]. The digestibility of protein can be as low as 56% in some plant foods such as potatoes, compared with >85% for most animal-source foods [12]. The low protein quality of a typical plant-based diet consumed

CHAPTER 7

Evaluating equity dimensions of infant and child vitamin A supplementation programs using Demographic and Health Surveys from 49 countries

CHAPTER SUMMARY

This chapter presents an original research article outlining a framework for evaluating the equity dimensions of national high-dose vitamin A supplementation programs using openly available Demographic and Health Survey (DHS) data from multiple countries. As the findings presented in Chapter 5 suggests lower potential contributions from large-scale vitamin A fortification in sub-groups with the lowest apparent vitamin A intake, this chapter aims to clarify whether other large vitamin A-supplying programmes are being equitably designed and monitored to reach population with the greatest needs using other openly available household survey systems. The main findings for this chapter indicate that sub-population differences in vitamin A supplementation (VAS) coverage characterized by various determinants of vitamin A status suggest that VAS programs may not be operating equitably in many countries. National VAS programs can use this analysis as a framework to use open-source data to improve targeting and prioritization of children who may likely be most in need.

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed <u>for each</u> research paper included within a thesis.

<u>SECTION A – Student Details</u>

Student ID Number	1600604	Title	Mr.
First Name(s)	Kevin Michael		
Surname/Family Name	Tang		
Thesis Title	Micronutrient adequacy of diets and contributions of large-scale interventions: secondary analyses of household surveys		
Primary Supervisor	Dr. Edward Joy		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

<u>SECTION B – Paper already published</u>

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Where is the work intended to be published?	BMJ Open
Please list the paper's authors in the intended authorship order:	Kevin Tang, Hallie Eilerts, Annette Imohe, Katherine P Adams, Fanny Sandalinas, Edward JM Joy, Grainne Moloney, Andreas Hasman
Stage of publication	Submitted

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	K.T., K.P.A. and A.H. designed the study. K.T., A.I., K.P.A., and A.H. defined the variables for disaggregation. K.T. and H.E. wrote the code for data extraction and analysis. All authors critically reviewed and approved the final manuscript.

SECTION E

Student Signature	Kevin M Tang
Date	23/09/2022

Supervisor Signature	Edward JM Joy
Date	23/09/2022

Evaluating equity dimensions of infant and child vitamin A supplementation programs using Demographic and Health Surveys from 49 countries

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ABSTRACT

Objectives: Vitamin A deficiency affects an estimated 29% of all children under five years of age in low- and lower middle-income countries, contributing to child mortality and exacerbating severity of infections. Bi-annual vitamin A supplementation (VAS) for children aged 6 – 59 months can be a low-cost intervention to meet vitamin A needs. This study aimed to present a framework for evaluating the equity dimensions of national VAS programs according to determinants known to affect child nutrition and assist programming by highlighting geographic variation in coverage.

Methods: We used open-source data from the Demographic and Health Survey for 49 countries to identify differences in VAS coverage between sub-populations characterized by various immediate, underlying, and enabling determinants of vitamin A status and geographically. This included recent consumption of vitamin A-rich foods, access to health systems and services, administrative region of the country, place of residence (rural vs urban), socioeconomic position, caregiver educational attainment, and caregiver empowerment.

Results: Children who did not recently consume vitamin A-rich foods and who had poorer access to health systems and services were less likely to receive VAS in most countries despite potentially having a greater vitamin A need. Differences in coverage were also observed when disaggregated by administrative regions (88% of countries) and urban vs rural residence (35% of countries). Differences in vitamin A coverage between sub-populations characterized by other determinants of vitamin A status varied considerably between countries.

Conclusion: Sub-population differences in VAS coverage characterized by various determinants of vitamin A status suggest that VAS programs may not be operating equitably

in many countries. National VAS programs can use this analysis as a framework to use open-source data to improve targeting and prioritization of children who may likely be most in need.

KEY QUESTIONS

What is already known on this topic?

- Vitamin A supplementation (VAS) programs for children aged 6 – 59 months can reduce risks of vitamin A deficiency, alleviating related mortality and exacerbated disease burden.
- VAS programs can operate alongside existing community-based health service delivery programs, but there are challenges accessing hard-to-reach populations who may have greater risks for vitamin A deficiency.
- VAS reception is included in the Demographic and Health Survey (DHS), but this data is often underutilized when informing decision making.

What does this study add?

- Children who likely have limited access to vitamin A-rich foods are less likely to receive VAS in most countries, and those who have impaired access to healthcare systems and services are also less likely to receive VAS in several countries.
- VAS coverage frequently varied by sub-populations within countries, defined both geographically and by other enabling determinants affecting vitamin A status.

How might this study affect research, practice, or policy?

- DHS data can be useful to inform national governments on how to orient their VAS delivery strategy to target population who potentially are most in need of vitamin A supplementation.

7.1 Introduction

The UNICEF Nutrition Strategy 2020 – 2030 commits to a goal of protecting and promoting diets, services, and practices that support optimal nutrition, growth, and development for all children to end child malnutrition in all its forms [1]. Central to achieving this goal requires recognizing the interaction between five core systems (food, health, water & sanitation, education, social protection) to improve nutrition outcomes. However, a strategy focused on working within established systems may exacerbate unequal nutrition outcomes rooted in deeper inequities that arise from already inequitable systems [2]. Therefore, when defining policies to ensure the most vulnerable have access to services, regular review of coverage must be implemented to allow for reorientation as needed.

Vitamin A deficiency affects an estimated 29% of all children under five years of age in low- and middle-income countries [3], contributing to child mortality and disease burden through direct clinical manifestation (e.g., xeropthalmia) and susceptibility to and exacerbated adverse outcomes from infection (e.g., measles, diarrhoea) [4]. For children with vitamin A deficiency or who have an increased risk of mortality, high-dose vitamin A supplementation (VAS) can be a low-cost intervention to meet vitamin A needs when delivered using infrastructure from existing community-based delivery programs [5]. Following an exhaustive review of the current evidence exploring the effect of VAS in preventing morbidity and mortality in infants and children [4,6], in 2011 the World Health Organization (WHO) confirmed a recommendation for infants and children 6 – 59 months of age to receive a dose of VAS every four to six months in contexts where vitamin A deficiency is a public health problem [7]. Although the past two decades have seen increases in global VAS coverage [8], stagnating VAS coverage in recent years brings into question whether current universal delivery strategies are consistently missing hard-to-reach children and whether a targeted approach should be considered [9]. This is particularly the case as VAS programs move away from delivery in campaigns towards routine delivery [8].

It is recommended that the delivery of VAS is integrated into community-based health service delivery programs [10]. In many countries, community-based delivery programs, such as the national Essential Programme on Immunization (EPI), offer the most consistent contacts between the youngest children and the health system, thus creating a platform for the large-scale administration of VAS. However, in contrast to VAS administration protocols, childhood immunization programs typically benefit only children up to one year of age when the last vaccine dose is administered, and few countries have a contact point for immunization at six months. Moreover, multi-country analyses of diphtheria-tetanus-pertussis (DTP) and measles containing vaccines (MCV) identified gaps in program coverage between geographic and socioeconomic subpopulations [11,12]. All together, these differences suggest that the services these community-based delivery programs provide are not equitably accessible to children with the greatest needs and may affect the VAS programs that depend on these services for delivery.

Global guidance for monitoring VAS programs relies on “two-dose coverage” as the primary metric for estimating global progress towards achieving universal VAS coverage [8,13].
In this context, “coverage” is estimated as the aggregated number of VAS doses administered in a country over a six-month period (also referred to as semester) divided by the estimated number of children ages 6 – 59 months in that country for that specific semester. “Two-dose

coverage" is thus established on an annual basis as the semester in a given year with lower coverage. While two-dose coverage increases the feasibility of collating national VAS program data bi-annually, the metric is limited in identifying differences in coverage among sub-populations within a country. This restricts national VAS programs from evaluating whether they are missing the children, particularly those with the greatest needs.

There is a significant information gap in evaluating the equity dimensions of nutrition interventions, or the extent to which a community-based nutrition program is reaching the children most in need [2]. Nationally representative household surveys, such as the Demographic and Health Surveys (DHS), can potentially provide insight into the equity dimensions of program delivery. Since 1985, the DHS program has conducted nationally-representative cross-sectional surveys in over 90 predominantly low-middle income countries, producing detailed, cross-sectional data on a variety of indicators describing demographics, health, economics, and social welfare [14]. DHS questionnaires and variable nomenclature are consistent between all countries in the DHS program, facilitating rapid analysis across multiple countries and survey years. DHS microdata enable the exploration of a variety of indicators to measure population health outcomes and the mechanisms influencing them in great depth.

As a result of these characteristics, DHS serve as a valuable resource to evaluate equity dimensions as they relate to development and public policy, where substantial groundwork has been established from prior research. For instance, Wagstaff et al. reported the use of DHS microdata as an essential element of a database constructed by the World Bank to create health equity and financial protection indicators [15]. More relevant to nutrition, Ricardo et al. previously demonstrated the use of DHS data to evaluate inequalities in vegetable, fruits, and animal source foods consumption by young children in multiple countries [16]. In addition, other secondary data analyses used DHS data to evaluate the equity dimensions of vaccination programs and behaviours, including ethnicity [17], caregiver empowerment [18], and other social depravations [19]. The broad inclusion of variables describing different social determinants and widespread availability of DHS data make them an appealing source of information to help understand the equity implications of public policy.

DHS collect detailed information on the reception of VAS by infants and children, however using such data to inform national VAS programs is not straightforward. The aim of this study was to present a framework for evaluating the equity dimensions of national VAS programs according to determinants known to affect child nutrition and geographically using DHS data from multiple countries.

7.2 Methods

Demographic and Health Surveys

We used the most recent DHS data from 49 countries in which a complete survey was conducted since 2010. The analysis depended on data from the Woman's Questionnaire, which contains information on the survival status of the children born to the respondent, and more detailed information on children born in the last five years, such as vaccination history, breastfeeding practice, recent illness, and anthropometry.

Sampling Strategy & Study Population

The DHS protocol employs a two-stage sampling procedure [20]. In the first stage, enumeration areas are defined geographically (stratified by urban/rural residence and administrative region) using the country's most recent population census to establish the survey's primary sampling unit. In the second stage, systematic sampling identifies 20 – 30 households for inclusion, where selected households are visited by trained interviewers who administer the Woman's Questionnaire to women of reproductive age (15-49 years).

Our analysis included all children aged 6 – 59 months with available VAS history data. VAS program participation is probed in the DHS questionnaire's *vaccination history section* by asking caregivers of children whether her child (or children) aged 6 – 59 months has (or have) received a vitamin A dose in the last six months [21]. If possible, caregivers are asked to present proof of VAS reception using a vaccination history card, and if not available, are asked to recall VAS administration from memory after probing the caregivers to describe post-natal care activities in which her and each child have participated [22]. The primary outcome of this study was defined as the percentage of children receiving VAS in the prior six months, or more simply, “VAS coverage”.

Equity and Geographic Covariates

Based on this thesis’ definition of equity in Chapter 1, dimensions of equity were identified to define various deprivations of the least advantaged in society. We stratified the primary outcome by several covariates describing various dimensions of equity, which were selected in accordance with the 2020 UNICEF Conceptual Framework on the Determinants of Maternal and Child Nutrition [1]. The framework used in this analysis was developed to guide nutrition programming by outlining three levels of determinants (i.e., immediate, underlying, enabling) that contribute to preventing malnutrition in all its forms. By using this framework to guide covariate selection, this study recognizes the levels and interconnectedness of various determinants affecting vitamin A status to define the underlying systems and processes that affect children with the greatest vitamin A needs. Geographic covariates were also selected as targeting geographically defined populations is more operationally feasible.

Covariates used to represent immediate and underlying child nutrition determinants included recent consumption of vitamin A-rich foods and access to healthcare systems and services. Recent consumption of vitamin A-rich foods from the DHS questionnaire is only collected for children aged 6 – 23 months, so this indicator refers predominantly to children who are within the age range where breastfeeding is recommended [23]. Access to healthcare systems and services is measured using the proxy variable of vaccine reception. The first dose of the DTP vaccine (administered at six weeks of age) is one of the first vaccines given to an infant, where children who do not receive it are expected to have the lowest access to healthcare systems and services. Reception of the first dose of MCV (administered at nine months of age) is expected to be delivered via similar platforms to VAS through both routine provisions and campaigns. Covariates serving as indicators for enabling child nutrition determinants included socioeconomic position, the caregiver's educational attainment, and two women's empowerment dimensions calculated according to the Survey-based Women's Empowerment (SWPER) index [24], which measure the caregiver's social independence and decision-making autonomy. Geographic covariates included urban vs rural residence and administrative regions specific to each country. Descriptions of all covariates are available in Table 1.

Table 7.1 Description of study covariates used to represent immediate, underlying, and enabling determinants of child nutrition and geography

Determinant	Type	Coding details
Recent consumption of vitamin A-rich foods	Immediate/ Underlying	Whether the following types of food were reported being consumed by the child (aged 6-23 months) in the 24 hours prior to the interview: eggs, any meat, fish, orange-fleshed pumpkin/carrot/squash/sweet potato, vitamin A-rich fruit (mango, papaya), liver/heart/organ meat, dark-leafy-green vegetables
Access to healthcare services & systems (DTP1 vaccine)	Immediate/ Underlying	Whether the child received the first dose of the diphtheria, tetanus, and pertussis (DTP1) vaccine, administered at 6 weeks of age per international guidelines
Access to healthcare services & systems (MCV1 vaccine)	Immediate/ Underlying	Whether the child received the first dose of the measles containing vaccine (MCV1), administered at 9 months of age per international guidelines
Administrative region	Geography	Administrative region the household is located, defined by the sub-national reporting area (provinces or groups of provinces) as defined by the DHS recode
Place of residence	Geography	Whether household is in an urban or rural location
Socioeconomic position	Enabling	Quintile of household wealth defined using a principal component analysis score comprised of household living conditions and durable assets (Poorest = 1st quintile, Wealthiest = 5th quintile)
Caregiver's social independence	Enabling	Women's empowerment indicator calculated as quintiles of SWPER index. Social independence domain included data related to education, frequency of reading newspapers/magazines, and age at first childbirth and at first cohabitation (includes children with partnered caregivers) (Least socially independent = 1st quintile, Most socially independent = 5th quintile)
Caregiver's decision-making autonomy	Enabling	Women's empowerment indicator calculated as quintiles of SWPER index. Decision-making autonomy domain included questions about involvement in household decisions and whether the respondent worked in the past 12 months (includes children with partnered caregivers) (Least decision-making autonomy = 1st quintile, Most decision-making autonomy = 5th quintile)
Caregiver's educational attainment	Enabling	Highest educational attainment of caregiver (None, primary school, secondary school or higher)

Statistical Analysis

Percentage of children receiving VAS in the prior six months was stratified by each equity covariate independently for every included country. All estimates were adjusted using population sample weights provided by the DHS Program [25]. Percentages of children receiving VAS in each stratum in the prior six months were presented with 95% confidence intervals (95%CI), where statistically significant differences in VAS coverage were identified as those with non-overlapping 95%CIs. VAS coverage by administrative region was mapped using shapefiles downloaded from GADM (version 3.6).

Data analysis was conducted in RStudio (version 3.6.1, the R Foundation for Statistical Computing). Data was accessed through the DHS program's application programming interface (API) on 1 February 2022 via the functions available on the *rdhs* package [26]. Survey weight adjustments and statistical analyses were conducted using the functions available on the *survey* and *srvyr* packages [27] and additional data cleaning and management used a variety of functions from the *tidyverse* package [28].

Patient and Public Involvement

As a secondary analysis of publicly available, de-identified data collected as part of the DHS, patients and the public that were included as part of the study population were not involved in the design of this study.

7.3 Results

Summary of included surveys & populations

In total, the birth history records of 1,464,997 women, corresponding to 608,578 children 6-59 months, were included in this study. For the survey question asking about VAS reception within the prior six month, the rate of response was >90% for all countries included. A summary of all included countries and the DHS data used in this study is available in Supplementary Table 1.

The national VAS coverage mean among included countries was 58% and ranged from 28% to 83%, where countries with the lowest national VAS coverage were Papua New Guinea (28%), Haiti (28%) and Kyrgyzstan (39%). The percentage of children who did not recently consume vitamin A-rich foods among included countries ranged from 19% to 74%, where countries with the lowest percentage of consumption were Burkina Faso (74%), Niger (73%), and Ethiopia (70%). For vaccinations, the percentage of non-vaccinated children among included countries ranged from 1% to 48% for DTP1 and 13% to 69% for MCV1. A descriptive summary of the survey population of children aged 6-59 months for each country is provided in Supplementary Table 2.

VAS coverage by immediate & underlying determinants

In figures 1 and 2, we present VAS coverage for all countries stratified by recent consumption of vitamin A-rich foods and access to healthcare systems and services. VAS coverage was significantly higher among children who recently consumed vitamin A-rich foods, compared to children who did not in 85% (n=41) of countries (Figure 1). For access to healthcare systems and services, VAS coverage was significantly higher in children who had access to their first dose of the DTP vaccine in 47 of the 49 countries compared to those who did not have access to these vaccines (Figure 2a). VAS coverage was significantly higher in children who had access to their first dose of MCV in all 49 countries (Figure 2b).

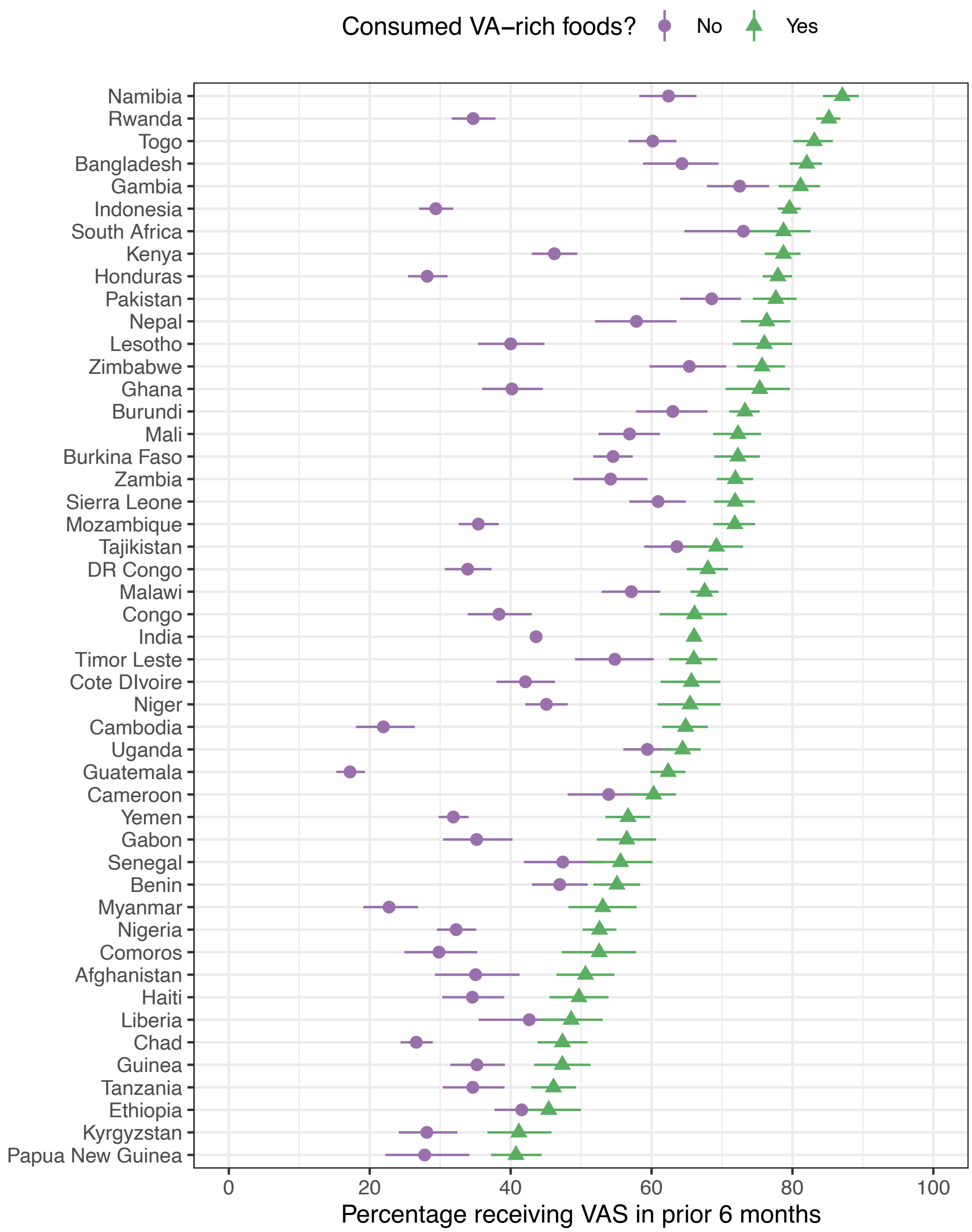

Figure 7.1 Vitamin A supplementation (VAS) coverage among children 6-23 months who have and have not recently consumed vitamin A-rich foods (in the 24 hours prior to the interview). Philippines DHS did not collect data on child consumption of vitamin A-rich foods.

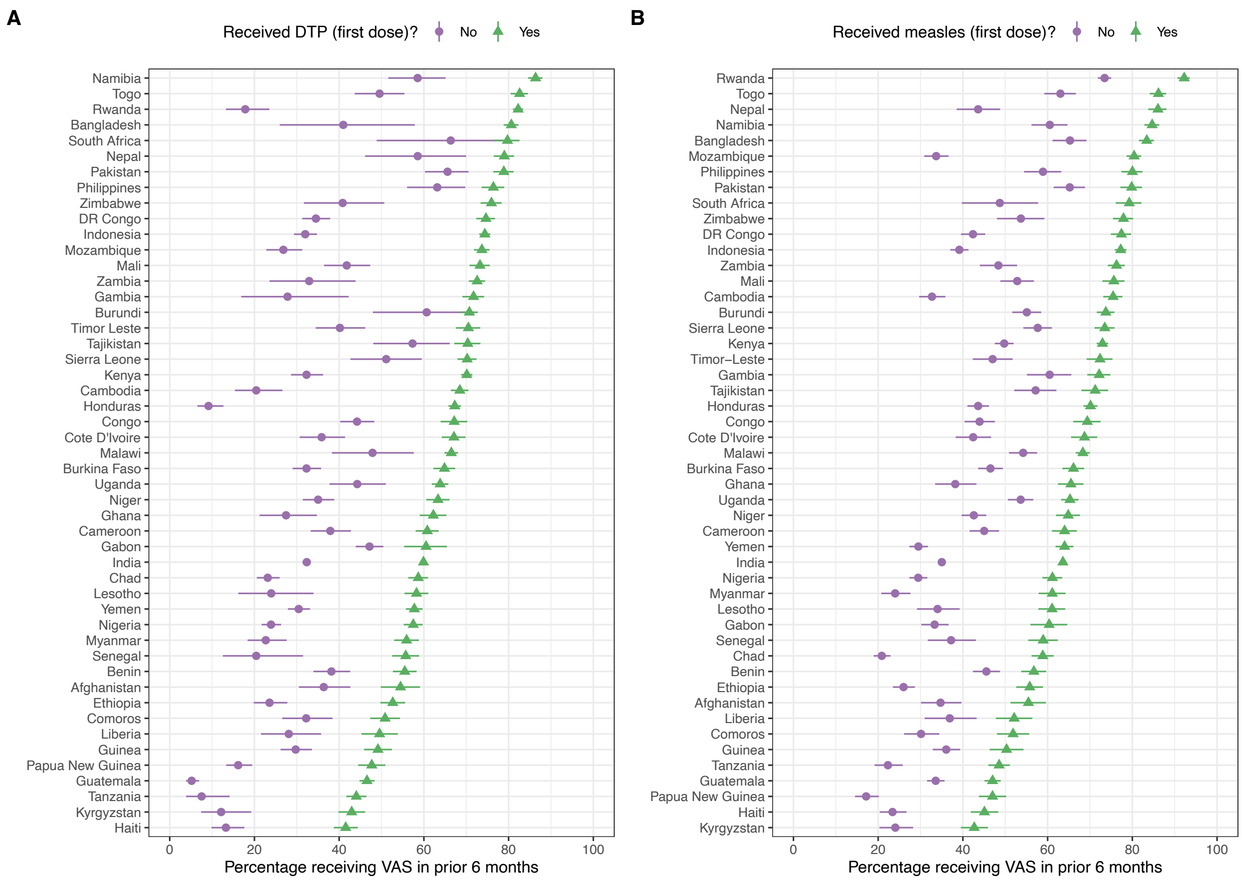

Figure 7.2 Vitamin A supplementation (VAS) coverage among children who have and have not received (A) the first dose of the diphtheria-tetanus-pertussis (DTP) vaccine and (B) the first dose of the measles containing vaccine (indicator of access to healthcare systems and services).

VAS coverage by geography and other enabling determinants

In Figure 3, VAS coverage is stratified by geographic covariates of vitamin A nutritional status for all countries. For place of residence, 31% of countries (n=15) had significantly lower VAS coverage in populations residing in rural versus urban areas. In countries where VAS coverage in rural residences exceeded that of urban residences, differences in coverage were never >8%. For administrative region, regions with the lowest and highest VAS coverage in each country had significant differences in 88% of countries (n=43) with spatial structure in sub-national VAS coverage visible when mapped (Figure 4 for Chad, India, Nigeria, Ethiopia, Yemen; full set of country maps available in Supplementary Figure 1-5).

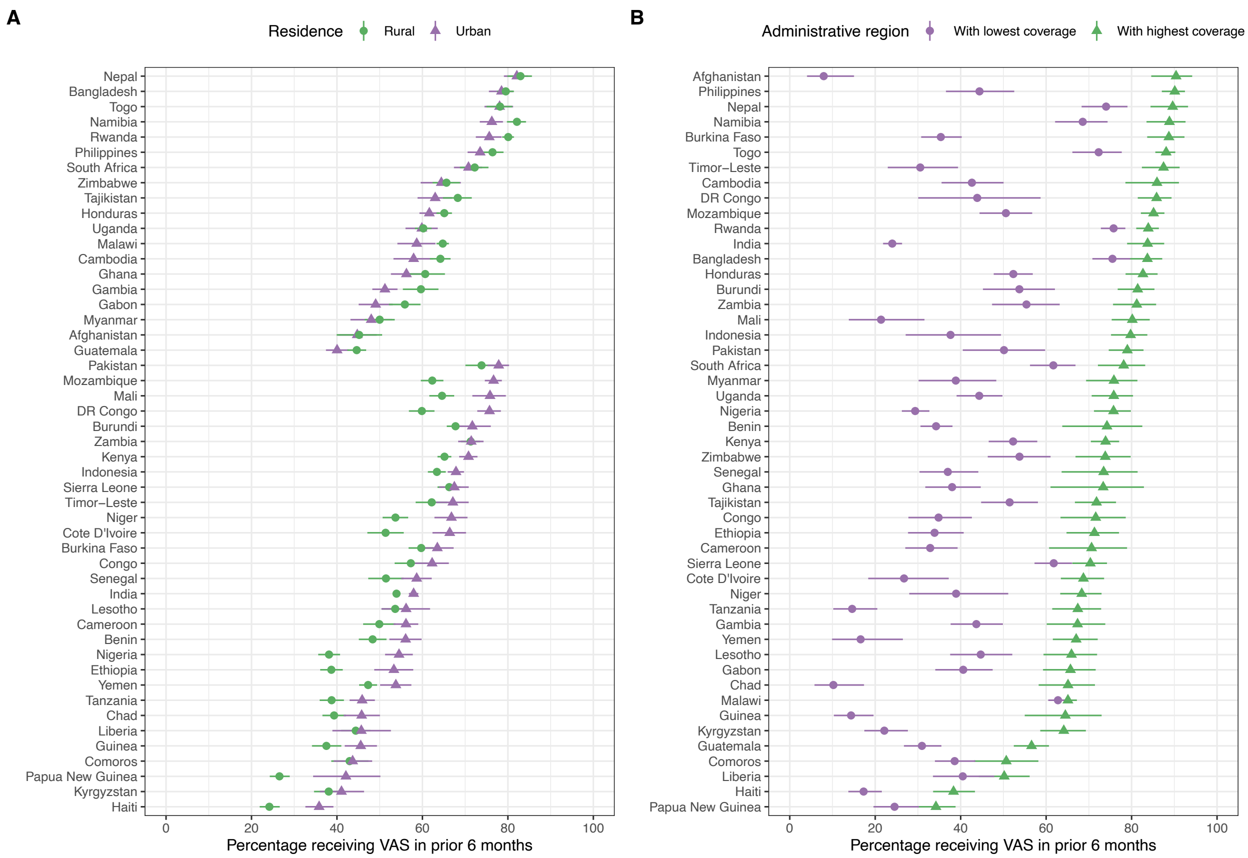

Figure 7.3 Vitamin A supplementation (VAS) coverage disaggregated by geography: (A) rural vs urban residence and (B) administrative regions.

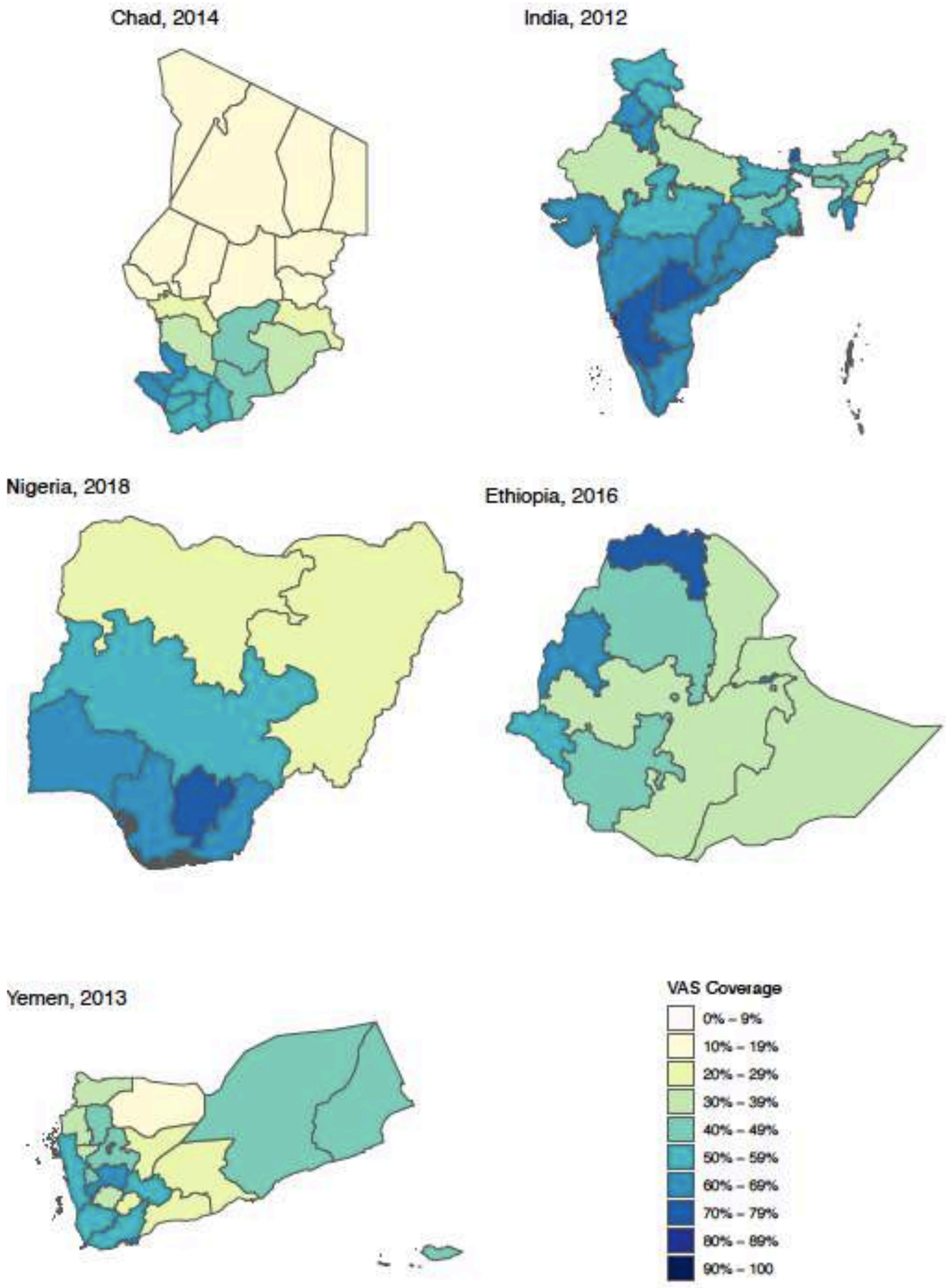

Figure 7.4 Vitamin A supplementation (VAS) coverage maps by administrative regions (maps of all countries available in the supplementary material)

In 73% of countries (n=36), VAS coverage was significantly higher in the wealthiest quintile of the population compared to the poorest quintile of the population, where the differences in coverage between poorest and wealthiest were greatest in Nigeria (33% difference), Cote D'Ivoire (25% difference), and the Democratic Republic of the Congo (25% difference) (Supplementary Figure 6). In 37% of countries (n=18), children of caregivers who were the most socially independent had significantly higher VAS coverage compared to caregivers who were the least socially independent (Supplementary Figure 7). In 20% of countries (n=10), VAS coverage in children of caregivers who were most autonomous in their decision-making was significantly higher compared to children of the least autonomous caregivers (Supplementary Figure 8). Caregivers with higher educational attainment had higher VAS coverage for their children compared to caregivers with lower educational attainment in several countries (Supplementary Figure 9).

7.4 Discussion

This study used open-source data to identify inequities in VAS program coverage so that strategies can be devised to improve VAS coverage among unreached populations. We found that children who likely have lower access to vitamin A-rich foods and who have impaired access to healthcare systems and services are also less likely to receive VAS. This pattern was consistent across most countries and highlights the challenges current VAS delivery faces to reach children that are likely most in need of VAS. The analysis also shows that in some countries, children missed by VAS also reside in the poorest households, in rural areas, and have caregivers who are more constrained by gender norms. Although these are the general trends, we also observed considerable variation between countries. While the use of DHS data to gain insight into VAS programs has been conducted in some countries [29–31], future analyses using DHS data can help inform VAS program operations in other country contexts. National programs can use the analysis presented here as a framework to improve targeting and prioritization of children who are likely to be most in need of VAS delivery programs.

The demonstrated use of DHS data to provide sub-national equity perspectives can provide useful VAS program insights. For example, this study indicated that lower VAS coverage for children who may have lower access to vitamin A-rich foods and healthcare systems and services was consistent across most countries. According to global estimates using UNICEF infant and young child feeding data, the consumption of vitamin A-rich foods by complementary feeding children is lowest in poorer and more rural children [32] suggesting that in combination multiple enabling determinants affecting nutrition are likely to contribute to reduced access to vitamin A-rich foods. However, this study suggests that in many countries, VAS coverage is either equal or lower in these rural and poorest populations despite likely having greater need for VAS.

To address these gaps, VAS programs may benefit from being more aligned with routine community-based delivery programs. In children aged 6 – 11 months, in countries where VAS coverage between vaccinated and unvaccinated children diverges, there is a potential opportunity to improve VAS coverage by aligning programs more closely to the country's EPI systems. This alignment with EPI systems will require program reforms, including the creation of a six month contact point in routine systems, inclusion of VAS dosing schedules on child health cards [33], and strengthening supply chains for vaccines and vitamin A capsules to ensure concomitant availability. For older children who are not serviced by the EPI (12 – 59 months), there may be other established routine early childhood programs where the routine delivery of VAS could be integrated, such as growth monitoring and promotion, counselling on breastfeeding and complementary feeding, early childhood development programs and the early detection and treatment of severe wasting [34]. Current reliance on polio vaccination campaigns to deliver VAS has presented a risk of declined VAS coverage as polio programs cease [30], so identifying other routine community-based delivery programs to integrated VAS should be prioritized.

As the global vitamin A landscape evolves, it is important for national governments to consider how VAS programs can be positioned in combination with other parallel vitamin A interventions to reduce risks for deficiency for all children. VAS has short-term benefits for children (boosting serum retinol for approximately two months after administration) [36], so other interventions are necessary to sustainably maintain adequate vitamin A intake through the diet. For the countries included in this study, 51% (n=25) have nationally mandated the large-scale vitamin A fortification of industrially produced foods items [37]. However, poorer and rural populations - where VAS coverage is often lower – often consume small quantities of fortified food items (e.g., cooking oil, sugar, wheat flour) and may therefore derive limited benefit from industrial vitamin A fortification schemes [38]. Programs aimed at broader improvements in dietary diversity have also been recommended [39], but variation in diets between and within countries pose challenges when scaling up across different contexts. With multiple parallel vitamin A interventions, future studies that simultaneously consider the individual and combined contributions of all vitamin A interventions could help governments orient their national vitamin A strategies.

Evaluating equity dimensions of VAS programs by stratifying coverage estimates using multiple variables can help identify potential gaps in national programs' delivery strategies. This analysis drew from the DHS Household and Woman's Questionnaires to identify enabling determinants to undernutrition that could affect VAS coverage. If differences in VAS coverage are detected between populations, some of these geographic determinants (e.g., place of residence, administrative regions of the country) can serve as indicators that lead to practical recommendations for programs to adopt to bridge coverage gaps (e.g., strengthening programs in a specific region of the country or for a specific demographic). In contrast, other determinants, while useful to evaluate whether VAS programs are broadly equitable, lack clear operational directions on how programs can specifically target populations that are left behind (e.g., socioeconomic position, caregiver's social independence, caregiver's decision-making autonomy). This study explored several different indicators made available in the DHS, and VAS programs could benefit from further research aimed at interpreting the combination of multiple indicators in the context of a country's current VAS delivery strategy (e.g., campaign versus routine delivery).

DHS data can be used to support a variety of nationally implemented child health programs, including developing strategies to increase overall VAS coverage. Insights into national VAS programs that can be drawn using analyses of DHS data include VAS coverage differences over multiple survey years, differences between sub-populations, the potential contributions of risk factors affecting VAS coverage, and differences between sub-national geographies and other spatial analyses [20]. DHS data is becoming increasingly more available in several low and lower-middle income countries and is being used more frequently in peer-reviewed studies to support evidence-based approaches to a variety of public health policies and programs [14]. While the importance of the data generated by the DHS program is reflected through increasing and continued investment, additional investment is necessary to prioritize training and capacity of local statisticians and researchers to use data from the DHS program to inform VAS programs at national levels.

When using DHS data to evaluate VAS programs, there are several limitations that are important to consider. First, the question specific to VAS in the DHS questionnaire is dependent on recall by the caregiver of the child. The percentage of respondents who could prove VAS reception using home-based vaccination records varied between countries, but for most countries (69%; n=34) less than half of respondents had proof of VAS reception (Supplementary Figure 10). For children whose records depend solely on recall by the caregiver, recall error (e.g., confusing VAS droplets with polio droplets, imprecision in the exact date of reception, confusion between multiple children) is more likely. Second, the dietary data collected as part of the DHS only contains one dichotomous recall of whether vitamin A-rich foods were consumed in the past 24 hours by complementary feeding children. No information is available regarding food consumption quantities, weekly variation in diets, or for children aged 24 – 59 months. With this kind of dietary data, it is not possible to understand whether VAS is being administered to children who have inadequate dietary vitamin A intake or who have intakes that exceed daily upper limits to put children at risk for toxicity. To fully understand whether VAS programs are addressing children with the greatest vitamin A needs, VAS coverage should be estimated alongside other sub-national nutritional assessment data (e.g., vitamin A inadequacy from dietary assessment) to identify populations with both inadequate dietary vitamin A intake and low VAS coverage. Third, DHS data are not available in all countries, and in countries where they are available, they are only collected approximately every five years. This study included most countries where recent DHS data are available, but in countries and survey years where DHS are not conducted, these kinds of analyses are not possible. Considering these limitations, VAS coverage data available as part of the DHS is not recommended to replace two-dose coverage estimates. However, two-dose coverage estimates and DHS data analysed in tandem can provide a more complete perspective to inform national programs on overall program performance and how to potentially reach children who are being missed by current delivery strategies.

Conclusion

This study presents a method that can be useful to inform national governments on how to orient their VAS delivery strategy with the potential to integrate with other available data to identify populations with the greatest unmet vitamin A needs. Three decades after the WHO first recommended high-dose vitamin A supplements to infants and children aged 6 – 59 months, the international community has galvanized support to provide countries burdened with high risks for vitamin A deficiency with necessary material resources to progress towards universal VAS coverage. Despite strong political support, in many country settings, VAS programs are unable to reach all eligible infants and children, resulting in a need for evaluations to describe populations that are left behind by current delivery strategies. Evaluations of these sorts, however, require representative subnational data, such as DHS, to describe multiple dimensions of equity to adequately identify populations with the greatest needs and those that are consistently missed. By evaluating the equity dimensions of micronutrient programs, such as VAS, this study can help frame the micronutrient policy agenda towards addressing underlying determinants of undernutrition to inform priority settings and target resources according to need.

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PART III

Discussion, Implications, & Future Research

CHAPTER 8

Discussion of thesis findings, policy implications, and future research

CHAPTER SUMMARY

This chapter summarises the findings presented in this thesis and the relevance to current policy and programme discussions and other related work in the broader field of research. Here, I highlight some of the key strengths and limitations of the body of research presented in this thesis and introduce some opportunities for future research on the use of household surveys to help inform micronutrient policy and programmes. Finally, I provide the overall conclusions to the thesis providing some key reflections on the PhD experience.

The aim of this thesis was to investigate the use of dietary data from large, established household surveys for informing the delivery of equitable micronutrient policies and programmes. Here, I provide an overall summary of the main findings, relevance of this thesis to other research, strengths and limitations, and suggestions for future research in this area.

8.1 Summary of main findings

This summary is divided into three parts which covers all five objectives of the thesis: a summary of dietary data from household surveys (objectives 1 & 2), dietary micronutrient assessment of vulnerable populations (objectives 2-5), and how to use these data to inform national micronutrient strategies (objectives 4 & 5).

8.1.1 Dietary data from different household surveys provide different kinds of micronutrient information

I used HCES dietary data from three different countries and DHS dietary data from 49 different countries to extract information that could be relevant to diet quality and the equity of micronutrient interventions. When assessing the micronutrient adequacy of diets across large populations, several kinds of data can be used to provide different, but complementary information. The kinds of data that should be used will depend on the question being posed as each kind of data will reflect a different population and have different assumptions implicit to how the data was collected. Overall, I find that nationally representative household survey data is particularly valuable for exploring gaps in diet quality between populations within a country and equity dimensions of food systems and micronutrient interventions.

In a systematic review of existing literature, we found the use of food consumption data from HCES to estimate nutrient intakes is growing with an increase in the number of published studies between 2000-2009 (n=9) and 2010-2019 (n=41). From these data, 'apparent intake' and 'nutrient density' were the two metrics used most frequently when assessing sub-populations at-risk for inadequate intakes using household food supply data. The two metrics provide different and potentially complementary insights into population micronutrient intakes. Apparent intake estimates present a wider range in population inadequacy between the poorest and wealthiest households (ranging from a 36- to 67-point difference for vitamin A between the three countries) compared to nutrient density (ranging from a 7- to a 34-point difference). The use of both metrics together can provide useful information when designing public health interventions to meet micronutrient needs, e.g., whether the fortification or biofortification of foods already being consumed by the population is sufficient or whether the provision of fortified staple foods through social protection programmes is necessary.

Common household surveys that dichotomously measure the consumption of micronutrient dense food items (e.g., the dietary data available as part of the DHS or MICS) can be used to measure the recent consumption of foods dense in a certain micronutrient (as done in Chapter 7 with vitamin A) or construct indicators of diet quality (e.g., Minimum Dietary Diversity Score for Women[1]). The data to generate these diet quality indicators are relatively simple to collect, which enables inclusion of these kinds of questions into large household survey systems and rapid analysis across multiple contexts. However, the omission of food consumption quantities and constraints resulting from a limited list of food items or groups of food items produces less information which limits the kinds of diet quality assessments that can be done. As long as these limitations are considered, data from these household surveys, which are regularly collected in many countries, can provide some opportunities for additional insights where the data are relevant.

8.1.2 Focus on the assessment of vulnerable populations

We found that across two countries, Malawi and Nigeria, the poorest populations, especially those that live in rural areas, have a lower total supply of micronutrients, suggesting that they have the most inadequate diets to meet micronutrient requirements. In Malawi, where we conducted a more comprehensive analysis of the national LSFF policy, the vitamin A fortification of oil, sugar, and wheat flour are predicted to contribute less to poorest, rural populations (reducing apparent intake inadequacy by 5 points from 91% to 86%) compared to the wealthiest rural populations (reducing apparent intake inadequacy by 50 points from 60% to 10%) and wealthiest urban populations (reducing apparent intake inadequacy by 47 points from 48% to 1%).

Our analyses first focused on defining subpopulations based on those with the greatest needs then focused on defining subpopulations geographically. In this thesis, the poorest population, especially those in rural areas, were found to have the highest risk of inadequate micronutrient intakes and the ability of micronutrient interventions to reach these populations formed a focus of subsequent analyses. From the perspective of policy and programme decision-making, disaggregation of results by geopolitical regions is appealing and practical as geographic maps can help inform the distribution of programme resources and regional policy priorities. However, certain characteristics of vulnerability cannot be well-defined geographically as drivers of these inequalities can exist within a geographic region. This includes factors such as affordability of micronutrient dense foods, education, and access to markets that can provide micronutrient dense foods[2,3]. Presentation of results geographically using maps continues to be practical and recommended, but ultimately the success of a micronutrient intervention should be defined by how equitably the intervention can fill micronutrient gaps for populations with the greatest needs.

Defining vulnerable groups is not straightforward. Some common approaches include focusing on groups defined as disadvantaged based on current economic indicators (as explored in this thesis) [4], groups with greater physiological needs (e.g., women, girls, children), and historically under-privileged groups (e.g., minorities, undefined settlement status). This thesis focused predominantly on measures of poverty, which is just one aspect of vulnerability. Further research on how well micronutrient policies and programmes can meet needs for other vulnerable groups would help guide the design of micronutrient strategies to be more equitable.

8.1.3 Informing national micronutrient strategies with available household survey data

The kinds of dietary information from household surveys relevant to national public policy will depend on the national micronutrient strategy in a country and the data available. For example, in Malawi the most recent micronutrient survey estimated a low prevalence of vitamin A deficiency in women and children and elevated vitamin A status in children[5] with some uncertainties surrounding appropriate inflammation adjustments and inconsistencies in biomarker measures relative to one another[6]. Our results indicated that the large-scale vitamin A fortification of oil, sugar, and wheat flour had important potential contributions of additional vitamin A, reducing national apparent vitamin A inadequacy from 75% to 41% and disproportionately benefitting the urban and wealthy groups. In addition, there was a low prevalence at-risk for excessive apparent vitamin A intake (3%) if compliance to national vitamin A fortification standards for the three vehicles were met. Additionally, potential inequitable VAS coverage in children between 6-59 months suggests that populations with greater access to vitamin A rich foods may more likely to receive VAS than those with less access. While biomarker data is necessary to estimate the prevalence of vitamin A deficiencies, household survey data can provide additional information to help understand dietary risk factors of deficiency and how to design micronutrient programmes to satisfy unmet needs.

Micronutrient interventions should be continuously monitored and periodically evaluated to assess several factors related to performance, where each should be informed by a different kind of data. According to the *WHO/FAO Guidelines on Food Fortification with Micronutrients* which outlines an extensive monitoring and evaluation framework for LSFF programmes (Figure 8.1), acceptable programme performance is based on the effectiveness and impact of an LSFF programme on the target population to ensure programmes are contributing to national nutrition goals [7]. Household monitoring plays an important role in its ability to identify population needs, such as characterising population diets that are apparently micronutrient inadequate or low density. Additionally, household monitoring can also provide information about the role of LSFF in the diet of target populations, such as whether certain populations consume fortification vehicles and in what quantity. Furthermore, household monitoring is substantially less expensive compared to individual-level monitoring systems[8], although a dependence on external funding and analytical support brings up questions related to sustainability which is important for establishing a lasting monitoring system.

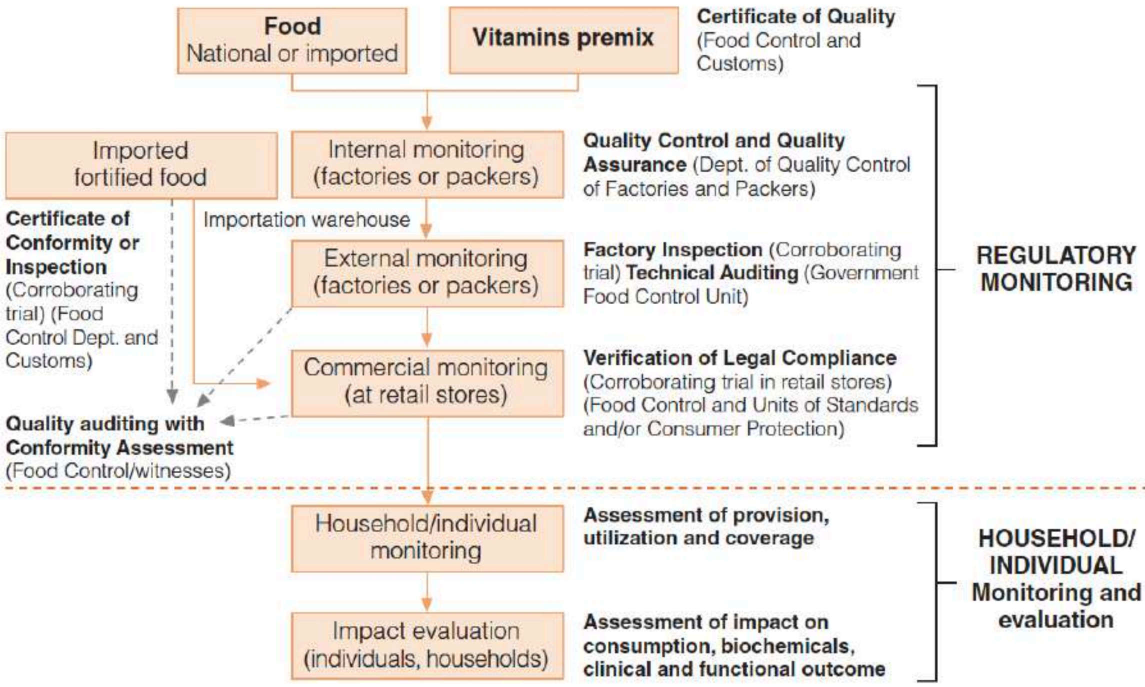


Figure 8.1 Monitoring and evaluation system for LSFF programmes according to the *WHO/FAO Guidelines on Food Fortification with Micronutrients*, where the outputs of this thesis contribute to household monitoring and impact evaluation (below the dotted line).

8.2 Relevance to other research

A variety of nutrition modelling tools have been recently developed to generate information relevant to nutrition policy and programmes. As with the MAPS tool, to which the outputs of this thesis contribute, each nutrition modelling tool is developed using a specific kind of data to answer a specific nutrition policy or programmatic question. The evidence generated by nutrition modelling tools alone are often not the sole motivation for a specific policy decision, but rather may be used alongside other sources of information and evidence, in the context of national priorities[9]. Therefore, simple, relevant communication of evidence generated from nutrition monitoring tools is essential so that consistent data-driven messages can be made part of the broader advocacy and decision-making strategies. Here, I will discuss links between the concepts presented in this thesis and three existing nutrition modelling tools most relevant to this work: IMAPP, MINIMOD, and a recent iteration of the GBD Study.

8.2.1 Intake Monitoring, Assessment, and Planning Program (IMAPP)

IMAPP, under the auspice of the WHO, is a tool developed to estimate whether a given fortification strategy would be safe and effective for most individuals of the population groups consuming fortification vehicles[10]. The tool relies on user provided individual-level micronutrient intake data and daily consumption of potential food vehicles (from 24-hour recall population surveys), sufficiently representative of the populations of interest (the programme developers recommend at least 100 individuals per population subgroup). With this data, along with some user-prespecified assumptions, the tool can calculate the predicted prevalence of inadequate and excessive intake of each micronutrient before and after fortification.

The aims of this thesis relevant to LSFF and those of IMAPP are similar but diverge in the kinds of dietary data each requires. IMAPP depends on user-provided 24-hour recall data, which are often not conducted to be nationally nor seasonally representative. When these data are available, IMAPP is uniquely positioned to provide specific information on the contributions a LSFF strategy can have for a specific demographic group (e.g., women, girls, children) or gaps between demographic groups (e.g., gaps between men/women, boys/girls) that cannot be determined from household level food consumption data. In contexts where data is available, there are opportunities for cooperation between the two tools: the HCES framework presented in this thesis can provide broad potential contributions of LSFF across all regions, between seasons, and between certain sub-populations of interest (e.g., poorest vs wealthiest), and can be used for several micronutrient interventions including LSFF and biofortification (individually and in combination). Smaller area samples of more labour intensive 24-hour recall data can use IMAPP to answer questions relevant to intrahousehold variation in micronutrient needs and the distribution of food vehicles between members of the household.

8.2.2 Micronutrient Intervention Modelling Project (MINIMOD)

MINIMOD is a tool that uses an economic optimisation model to identify the combination of micronutrient interventions that could be delivered to specific target groups in particular geographic areas to achieve a desired level of effective coverage (or proportion of inadequate diets made adequate as a result of an intervention) at lowest cost[11,12]. When originally developed in Cameroon, the tool combined data describing programme intervention costs and data describing dietary micronutrient inadequacy using individual-level 24-hour recall assessment of women of reproductive age and young children. The tool outputs provide a framework for examining trade-offs among alternative micronutrient interventions and lays a foundation for future data investments to improve model inputs to better guide decision-making relevant to micronutrient interventions.

While MINIMOD originally depended on individual-level 24-hour recall data to identify populations in need and predict those effectively covered, recent work on a variation of the tool called MINIMOD-SD (which stands for “Secondary Data”) validated the tool using HCES food consumption data in lieu of individual-level 24-hour recall data[13]. Our work has been conducted in parallel with the MINIMOD HCES work (where K.P. Adams sits on my PhD advisory committee and is part of the MAPS project), and both projects are working to understand how to analyse and interpret micronutrient adequacy metrics from HCES. Both tools contribute important information for public policy; MINIMOD includes information on intervention costs where this thesis contributes a more focused understanding on how vulnerable groups can be targeted. Together, both tools provide different, yet complementary insights to help inform micronutrient policy and programme decision-making.

8.2.3 2019 Global Burden of Disease Study (GBD19)

The GBD19, led by the Institute for Health Metrics and Evaluation, conducted an assessment of the magnitude of risk factor exposures (including iodine, iron, zinc, and vitamin A deficiency) and attributable burden of disease for 204 countries[14,15]. Two main methods are used to estimate prevalence of deficiencies and associated burdens (expressed in DALYs). The first, causal attribution methods, estimates micronutrient deficiencies as the underlying cause of specific diseases where data are available (e.g., extrapolating from data describing incidence of xeropthalmia manifesting directly from vitamin A deficiency)[14]. The second, the risk factor method, estimates deficiencies as a risk factor proportionally attributable to other measurable conditions (e.g., extrapolating the proportion of diarrhoea cases attributable to vitamin A deficiency)[15]. Notably, while micronutrient deficiencies are defined by recommended biomarkers and deficiency cut-off points, none of the micronutrients included in GBD19 use direct biomarker measurement in global burden estimates, except for vitamin A[16].

Estimating the burden of micronutrient deficiencies is necessary to understand the scale and distribution of the problems that manifest from inadequate micronutrient intake. This is estimated using scarcely available micronutrient status data from population biomarker surveys or modelled approaches using proxies. While these models may be considered for use to identify population micronutrient needs, they have limitations when using them to indicate which interventions would be most effective, especially for food system interventions that require dietary data. Our modelling framework can be used to identify the potential effectiveness of food system interventions solutions and predict whether an intervention is capable of meeting needs for certain target groups and whether combined interventions put populations at risk for excessive intake. It is important to note that both approaches are constrained by limitations in the data inputs, and further investment in both population biomarker and dietary data is essential to improve deficiency and inadequacy estimates. However, insights from both are still useful as long as these limitations are acknowledged.

8.3 Research Impact

The outputs of this research have made a novel and impactful contribution to a diverse group of stakeholders invested in dietary assessment and micronutrient programmes. This research greatly benefitted from being well positioned within ongoing national and international discussions related to large-scale food fortification, the use of existing data systems for nutritional assessment, and equitable decision-making for micronutrient policies and programmes. I have divided the impact of my research into two parts: knowledge generation and policymaking.

8.3.1 Novel knowledge generation

The outputs of this research contributed novel understanding of how standard household surveys can be leveraged for micronutrient assessment and policy guidance. There are other bodies of work have used HCES in this manner before, such as to explore equity dimensions of micronutrient programs at national levels[17,18] , or as an advocacy tool for to promote government micronutrient interventions[19]. Uniquely, rather than focusing on a particular country context or intervention, this research was intended to focus on the data itself, and to provide a framework for how these data can be applied (where they exist) in any context for several different micronutrient interventions.

With this open framework available for use for several different purposes, this research was also novel in the way that analyses were aligned so that they ran in parallel with legislative discussions to help guide policy decisions. Hypothetical scenarios were designed based on relevance according to national policy stakeholders and scientific evidence from leading experts. While the base model was developed as part of a research project, the objectives were tailored to address current policy and programme needs through inclusion of several scenarios and a willingness to adapt parameters according to newly emerging evidence. This flexibility in evidence generation provided a case study for how mathematical modelling and evidence generation using HCES data can be brought closer to decision-making.

8.3.2 Impact on policymaking

The outputs of this research have played a valuable role in guiding ongoing national and international policy discussions. At the international level, this research has contributed additional evidence to discussions on how to appropriately use HCES for dietary micronutrient assessment. Several outputs of this research were included in the

WHO/UNICEF/FAO led Technical Consultation on Measuring Healthy Diets: Concept, Methods, and Metrics. The aim of the meeting was to bring together high-level policy makers and leading experts to promote increased communication, coordination, and collaboration, for the purpose of accelerating progress toward identifying or developing a parsimonious set of metrics for global monitoring of healthy diets. Following the initial work helping define the role of HCES dietary assessment methods within the GAVA decision-making framework (as demonstrated in Chapter 6), these key pieces of evidence presented at the Technical Consultation were intended to reflect broader applications and opportunities HCES dietary assessment can have in the dietary data landscape.

In addition, this research played a role in helping inform some key national level discussions on the potential contributions of micronutrient interventions, and identifying opportunities and shortfalls in programme and policy design. Several examples were mentioned in Chapter 6 (e.g., LSFF in Malawi, protein quality maize interventions in Malawi, cassava biofortification in Nigeria), where each analysis was conducted directly alongside a related discussion about reforms to public policy in the respective country. For instance, the Government of Malawi chose not to scale down high-dose vitamin A supplementation programs, where the gaps in the potential contributions of LSFF was one piece of evidence considered in the GAVA decision-making framework. Findings from the Malawi case study were also used in a parliamentary consultation on the importance of edible oil for vitamin A programmes, at a time the government were considering introduction of VAT on imported edible oil.

These research outputs were conducted and disseminated during critical strategic periods of large global health donors, which mobilise additional investment in dietary micronutrient assessment and nutrition modelling. First, this PhD was conducted during the launch of the Bill & Melinda Gates Foundation Nutrition Strategy Refresh, where LSFF was explicitly announced as one of the institution's key investment interests. Second, this PhD was also conducted in parallel with USAID-Advancing Nutrition, the agency's flagship five-year multi-sectoral nutrition project. The outputs of this research were interwoven into a series of investments aimed to better understand data, methods, and metrics to assess diet quality and helped guide USAID missions to make better use of existing data systems. In all cases, the research conducted as part of my thesis were of very high public interest eliciting further research, investment, and questions about further applications of HCES.

8.4 Strengths and limitations

My PhD had several strengths that helped facilitate the research outputs included in this thesis and limitations that warrant further research in the general area. While strengths and limitations specific to each study were described in detail in previous chapters, this section will focus on the overarching strengths and limitations of the PhD overall.

8.4.1 Strengths

Contribution to a broad research agenda: This research is just one piece of a larger body of work that aims to understand how existing data systems can be used to best inform food system policies and programmes. This body of work spans the past 20 years including multiple collaborators representing several institutions globally. Particularly with our research using HCES data, drawing from past experiences from prior research and collaboration with new initiatives have fostered an environment that encourages effective partnerships. While several institutions were directly involved with this research through the MAPS project and other funding ties, academic inputs was graciously provided from institutions including the Living Standards and Measurement Study at the World Bank, the Bill & Melinda Gates Foundation, the World Food Program, Tuft's Friedman School of Nutrition Science and Policy, University of California, Davis, the Malawi Ministry of Health, the Rollins School of Public Health at Emory University, TechnoServe, and the Global Alliance for Improved Nutrition. The foundation established by other researchers and the sharing of expertise, data, and relationships greatly benefitted this thesis.

Sustainability/Impact: This PhD, under the auspice of the broader MAPS project, had strong connections with two large funding agencies during periods where institutional nutrition priorities were being redefined and thus directly impacting the global nutrition agenda. First, the MAPS project was funded during the BMGF nutrition strategy refresh with key programme areas in the strategy refresh focusing on LSFF and nutritious food systems. This PhD had the opportunity to contribute key knowledge about available existing dietary data systems that could potentially be useful for monitoring the development of the BMGF new nutrition strategy. Second, key outputs of this PhD were funded by USAID-Advancing Nutrition, the agency's flagship multisectoral nutrition project. These research outputs were strategically positioned to help USAID's food system work streams that aims to sustain improved diets. As a result of these parallel efforts, the outputs of this PhD were included in the WHO/UNICEF/FAO Technical Consultation of Measuring Healthy Diets on 18-20 May 2021 that aimed to promote increased communication, coordination, and collaboration, for the purpose of accelerating progress toward identifying or developing a parsimonious set of metrics for global monitoring of healthy diets. Overall, the close collaboration with these large global health funding institutions during periods of strategic reform meant that these research outputs contributed to large initiatives with longstanding impacts on global nutrition.

Generalisability: Multiple household survey data sets were used to support the arguments of this thesis with the intent to improve generalisations across several country contexts in sub-Saharan Africa. The project ensured that in-country support from leading research institutions were central to the entire research process. Furthermore, these research methods were developed and conducted in collaboration with other in-country early career researchers and data and code will be made available through online repositories to ensure that the research can continue to evolve. The entirety of this PhD abided by the GATHER checklist[20] and all data processing, analysis and modelling scripts were written in R, a free, open-source software programme. The data from the HCES analyses will be available open access via the MAPS project website after the website's public launch.

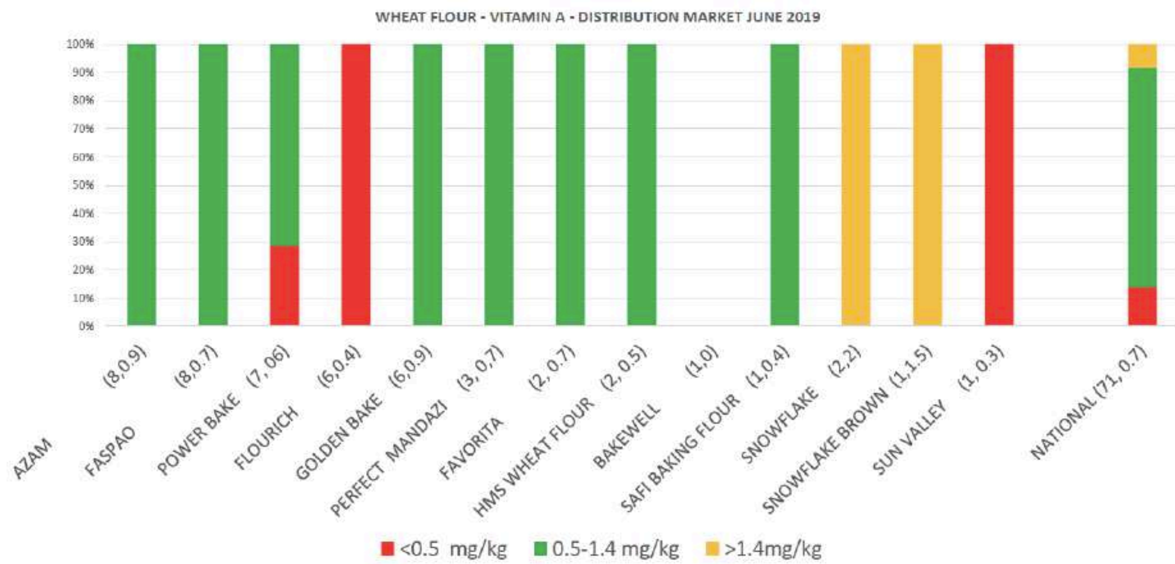
8.4.2 Limitations

Poor understanding of gender differences*:* A key limitation of our work with household survey data are the limited perspectives on gender dimensions of diets. In theory, a household survey would be defined as gender intentional if it is capable of measuring gaps in micronutrient intake between women and men/girls and boys, in addition to linking potential gender gaps in micronutrient intake to broader societal factors that may influence potential sex differences[21]. For HCES dietary data, gaps in micronutrient intake cannot be estimated since any estimate of intake by individual members within a household will be based on adult male or female equivalent assumptions, where food consumed is assumed to be proportionally distributed according to household member MDER. While this assumption is appropriate when constructing population estimates of apparent intake, these assumptions are not appropriate for measuring differences between sexes as actual food distribution versus assumed food distribution within the household is likely to be different[22]. For common household surveys which do collect information at the individual level, dietary data is often collected only in the women's questionnaire meaning that without comparison data from men, potential gaps cannot be measured.

Poor representation for key vulnerable groups*:* National surveys are designed to be representative of an entire country's population, and therefore some groups will not have sufficient data for analysis including minority populations, populations unrepresented in the national census, new populations established in a country after the most recent census, and undocumented populations. While it may be convenient to exclude the analysis of these populations due to data constraints, it is critical to invest in alternative ways of collecting dietary data on these sub-populations through bespoke population surveys or small area estimates as oftentimes there is little to no information to understand how vulnerable these populations are to micronutrient deficiencies. Based on other research that indicate poorer living standards and social barriers within these groups[23,24], access to micronutrient dense foods may also be hindered making these groups high-priority targets for micronutrient programmes.

Intervention scenario assumptions*:* When modelling the potential micronutrient contributions of a fortification scenario using the HCES estimates, our models must assume that all fortification vehicle suppliers are equally compliant or non-compliant to national fortification standards. For example, data from national monitoring systems in Malawi indicates that substantial heterogeneity exists between private producers of fortifiable products, where compliance to LSFF standards varies on a company-by-company basis (Figure 8.2). In many countries, national monitoring systems are in place to identify how well producers adhere to national fortification standards. Linking these standards adherence data from the production perspective to our consumer-perspective models is not possible as HCES do not collect data on the brands of most purchased fortification vehicles. Our models measure the maximum potential micronutrient contributions of a fortification vehicle relying on assumptions that entire industries are responding to national standards equally. If our consumption-based models were paired up with production-based data on adherence to standards, information from both the producer and consumer perspectives could be developed to better inform national strategy.

A. Wheat flour



B. Edible oil

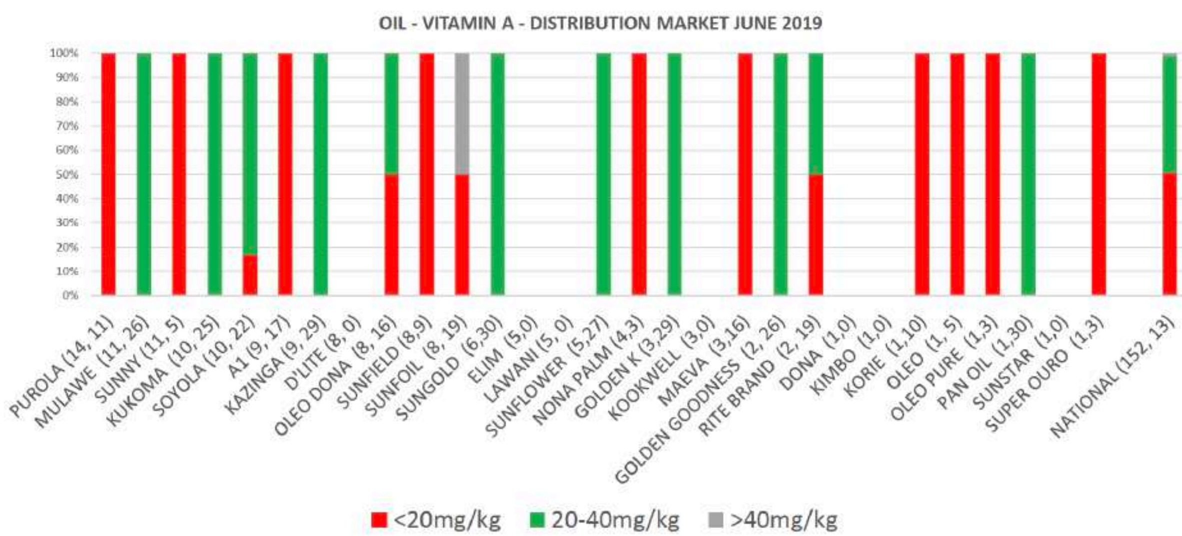


Figure 8.2 Wheat flour and edible oil vitamin A fortification adherence by brand based on the January 2020 National Joint Monitoring Exercise from the Ministry of Health and Population of Malawi.

8.5 Current discussions and future research

Here, I describe current discussions that have persisted throughout the entirety of my PhD and present some suggestions for future research. I will focus my suggestions on HCES as it constitutes a majority of my work and since other research initiatives are already working to improve the DHS/MICS style dietary data.

8.5.1 Reforming HCES to improve micronutrient assessment

HCES food consumption questionnaires have several constraints. There is potential to improve the quality of quantifying foods consumed and estimating household micronutrient supply.

Food item lists: Research on the length and composition of the food item lists could lead to improved quality of household food consumption data. The impact of the length and composition of food item lists has been previously explored in depth in Bangladesh, where Bell et al. found that additional 24-hour recall data could help create a concise food item list that captures most foods consumed and eliminate rarely consumed items[25]. In HCES questionnaires, a fixed food item list constrains respondents to predominantly recall food items included on the list, so the composition of the list will greatly influence the quality of dietary data collected. The construction of food item lists varies between countries. In some countries, lists evolve over several rounds of an HCES (e.g., the Ethiopian Socioeconomic Surveys), where in others a new list is intentionally created and sometimes used in several countries within a region (e.g., the Household Survey Harmonisation Project implemented in Benin, Burkina Faso, Chad, Cote d'Ivoire, Guinea Bissau, Mali, Niger, Senegal, and Togo). A list that is not representative of most foods consumed by a population risks underestimating intakes and inflating apparent micronutrient inadequacy. Lists that are too long risk deteriorating the quality of the data due to increased respondent fatigue. Additionally, poor representation of food items used as potential LSFF or biofortification vehicles on the list further complicates modelling of micronutrient interventions, as we experienced with the poor definition of edible oil on the Nigerian Living Standards Survey.

Quantities consumed: HCES methods rely on respondents' self-reported quantities consumed, which has low precision considering the longer recall period, administration at household level, and reliance on a variety of non-standard units. To improve the accuracy of quantitative food consumption estimates, additional field research could explore novel uses of visual aids/photographs standardising portion quantities, proxy containers for reference, or other measurement tools to guide respondents’ estimation. Additionally, multipass methods and other verbal probes for certain food items prone to overestimation (e.g., Did you consume that quantity of food or acquire it? Did any of that food go to waste?) may be helpful to discern quantities of food actually consumed by households.

Food-Away-From-Home (FAFH): HCES often do not capture food consumed outside the household, such as in restaurants, street food vendors, or through school feeding programs, which can lead to underestimation of the total intake. FAFH can contribute a substantial proportion of foods consumed in a diet, especially for certain populations, and their relative contribution is likely to grow with economic growth and increased access to FAFH. The potential impact of FAFH in the context of HCES has been explored in more detail by Fiedler and Yadav using HCES data from India, where they argue that FAFH data collected at the household level is subject to recall error and the extent of which varies greatly on urban versus rural and the typology of the consumer (e.g., children partaking in school feeding programs, urban populations consuming vendor/restaurant foods)[26]. They argue that household-level data (i.e., food consumption, FAFH) could be recalled more accurately by using a question-based conceptual framework of typologies of meal patterns developed from individual-level data describing meals-away-from-home. While several national HCESs include a FAFH module, more research would improve our understanding of how this conceptual framework and these typologies apply to various contexts.

8.5.2 Evaluating gender dimensions of diets using household survey data

A key limitation to micronutrient assessment using household surveys is the limited insights HCES can provide about the differences in the micronutrient adequacy of diets between sexes and social phenomena that contribute to potential gender gaps. Our research indicated that HCES micronutrient assessment methods are not sufficient to address questions of sex-differences in intake as estimates greatly depends on ungrounded assumptions of how foods are distributed between members of the household. In order to answer important questions about whether current diets and micronutrient programmes are capable for meeting the specific needs of women and girls, new investments in primary data are necessary.

New data that can help answer existing questions on whether micronutrient programmes are gender equitable are one of the most worthwhile investments for future research in this field. Small sub-samples in HCES where individual level food consumption data are collected for all members of households would provide critical information about how foods are distributed between household members. If sub-sampled households can be linked to the full

HCES, gender gap analyses could be tied to other variables collected in the full survey allowing a linkage between gender gaps in diet quality and other socioeconomic variables commonly measured via HCES.

8.5.3 Consolidated metrics of micronutrient programme inequity

This thesis found that LSFF programmes in some countries may not be equitably designed to reach populations with the greatest micronutrient needs and that HCES data can be used to characterise inequalities in diets and inequities in LSFF programmes. Characterising inequalities in diets using HCES is challenging because multiple metrics sometime provide conflicting public health messages making policy decisions challenging. The communication framework presented in Chapter 5 was a modest attempt to start exploring mechanisms to combine results of multiple metrics together for improved messaging, but I think a sizable research gap exists for exploring new techniques to characterise and highlight micronutrient programme inequities. Existing research in the fields of development and health economics have developed ways of presenting economic inequality and programme inequity in clear and concise language to help inform decision-making[27,28]. Further research applying HCES micronutrient adequacy assessment to some of these established methods of describing programme inequity may provide another useful perspective when monitoring and evaluating micronutrient programmes.

8.6 Overall conclusions

This thesis represents a modest attempt at understanding how to measure diet quality in relation to the micronutrient status of a population. Several types of data can be used to determine micronutrient needs in a population (chapter 3), where household survey data present distinct advantages due to their wide availability and ability to capture variability at a sub-national scale (chapter 4). Evidence generated from HCES data can be used as an effective tool for informing micronutrient policies and programs to highlight the populations who are most vulnerable and who have the potential to benefit from specific programs (chapter 5 & 6). Here, we were able to disentangle the kinds of information each metric presents, the sensitivities of our population estimates to assumptions, and how to communicate these results for more actionable dissemination. Using information from diverse sources can reveal a more complete understanding of a population's potential micronutrient vulnerabilities (chapter 6 & 7).

In this micronutrient-focused thesis, it is becoming increasingly clear that one kind of data is likely not sufficient to provide a complete understanding of the micronutrient status of a population. Pre-established household survey systems can generate useful information about the micronutrient adequacy of diets, but it must be made clear that these proxy data provide just one perspective and have substantial limitations. Recognising these limitations should not discourage their use, but rather encourage improvements to current survey design or investment in entirely new surveys to generate more individual level intake data. When engaging in discussions between researchers, donors, policymakers, and programmers about potential micronutrient policy action, we often refer to 'data' as necessary when informing decision-making. This is a good start, however I think these discussions need to be more nuanced where questions about what ‘data’ exists are immediately followed up with the extent to which these data are capable of answering our questions. This is an exciting time where greater recognition about what each micronutrient data type can and cannot inform will encourage researchers from diverse backgrounds to weave their contribution into the broader body of evidence. With ambiguity on the best approach forward, further backed by considerable momentum to make diets healthier, there is a huge amount of potential to improve diets for the most vulnerable through improved data collection, harmonised metrics and models, and collaborative partnerships.

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Appendices

I. Original Micronutrient Action Policy Support (MAPS) project protocol
II. Ethical approval letter
III. Supplementary material for Chapter 4: Systematic review of metrics used to characterise dietary nutrient supply from Household Consumption and Expenditure Surveys
IV. Supplementary material for Chapter 6: Modelling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys
V. Additional publication: Limited supply of protein and lysine is prevalent among the poorest households in Malawi and exacerbated by low protein quality
VI. Final published version of Chapter 7: Evaluating equity dimensions of infant and child vitamin A supplementation programmes using Demographic and Health Surveys from 49 countries

Original Micronutrient Action Policy Support (MAPS) project protocol

MAPS

Micronutrient Action Policy Support (MAPS) Tool

Version 3.1, 18th November 2021

FUNDERS: Bill & Melinda Gates Foundation

LSHTM ethics reference: 21903

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GLOSSARY OF ABBREVIATIONS

BMGF	Bill & Melinda Gates Foundation
DALY	Disability-Adjusted Life Year
FAO	Food and Agriculture Organization of the United Nations
GCS	Geographic Coordinate System
GDPR	General Data Protection Regulation
HCES	Household Consumption and Expenditure Surveys
IHME	Institute for Health Metrics and Evaluation
MAPS	Micronutrient Action Policy Support
LSMS	Living Standards and Measurement Surveys
MND	Micronutrient Deficiency
MNS	Micronutrient Surveys
OSM	Open Street Map
SSA	Sub-Saharan Africa
WB	World Bank
WHO	World Health Organization
WP	Work Package

KEYWORDS

Micronutrients; Data; Online tool; Assessment; Cost-effectiveness; Ex-ante

STUDY SUMMARY

TITLE	Micronutrient Action Policy Support Tool
DESIGN	Secondary data analysis
AIMS	To provide and make accessible information on population micronutrient status in sub-Saharan Africa and India
DURATION	01/04/2020 to 31/12/2022

1. INTRODUCTION

1.1 Background

Micronutrient deficiency (MND) risks need to be understood better at various scales and time-horizons, to support evidence gathering for policy interventions and programme investments. This is especially true for nations which have not yet conducted detailed or recent micronutrient surveys (MNS). Even where data do exist, communicating how MND risks will change over time and with different interventions is essential as food systems evolve and respond to socioeconomic and environmental change.

The MAPS project will deliver a co-designed, web-hosted tool, to enable the best possible estimates of MNDs to be communicated at national and sub-national scales in Africa. Through novel functionality, this tool will allow users to view and explore MND risks at various spatial and temporal scales, in both data-rich and data-poor nations. We will also scope the ability to extend the tool to three states in India – Utter Pradesh, Odisha and Bihar.

The tool will provide users with estimates of population micronutrient status and prevalence of deficiencies using existing secondary datasets. The information will be drawn from MNS that include biomarkers of micronutrient status, or proxies thereof such as anaemia. In addition, dietary micronutrient supply estimates of all nations in sub-Saharan Africa (SSA) will be made calculated and presented using national-scale data, which can be spatially disaggregated by population data. Where survey data on food consumption (e.g. Household Consumption and Expenditure Surveys, HCES) or food composition (e.g. GeoNutrition surveys) are available for a nation, these data will support delivery of sub-national estimates of dietary micronutrient supplies and risks of deficiency. Where both types of data are available with good spatial resolution for the geography of interest, these will provide the most spatially disaggregated estimates possible.

Baseline estimates of MNDs from these initial assessments in the user's geography of interest can then be taken forward in the tool to allow, for example, (1) foresights of food system changes, (2) estimates of cost-effectiveness of food system interventions, including dietary diversification, fortification, and biofortification, and (3) exploration of linkages between MNDs and associated health burdens. The tool will be implemented through a Food System - Nutrition Module and a Cost - Effectiveness Module. The MAPS tool will be a unique enabling environment for the wider Agriculture-Nutrition community and beyond.

This protocol covers the activities relating to the identification, extraction, processing, analysis, storage and integration of micronutrient biomarker and food system data into the MAPS tool, as well as the communication of tool outputs to support appropriate use of the information. This component of the project is led by LSHTM with contributions from all project partners.

1.2 Rationale for current study

Micronutrient deficiencies (MNDs) are a widespread global problem, especially in SSA and south/southeast Asia, generally impacting the poorest nations the most. The scale and impact of MNDs are unequally distributed within nations due to geographical, socio-economic and dietary factors. The consequences of MNDs include impaired growth, cognitive development and immune function, with women of reproductive age and young children at particular risk due to their greater micronutrient requirements.

Estimating the prevalence of MNDs in a population can be achieved through national MNS based on tissue biomarkers, or MND risks can be inferred from dietary intake assessments. These metrics can be mapped at sub-national scales and this information can inform action to redress MNDs; however, underlying data (including geographically appropriate, spatially referenced food composition data) are required to support these estimates (e.g. Joy et al., 2015a).

It is widely recognised that good nutrition underpins the successful achievement of many of the Sustainable Development Goals and, in a rapidly changing world, understanding how some of these deficiencies may change without further direct action considering projected economic growth and environmental change is important (Nelson et al. 2018). Furthermore, maintaining healthy micronutrient intakes may be challenging in a context of reducing the environmental impacts of food systems (Willett et al. 2019), and the potential increase in intake of anti-nutritional factors such as phytate through increased consumption of whole grains, legumes and seeds/nuts.

The policy need of the MAPS tool was established with key users in the project formulation phase, and the continued user participation throughout the design and testing process will ensure this focus is retained. The tool interface and output designs will also be co-designed by stakeholders to ensure that these meet priority needs of users. The tool itself will be open-access to allow future extension; input/output data will also follow this principle where licencing agreements permit. Users will also be able to use the tool with their own datasets, through a secure 'bring your own' capability, e.g. where new HCES or food composition data become available.

The MAPS tool will use the best-available data to assess current and near-future MNDs, with rigorous approaches to spatial predictions, to enable users to gain an understanding of the current MND status in their geography of interest and enable informed investments. This will be the case even in data-poor countries in Africa, where only national-level aggregated data are available, in which case the tool may also help inform and advocate for future survey and surveillance activities. It will also embed a functionality that allows exploration of different food system interventions and how these may affect single or multiple MNDs, before using the cost-effectiveness functionality.

2. STUDY OBJECTIVES

The objectives of this study are:

(a) To identify relevant datasets on micronutrient biomarkers, dietary data and food composition together with information on their accessibility and an acquisition strategy.
(b) To acquire and compile all relevant pre-existing data (see data types in section 5), which will have varying conditions for access, re-use and licensing.
(c) To clean and prepare raw datasets including the extraction, standardisation and consolidation of data for downstream use to populate the tool.
(d) To review existing studies using household consumption and expenditure survey (HCES) data to measure food consumption and/or nutrient intake in low and low-middle income countries:
    i. To describe methods used to match nutrient composition of food items and quantify intra-household consumption of food and/or intake of nutrients using HCES data;
    ii. To assess the extent to which existing studies have included evaluations of the equity dimensions of nutrient intake as an objective in their analysis;
    iii. To define current communities of practice who use HCES data to measure food consumption and/or nutrient intake in LMICs.
(e) To estimate dietary micronutrient supplies and the prevalence of deficiencies in Malawi, Ethiopia, Zambia, Nigeria, Tanzania and Burkina Faso using HCES and micronutrient survey data. Additionally, we will compare the use of Adult Male Equivalent and Nutrient Density metrics for reporting supplies in Malawi, with an assessment of equity implications.
(f) To compare estimates of dietary micronutrient supplies and deficiency risks arising from individual-level dietary data and HCES-derived data in Malawi.
(g) To model the potential maximal coverage and predicted effectiveness of sugar, salt, oil and wheat flour fortification in Malawi.
(h) To scope the extensibility of the MAPS tool to three States in India – Uttar Pradesh, Odisha and Bihar – primarily through secondary data landscaping.

3. STUDY DESIGN

The MAPS project is structured around five activity-based Work Packages (WPs):

WP1. User co-design of tool interface and output formats

WP2. Data curation
WP3. Modelling and uncertainty visualisation
WP4. Tool Development
WP5. Sustainability
WP6. India scoping study

The ethical considerations of each of these WPs is quite different, and WPs will operate under separate ethical approvals. The current application covers activities related to WP2 and related methodological development, some of which will occur through partnerships between the MAPS team and academic collaborators, and through aligned PhD projects. Where these PhD projects have objectives distinct from this protocol, separate ethical review applications will be made.

For the MAPS tool, data will be required on food systems, agriculture systems, human health, population demographics, and potential interventions to improve micronutrient status. Currently, these data exist in various locations and formats, and a substantial amount of work is required to prepare these data for use in the tool. The MAPS study will draw exclusively on secondary data. Datasets which are not fully open-access (i.e. CC-BY) will need licenses agreed with data owners before they can be used in the tool. This is a process which will start early in the project as it may take many months.

Before embarking on the data acquisition and preparation, the project will make use of previously formatted data and methods of standardisation (with appropriate acknowledgement) and use these to avoid duplication of effort. We will do this by directly contacting other research projects to understand and use data they make available. We shall similarly make data available to re-purpose by other funded projects. The project will maintain a record of the tool's data ecosystem, which will be linked to the meta-data on each data set: this will be version-control updated as the project progresses.

The study will be exclusively desk-based and will not involve research participants. There are, however, potential ethical issues relating to the storage and use of secondary data and these are addressed in the data management plan below.

4. STUDY OUTPUTS

- Documented license agreements for the use of data within MAPS and report to BMGF on barriers and opportunities in this area.
- Data import and processing scripts, SOPs and documentation for repeated or large datasets
- Data and metadata architectures that are interoperable with WP3 model catalogue and will support WP4 development requirements.
- A populated data catalogue required for WP4 implementation and tool release.
- Peer-reviewed publications on methodological developments and novel insights into the estimation of population micronutrient status from secondary datasets
- Data analysis scripts, tables and figures delivered to Zambia national micronutrient survey team for inclusion in the national micronutrient survey report
- Training and skills development of Tanzania Food and Nutrition Centre staff, to enable their independent use of the MAPS tool for micronutrient surveillance and intervention exploration based on Tanzania Household Consumption and Expenditure data
- A nutrition data landscape document for India

5. DATA MANAGEMENT

5.1 Data types

For the MAPS tool, data will be required on food systems (e.g. food consumption, composition, fortification, market availability, trade), agriculture systems (e.g. crop/livestock production, fertiliser use), human health (e.g. population micronutrient status, disease burdens), population demographics and potential interventions to improve micronutrient status (e.g. programme coverage and costs). Data will be derived from focus geographies of the MAPS project: Ethiopia, Malawi, India, Burkina Faso, Zambia and Zimbabwe. Currently, these data exist in various locations and formats.

Food consumption and dietary supply data

A critical WP activity will be wrangling of data from large household consumption and expenditure surveys (HCES), which present the most detailed dietary intake proxy data likely to be available in many countries where no biomarker or individual dietary intake surveys are available. The World Bank (WB) Living Standards and Measurement Surveys (LSMS) contain valuable socioeconomic and food and agriculture system data from large sample populations that are representative at national level and in some cases at least one level of sub-national administrative unit, e.g. 'Region' or 'District'. The LSMS are repeated every ~3-5 years with consistent methodology and microdata are publicly available. The value of LSMS for modelling food systems and micronutrient interventions has been demonstrated previously (Fiedler et al., 2012) and will be used at scales which are supported by the power in the sampling design.

The raw LSMS data are publicly available to download on completion of a short form detailing planned uses for the data, and on agreement not to share the data. Other HCES may require formal approaches, likely involving requests to the National Statistical Offices. For India, a request will be made for access to data from the Comprehensive National Nutrition Survey 2016–2018 and the National Family Health Surveys 4 and 5.

In order to work most efficiently with the available LSMS data, and to ensure that any findings support continued appropriate use of the datasets we shall liaise closely with the WB LSMS team, who will also benefit from the interaction with this part of the project. Specifically, we will work with them to: (1) develop guidance on the use of LSMS data in nutritional contexts, especially using the data at sub-national levels; (2) using the data to estimate individual-level dietary intake (via, e.g., the adult male equivalent method); (3) options to access data without spatial offsets, given appropriate secure management agreements (see section on biomarker data for details on maintenance of privacy/anonymity); (4) provide information on the expected cycle of LSMS surveys in African nations, in order to identify where new data may become available during MAPS project lifetime; and, (5) facilitate access to in-country data owners of LSMS datasets. We will also explore possible enhancements of the LSMS questionnaire portfolio. This engagement with LSMS will allow us to design the tool so that LSMS data are applied by MAPS users in ways which are consistent with the LSMS team's own understanding of the data and how they can be used appropriately. This will also help tool sustainability, as these are likely to be the most comprehensive HCES data which continue to become available after the funded project lifetime: facilitating input of these data will greatly benefit post-project availability of data and visualisations from the tool.

The MAPS project will develop and follow SOPs for HCES data preparation. These will include steps to remove or nullify clearly erroneous data points, prior to their use in the tool. Data can then be aggregated at an appropriate spatial scale, depending on survey design and data quality with the latter implemented using methods developed in WP3.

Where HCES data are not available, national level FAO Food Balance Sheet data may provide a proxy for consumption (e.g. Joy et al., 2014; Kumssa et al., 2015; Nelson et al., 2018). These data are fully open access. Whilst there are recognised weaknesses, this source provides a systematic approach for all nations which report to the FAO, and for some nations will be the best available estimates of food consumption. The most recent African country data (and potentially India) will be imported using protocols already established by the project team in previous work, and published in project documentation. Corrections routinely employed, such as for non-edible portions (e.g. banana skins) will also be documented. Previously prepared data, or data correction protocols, held within the project team (or published elsewhere) will be used to avoid duplication of effort.

Other sources of secondary data will be explored, particularly for nations where there are not HCES. Sources of many of these data are captured already in the FAO/WHO GIFT tool, with varying access restrictions. This activity will also seek nationally or regionally representative individual dietary intake survey data, which are less common due to the cost and time requirements. Where multiple data layers exist, protocols will be developed in WP3 to compare the extent to which the different approaches to estimating dietary supply draw the same conclusions.

Food composition data
Food composition data are required to estimate dietary micronutrient supply and intake. The lack of appropriate food composition data is often cited as a major limiting factor to calculating dietary micronutrient supplies. The MAPS project will draw on the substantial new crop composition datasets being generated through the ongoing GeoNutrition project. Currently, spatial maps of concentrations of elements in cereal crops are being developed for Ethiopia and Malawi, and these data will be integral to full tool development. A high spatial resolution of food composition data is essential for mineral micronutrients (e.g., selenium) where crop uptake is influenced to a large degree by spatial factors such as soil properties, climate, etc. WP3 will develop systematic statistical approaches to evaluate where spatial variation in crop composition may influence dietary estimates and explore the extrapolation of GeoNutrition data to data-poor settings. The GeoNutrition data will be open access following peer-reviewed publication.

Other composition data including for non-cereal crops and for vitamins and phytic acid will be drawn with appropriate acknowledgement from a variety of sources, including primary literature. For other food items and for countries outside of the GeoNutrition project, food composition data will be drawn from the most geographically relevant food composition tables. National-level food composition tables will be prioritized for matching. In countries without open-access food composition tables, food items will be matched to food composition data from neighbouring countries. If food composition data is still unmatched. Food composition data will be drawn from regionally compiled data (e.g. FAO West African food composition tables) or international equivalents (USDA food composition tables).

Foresight scenario data – food system changes
The IMPACT model scenario outputs for food system futures will be immediately available and open access in the context of the MAPS project and tool development. IMPACT provides yearly projections data for what the future (out to 2050) "average" plate available to the average consumer in any given country or aggregated region will be. IMPACT scenarios show the changes in food availability across several climate and socioeconomic futures (see details in Annex 1). In addition, alternative futures in IMPACT also explore the potential impacts of different key drivers of the food system productivity, consumer preferences, evolution of value chains, and many other topics.

While the output data would be immediately at the disposal of the MAPS tool in open access format, there are many input data for the IMPACT model that come from a variety of sources (see Robinson et al. 2015 for details) with different levels of open access. The MAPS project will develop a strategy to navigate the multiple levels of intellectual property rights for these datasets.

Agricultural and environmental data
Existing soil information will be used from sources such as AfSIS and the Soil Atlas of Africa, alongside crop production areas (e.g. Sentinel-2 data) and other open-source data currently used in modelling activities by the project partners, or in the literature (e.g. Herrero et al., 2017). The high-density data currently arising from GeoNutrition, and data from selected published sources, will be used to predict where a locally-appropriate food composition table should be used, which this project will uniquely use in addition to subnational cropping area data already available (e.g. Herrero et al., 2017; Nelson et al., 2018). Fertiliser formulations may also be examined in case studies to look at possible changes to influence dietary supply of micronutrients (e.g. Joy et al., 2015b).

Biomarker and proxy deficiency data
Directly measured biomarkers (e.g. serum retinol, urinary iodine) and recognised proxies (e.g. anaemia as a proxy for iron deficiency) are collected in micronutrient surveys. These are available for many nations and demographic groups and are regularly used to draw inferences at the national-scale (e.g. James et al., 2018).

The biomarker data are potentially sensitive. However, only de-identified data will be accessed, prepared and entered into the tool. For the majority of national surveys, anonymity is further preserved through reporting only of cluster data, often with a 5 or 10 km spatial offset. The project team have demonstrated that it can be possible to use these data to make subnational predictions of micronutrient status (e.g. Phiri et al., 2019), with agreement on sharing original locations of the cluster data. This geostatistical process also removes all original sample location information to further preserve participant anonymity and remove all possibility of "reverse engineering" the primary data, as it does not disclose sample locations, nor the individual-level data from the clusters. This approach has been demonstrated with confidential data used in Lark et al. and outputs, which do not disclose the confidential data locations or values, made publicly available as a result of that work (http://www.ukso.org/static-maps/magnesium-network-project.html and see the link to the Map Viewer). The MAPS tool will first demonstrate this for Malawi and Ethiopia, where existing data agreements are in place with the appropriate Ministries and data owners. Data agreements with other countries (Burkina Faso, Zambia, India and Zimbabwe) will be developed during the second year of the project.

When using this approach, the files containing the confidential data locations or values will be stored separately from MAPS input data files. They will be stored in a password-protected folder on a secure server at BGS. Only the MAPS project statistician and data manager will have access to these files by default. Other research team members will be granted access only to the files they require for the research and tool development.

Burden of micronutrient deficiency data

The DALYs framework will be used to explore the burden of MNDs where suitable frameworks exist (currently for iron, zinc, iodine and vitamin A) (e.g. Joy et al., 2015b). We will explore the use of data already calculated by Institute for Health Metrics and Evaluation (IHME) for these, which are based on biomarker measurements for iron and vitamin A, and on dietary supply and stunting prevalence rates for zinc, and goitres for iodine (James et al., 2018). Our approach will also allow the use of dietary estimate from dietary supply data and locally relevant food composition tables, and direct measures of micronutrient status available from national micronutrient surveys where these are not already captured in the IHME tool (e.g. zinc deficiency prevalence estimated using serum or plasma zinc concentrations).

As with other aspects of data assimilation, we will not replicate activities where outputs (e.g. DALY estimates) using a consistent format are already available from existing funded activities, and will liaise with those programs to ensure this is the case. Where there may be differences in approach we will consider the benefits of these against the other priority activities and seek views beyond the project where appropriate (such as referenced in Critical Relationships).

Cost of interventions data

As described in Fiedler and MacDonald (2009), the costing methodology will be based on the specification of a series of activity- and ingredients-based algorithms to fully characterise an intervention. National and/or subnational cost estimates will depend on local ingredient prices, the structure of industry, etc. Cost data will be drawn from a wide range of sources, including:

- Global Fortification Data Exchange: https://fortificationdata.org/
- Food Fortification Initiative: http://www.ffinetwork.org/
- GAIN Premix Facility: http://gpf.gainhealth.org/
- International Labor Organization: https://www.ilo.org/global/statistics-and-databases/lang--en/index.htm
- United Nations Industrial Development Organization (UNIDO) databases: https://www.unido.org/researchers/statistical-databases
- World Bank Development Indicators (GDP/capita): https://datacatalog.worldbank.org/dataset/world-development-indicators
- Trade association reports (e.g., World Grain Report)
- the SEEMS-Nutrition project

We will also conduct a thorough review of the literature (both published and grey literature) and develop a database of food-system-based micronutrient intervention costs estimates. We will also consider the beneficiaries of such interventions, for instance it has been shown that small-scale producers using local flour mills may be unlikely to benefit from flour fortification (Fiedler et al., 2013).

Administrative data
Boundary files are essential in order to create a maximum extent of area-based data queries or for running WP3 modelling procedures, and for visualisation of data inputs and outputs. These spatial data are widely available at national boundary scale, although not often updated (e.g. GAUL), but there is variable data available at sub-national scales. Open Street Map (OSM) data will be used where there is not an 'official' source of spatial data, such as released by Malawi or other nations. Whilst OSM is CC BY-SA open-access, the crowd-sourced nature of the data means that this will need considerable cleaning before use. We will explore other data creators, including World Bank and BMGF grantees. The project will tackle access to these datasets in order of priority of the sub-national datasets.

Other datasets will be necessary to populate spatial information on populations, such as urban and rural areas, which is relevant to both predictions of micronutrient deficiencies and costs of interventions. Again, OSM is a source of these data, but other sources and models exist and are found in portals such as the FAO GeoNetwork and the most useful/efficient will be explored, including the use of night lights (which have been linked to socio-economic status).

These data are also relevant to the cost-effectiveness modelling. Evaluation of distribution costs may require information on road networks and population hubs, for instance, to create spatial estimates of costs. Alternative spatial data approaches, such as IFPRI distance-to-market information, will be explored.

5.2 Management of secondary data

Appropriate use of data is critical to the integrity of the tool outputs and the presentation of results. The project will obtain ethical approval for the use of the secondary datasets, following international best practice in this area (Ienca et al., 2018) and relevant guidelines, and will manage processes and data compliant with the requirements of the EU's 2016 General Data Protection Regulation (GDPR).

Additional metadata which the MAPS data catalogue requires will be created to enable data to be functional within the tool (see Figure 6). Metadata variables will include the date of the data collection, the geographical extent and coordinate system, data ownership and licencing for use/reuse, and the original data source. Additionally, metadata describing the statistical basis of the study design and the methods used for sample analysis will be included. These metadata will be stored in the data catalogue and will be reported in user outputs along with their respective dataset(s).

Where importing large or multiple datasets of the same or similar formats, we will develop standardised processing algorithms scripted into "chunks" of R-code (using open-source R-packages, and where necessary developing our own scripts) to semi-automate this process. For clarity, R-code "chunks" will be annotated (using R-Markdown) with step-by-step methods to guide end-users through instructions for processing. The code and methodologies will be made publicly available through GitHub as stand-alone resources, similar to work by the Evans School of Public Policy and Governance, University of Washington (https://evans.uw.edu/policy-impact/epar/research/agricultural-development-indicator-curation). The quality control, versioning and automation routines will all be documented, checked and published on the project website as part of the tool quality procedures.

The tool will include spatial and non-spatial data, which will need to be linked in a common spatial framework. The project will adopt WGS 84 datum as the native geographic coordinate system (GCS) as it is used widely in web-delivered mapping systems and thus robust to any future withdrawals of projected systems. Consistent geographic identifiers will be used to allow point data attributed with a location name) to be linked to spatial data-files via a common nomenclature.

The raw secondary data will not be accessible via the MAPS tool; rather, users will be able to locate the source of the data in the metadata documentation, and access this from its source.

Transfer of data between partners within the project will be required, particularly between WP2 and WP3. Shared folders hosted via Microsoft Teams on institutional servers at LSHTM, the University of Nottingham and British Geological Survey will be used, with access limited by password to the relevant project members. The folders will contain appropriate metadata alongside the data files. Data sets will be version controlled.

5.3 Bring your own data

This functionality is intended for advanced users and will link strongly with WP5 Sustainability activities including training. We anticipate that some users will wish to use proprietary data, in 'bring your own' modes, without making these data sharable or accessible to others. The tool will need the capability to integrate and serve data with varying license restrictions to maximise the likelihood of use, and to be open to further development. Data availability shall be managed through secure work areas and requirement on users to populate some metadata when loading the data into their area. Users will be responsible for the quality of their own data and the outputs arising from use of this data. These data will only be visible and accessible to the user who uploaded them.

When operating in this mode users will need to select their geographic domain and identify the native coordinate system(s) of their data from a pre-supplied list, as well as the statistical basis of the sampling design, if appropriate. Imported user spatial data will need to be converted to GCS WGS 84 prior to integration and processing within the system. In the rare examples where a standard conversion from the user's coordinate system(s) to GCS is not available, to address this issue there will be direct support from a member of the core technical team (during the period of project funding), and information shared will contribute to sustainable 'help' content for all users (in WP5). The team will provide support and guidance to other queries relating to 'bring your own' scenarios during the project, insofar as these benefit the sustainability of the project, and the development of generic user support content that can be made available via the website.

5.4 Deployment and hosting

BGS (a component organisation of UKRI) will host the MAPS website and tool on one of its servers, with a standalone project URL and email/social media addresses. These will be secured on establishment of the project. This will enable 'soft' launch of the tool through blog style update postings prior to the beta release going live. BGS has a long history of using web technology to manage, process, analyse and provide access to information. BGS are expert at developing intuitive web applications, smartphone apps, data portals and interoperable, open standard web services that enable users to search, visualise, download and interact with our geoscience data and information. BGS have played a major role in influencing the development of the data specifications and technical implementation standards that underpin the EU INSPIRE spatial data infrastructure legislation and are held up as an exemplar organisation for its delivery of open data.

BGS have been making spatial data publicly available via the web for 20 years. Their role as responsible for running the UK's National Geoscience Data Centre provides the infrastructure for long term hosting of web and data platforms. Following the development phases outlined above, the MAPS tool will be hosted on BGS infrastructure (accessed via a custom domain name) allowing the tool to be reliably accessed worldwide throughout and beyond the lifecycle of the project. Whilst initially hosted on BGS infrastructure, the tool will be designed and implemented in a manner which will allow it to be easily transferred to other hosting environments (e.g., within governmental or intergovernmental organisations or in the cloud), within limits on data-sharing permitted by license agreements.

As part of the sustainability aspects of WP5, partners will be sought within key countries who may be able to host, or mirror, the system on their own infrastructure alongside development of additional functionalities or capabilities of the tool not yet envisaged. If achieved, this will ensure local ownership, buy-in and uptake of the tool aiding its long-term success and longevity.

6. ETHICAL APPROVAL AND PROTOCOL DEVELOPMENT

The activities encompassed by WP2 are covered in this protocol and will begin once ethical approval is secured from the LSHTM observational ethics committee. Substantial amendments to the research protocol will be submitted for consideration by the ethics committee prior to adoption.

This protocol was developed by the lead project investigators. The Project Governance Board are responsible for the development of, and agreeing to, the final protocol and any subsequent changes:

Governance Board	
Name	**Organisation**
E Louise Ander	UoN
Katherine Adams	UCD
Andrew Bean	BGS
Martin Broadley	UoN
Dawd Gashu	AAU
Alexander Kalimbira	LUANAR
Edward Joy	LSHTM
Tim Sulser	IFPRI

7. PUBLICATION POLICY

Publications and presentations reporting methodological steps undertaken for developing the MAPS tool, and those that rely on the MAPS tool as the primary mode of data analysis will be authorised by the Project Governance Board and will acknowledge the role of the funder. Publications will be open access in compliance with the policies of the Bill & Melinda Gates Foundation.

A successful MAPS project will see widespread use of the tool beyond the study investigatory team and beyond the lifetime of the project. The MAPS project website will provide suggested citation/acknowledgement text.

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Ethical approval letter

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Observational / Interventions Research Ethics Committee

Dr Edward Joy

LSHTM

25 November 2021

Dear Dr Joy,

Study Title: MAPS - Micronutrient Action Policy Support

LSHTM Ethics Ref: 21903 - 2

Thank you for your letter responding to the Observational Committee's request for further information on the above amendment to research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above amendment to research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval for the amendment having been received, where relevant.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document Type	File Name	Date	Version
Other	MAPS-protocol-LSHTM-ethics_version-3.1_track-changes	18/11/2021	3.1
Other	MAPS-protocol-LSHTM-ethics_2021-11-18_table-of-changes	18/11/2021	3.1
Covering Letter	MAPS-ethics_amendment 2 - clarifications cover letter	23/11/2021	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the Committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study.

At the end of the study, the CI or delegate must notify the committee using an End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk

Additional information is available at: www.lshtm.ac.uk/ethics

Yours sincerely,

[redacted]

Professor Jimmy Whitworth
Chair

ethics@lshtm.ac.uk
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Improving health worldwide

Supplementary material for Chapter 4: Systematic review of metrics used to characterise dietary nutrient supply from Household Consumption and Expenditure Surveys

Systematic review of metrics used to characterise dietary nutrient supply from Household Consumption and Expenditure Surveys

SUPPLEMENTARY MATERIAL

Table of Contents

Table S1. Publications reviewed and the metrics reported

Ref #	Reference	Country	Household consumption & expenditure data source	Supply/ per capita /day	Supply/ AME/day	Nutrient density	Estimated inadequacy
(1)	Ambagna & Dury (2016)	Cameroon	Deuxième/Troisième Enquête Camerounaise auprès des Ménages		X		X
(2)	Beegle et al. (2010)	Tanzania	Survey modelled after Household Budget Survey (2006/07)	X			
(3)	Bell et al. (2019)	Bangladesh	Bangladesh Integrated Household Survey (2011/12)				
(4)	Bermudez et al. (2012)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2005)		X		X
(5)	Bogard & Mamun (2016)	Bangladesh	Bangladesh Integrated Household Survey (2011/12)				
(6)	Bogard et al. (2017)	Bangladesh	Household Income and Expenditure Survey (1991, 2000, 2010)		X		
(7)	Bromage et al. (2018)	Mongolia	Mongolian Household Socio-Economic Survey (2012, 2014)	X	X	X	
(8)	Chakrabarti et al. (2018)	India	61st/68th round of the National Sample Survey (2004/05, 2011/12)				
(9)	Chege et al. (2015)	Kenya	Survey modelled after standard HCES food consumption module		X		X
(10)	D'Souza & Tandon (2019)	Bangladesh	Bangladesh Integrated Household Survey (2011/12)		X		X
(11)	Dary & Jariseta (2012)	Uganda	National Household Survey (2005/06)		X		
(12)	de Weerdt et al. (2014)	Tanzania	Survey modelled after Household Budget Survey (2006/07)	X			X
(13)	DeFries et al. (2018)	India	7 rounds of the National Sample Survey	X			X
(14)	Donovan & Massingue (2007)	Mozambique	Trabalho de Inquérito Agricola (2002, 2005)		X		
(15)	Dop et al. (2012)	Cape Verde	Inquérito às Despesas e Receitas Famílias (2001/02)		X	X	
(16)	Ecker & Qaim (2011)	Malawi	Second Integrated Household Survey (2004/05)	X			X
(17)	Ecker & Qaim (2008)	Malawi	Second Integrated Household Survey (2004/05)	X			X
(18)	Engle-Stone & Brown (2015)	Cameroon	Troisième Enquête Camerounaise auprès des Ménages		X		
(19)	Engle-Stone et al. (2017)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2010)		X		X
(20)	Euler et al. (2017)	Indonesia	Survey modelled after Household Socio-Economic Survey		X		X
(21)	Fiedler (2014)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2010)		X	X	X
(22)	Fiedler et al. (2012)	India	61st round of the National Sample Survey (2004/05)		X		X
(23)	Fiedler & Lividini (2014)	Zambia	Living Conditions Monitoring Survey V (2006)		X		X
(24)	Fiedler et al. (2015)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2010)		X		X
(25)	Fiedler et al. (2016)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2005)		X		X
(26)	Fiedler et al. (2015)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2005)		X		X
(26)	Fiedler et al. (2013)	Zambia	Living Conditions Monitoring Survey V (2006)		X		X
(27)	Fiedler et al. (2013)	Zambia	Living Conditions Monitoring Survey V (2006)		X		X
(28)	Gilbert et al. (2019)	Malawi	Third/Fourth Integrated Household Survey (2010/11, 2016/17)	X			X
(29)	Hall et al. (2019)	Malawi	Third Integrated Household Survey (2010/11)		X		X
(30)	Hirvonen et al. (2016)	Ethiopia	Household Consumption Expenditure Survey (2010/11)	X			
(31)	Hjelm et al. (2016)	Madagascar, Malawi, Nepal, Tanzania, Uganda	Enquête Nationale Sur le Suivi des Objectifs du Millénaire pour le Développement à Madagascar (ENSOMD) ; Third Integrated Household Survey (2010/11); Nepal Living Standard Survey (2010/11); Tanzania National Panel Survey (2010/2011); Uganda National Panel Survey (2009/2010)	X	X		X

Ref #	Reference	Country	Household consumption & expenditure data source	Supply/ per capita/ day	Supply/ AME/day	Nutrient density	Estimated inadequacy
(32)	Imhoff-Kunsch et al. (2019)	Solomon Islands	Household Income and Expenditure Survey (2012/13)		X		X
(33)	Jarista et al. (2012)	Uganda	National Household Survey (2005/06)		X	X	X
(34)	Jati et al. (2012)	Indonesia	Household Socio-Economic Survey (BPS 2008)			X	X
(35)	Johnecheck & Holland (2007)	Afghanistan	National Risk and Vulnerability Assessment (2003)	X			X
(36)	Joy et al. (2015)	Malawi	Third Integrated Household Survey (2010/11)		X		X
(37)	Kankwamba & Kornher (2019)	Malawi	Third/Fourth Integrated Household Survey (2010/11, 2016/17)	X			
(38)	Karageorgou et al. (2018)	Bangladesh	Bangladesh Integrated Household Survey (2011/12)	X	X		
(39)	Lividini & Fiedler (2015)	Zambia	Living Conditions Monitoring Survey V (2006)		X		X
(40)	Lividini et al. (2013)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2005)		X		X
(41)	Marivoet et al. (2018)	Dem. Rep. of the Congo	Enquête 123: données transversales sur la consommation des ménages collectées		X		X
(42)	Mathiassen & Hollema (2014)	Nepal, Uganda	Uganda National Panel Survey (2009/10); Nepal Living Standard Survey (2010/11)				X
(43)	Mishra & Ray (2009)	Vietnam	Vietnamese Household Living Standard Surveys (1993, 1998, 2004)	X			X
(44)	Molini (2006)	Vietnam	Vietnamese Household Living Standard Survey (1993, 1998)	X			
(45)	Mwangi et al. (2016)	Bangladesh	Bangladesh Integrated Household Survey (2011/12)		X		X
(46)	Nguyen & Winters (2011)	Vietnam	Vietnam Household Living Standards Surveys	X			
(47)	Rahman (2012)	Bangladesh	Bangladesh Household Income and Expenditure Survey (2005)	X			
(48)	Rose & Charlton (2002)	South Africa	Income and Expenditure Survey (1995)		X		X
(49)	Skoufias (2002)	Indonesia	National Socio-Economic Surveys (1996, 1999)	X			
(50)	Smith et al. (2006)	Burundi, Ethiopia, Ghana, Guinea, Kenya, Malawi, Mozambique, Rwanda, Senegal, Tanzania, Uganda, Zambia	Étude nationale sur les conditions de vie des populations (1998) Household Income, Consumption & Expenditure Survey (1999/2000) Ghana Living Standards Survey 4 Enquête intégrale sur les conditions de vie des ménages guinéen Kenya Welfare Monitoring Survey III Malawi Integrated Household Survey (19997/98) Mozambique Inqerito nacional aos agregados familiareas sobre as condicoes de vida Enquête intégrale sur les conditions de vie des ménages rwandaise Enquête Sénégalaise auprès des ménages II Tanzanian Household Budget Survey Ugandan National Household Survey (1999/2000) Zambia Living Conditions Monitoring Survey I (1996)	X			X
(51)	Smith et al. (2019)	India	7 rounds of the National Sample Survey	X			X
(52)	Tandon & Landes (2010)	India	61st round of the National Sample Survey (2004/05)	X			
(53)	Trinh Thi et al. (2018)	Vietnam	Vietnam Household Living Standards Survey	X			
(54)	Troubat & Grünberger (2017)	Mongolia	Mongolian Household Socio-Economic Survey (2007/08)	X			
(55)	Ulimwengu et al. (2011)	Uganda	National Household Survey (2005/06)	X			X
(56)	Verduzco-Gallo et al. (2014)	Malawi	Second/Third Integrated Household Survey (2010/11, 2016/17)	X			X
(57)	Weinberger (2004)	India	50th round of the National Sample Survey (1993/94)		X		X
(58)	Worku et al. (2017)	Ethiopia	Household Consumption Expenditure Surveys		X		

Table S2. Characteristics of Household Consumption & Expenditure Survey (HCES) food consumption data used in the included publications

Ref #	Reference	Country	HCES: Type of dietary data	HCES: Time horizon	Compared HCES to individual intake data?	Individual intake: type of data	Individual intake: comparability to HCES	Individual intake: demographics of individuals
(1)	Ambagna & Dury (2016)	Cameroon	Consumption recall	10 days (rural) & 15 days (urban)				
(2)	Beegle et al. (2010)	Tanzania	Consumption recall	7 days, 14 days, & 12 months				
(3)	Bell et al. (2019)	Bangladesh	Consumption recall	7 days				
(4)	Bermudez et al. (2012)	Bangladesh	Acquisition recall	14 days				
(5)	Bogard & Mamun (2016)	Bangladesh	Consumption recall	7 days				
(6)	Bogard et al. (2017)	Bangladesh	Consumption recall	7 days				
(7)	Bromage et al. (2018)	Mongolia	Consumption recall	7 days (rural) & 10 to 30 days (urban)	X	Multipass 24-hour individual recall	Individuals of households from HCES sample	All household members
(8)	Chakrabarti et al. (2018)	India	Consumption recall	1 month				
(9)	Chege et al. (2015)	Kenya	Consumption recall	7 days				
(10)	D'Souza & Tandon (2019)	Bangladesh	Consumption recall	7 days				
(11)	Dary & Jariseta (2012)	Uganda	Consumption recall	7 days	X	Multipass 24-hour individual recall	Different sample[1]	Children <5 years old & women
(12)	de Weerdt et al. (2014)	Tanzania	Consumption recall	7 days, 14 days, & 12 months				
(13)	DeFries et al. (2018)	India	Consumption & expenditure recall	1 month				
(14)	Donovan & Massingue (2007)	Mozambique	Acquisition recall	1 year				
(15)	Dop et al. (2012)	Cape Verde	Direct weighed observation	7 days				
(16)	Ecker & Qaim (2011)	Malawi	Consumption recall	7 days				
(17)	Ecker & Qaim (2008)	Malawi	Consumption recall	7 days				
(18)	Engle-Stone & Brown (2015)	Cameroon	Acquisition recall	3 & 7 days	X	Single-pass 24-hour individual recall[2]	Different sample[1]	Children <5 years old & women
(19)	Engle-Stone et al. (2017)	Bangladesh	Consumption recall	2 days				
(20)	Euler et al. (2017)	Indonesia	Consumption recall	7 days				
(21)	Fiedler (2014)	Bangladesh	Consumption recall	2 days				
(22)	Fiedler et al. (2012)	India	Consumption recall	1 month				
(23)	Fiedler & Lividini (2014)	Zambia	Acquisition recall	14 days				
(24)	Fiedler et al. (2015)	Bangladesh	Acquisition recall	14 days				
(25)	Fiedler et al. (2016)	Bangladesh	Consumption recall	2 days				
(26)	Fiedler et al. (2015)	Bangladesh	Consumption recall	2 days				
(26)	Fiedler et al. (2013)	Zambia	Acquisition recall	14 days				
(27)	Fiedler et al. (2013)	Zambia	Acquisition recall	14 days				
(28)	Gilbert et al. (2019)	Malawi	Consumption recall	7 days				
(29)	Hall et al. (2019)	Malawi	Consumption recall	7 days				
(30)	Hirvonen et al. (2016)	Ethiopia	Consumption recall	3 & 4 days				
(31)	Hjelm et al. (2016)	Madagascar, Malawi, Nepal, Tanzania, Uganda	Acquisition recall	Varies				

[1] Individual dietary data surveyed from a different sample of household compared to HCES sample

[2] 10% of individuals in the total sample were randomly selected for multipass dietary recall methods

Ref #	Reference	Country	HCES: Type of dietary data	HCES: Time horizon	Compared to individual intake data?	Individual intake: type of data	Individual intake: comparability to HCES	Individual intake: demographics of individuals
(32)	Imhoff-Kunsch et al. (2019)	Solomon Islands	Expenditure diary	14 days				
(33)	Jarista et al. (2012)	Uganda	Consumption recall	7 days				
(34)	Jati et al. (2012)	Indonesia	Expenditure recall	7 days				
(35)	Johnecheck & Holland (2007)	Afghanistan	Consumption recall	7 days				
(36)	Joy et al. (2015)	Malawi	Consumption recall	7 days				
(37)	Kankwamba & Kornher (2019)	Malawi	Consumption recall	7 days				
(38)	Karageorgou et al. (2018)	Bangladesh	Consumption recall	7 days	X	Single-pass 24-hour individual recall	Individuals of households from HCES sample	All household members
(39)	Lividini & Fiedler (2015)	Zambia	Acquisition recall	14 days				
(40)	Lividini et al. (2013)	Bangladesh	Consumption recall	14 days	X	2-day observed-weighed food records	Individuals of households from HCES sample	Children <5 years old & women
(41)	Marivoet et al. (2018)	Dem. Rep. of the Congo	Acquisition & expenditure recall	15 days & 6 to 12 months				
(42)	Mathiassen & Hollema (2014)	Nepal, Uganda	Acquisition recall	7 days				
(43)	Mishra & Ray (2009)	Vietnam	Expenditure recall	1 year				
(44)	Molini (2006)	Vietnam	Expenditure recall	1 year				
(45)	Mwangi et al. (2016)	Bangladesh	Consumption recall	7 days				
(46)	Nguyen & Winters (2011)	Vietnam	Expenditure recall	1 year				
(47)	Rahman (2012)	Bangladesh	Consumption recall	14 days				
(48)	Rose & Charlton (2002)	South Africa	Expenditure recall	1 month				
(49)	Skoufias (2002)	Indonesia	Consumption recall	7 days				
(50)	Smith et al. (2006)	Burundi, Ethiopia, Ghana, Guinea, Kenya, Malawi, Mozambique, Rwanda, Senegal, Tanzania, Uganda, Zambia	Acquisition & expenditure recall	Varies				
(51)	Smith et al. (2019)	India	Expenditure & consumption recall	1 month				
(52)	Tandon & Landes (2010)	India	Expenditure recall	1 month				
(53)	Trinh Thi et al. (2018)	Vietnam	Expenditure recall	1 year				
(54)	Troubat & Grünberger (2017)	Mongolia	Consumption recall	10 days				
(55)	Ulimwengu et al. (2011)	Uganda	Consumption recall	7 days				
(56)	Verduzco-Gallo et al. (2014)	Malawi	Consumption recall	7 days				
(57)	Weinberger (2004)	India	Expenditure recall	30 days				
(58)	Worku et al. (2017)	Ethiopia	Consumption recall	7 days				

Table S3. *Publications comparing apparent nutrient or energy intake estimates using HCES adult male equivalent methods to intake estimates calculated using individual-level dietary intake data for total populations (expanded to include all reported nutrients)*

Reference; country; summary metric	Individual consumption data (N)	HCES dietary data, (n)	Study sample population (n)	Nutrient	Individual estimate	HCES AME estimate	Percentage point difference
I. Study compared intake estimates derived from individual-level versus HCES dietary data							
Bromage *et al.* (2018) [7]; Mongolia; means	24H individual recall (N=4070)	7-30 day recall of household meals (n=1012)	Total population (n=4070)	Energy, kcal	1863	2951	58
				Carbohydrates, g	241	364	51
				Protein, g	70	120	71
				Total fat, g	66	113	71
				Thiamin, mg	0.8	1.3	72
				Riboflavin, mg	1.2	2.2	83
				Niacin, mg	13	23	72
				Pantothenic acid, mg	3.1	5.5	77
				Vitamin B6, mg	0.6	1.1	88
				Folate, μg	132	208	58
				Vitamin B12, μg	6.4	8.4	31
				Vitamin C, mg	12	33	167
				Vitamin A, μg	448	621	39
				Vitamin D, IU	26	48	85
				Vitamin E, mg	5.3	9.6	82
				Calcium, mg	432	898	108
				Copper, mg	1.0	1.5	48
				Iron, mg	10	16	60
				Magnesium, mg	168	283	68
				Manganese, mg	2.2	3.4	55
				Phosphorous, mg	907	1567	73
				Potassium, mg	1436	2645	84
				Zinc, mg	11	19	72
D'Souza & Tandon (2015) [10]; Bangladesh; means	24H recall of household meals and proportions consumed by individuals (N=21,795)	7-day recall of household meals (n=5319)	Total population (n=21,795)	Energy, kcal	2436	2718	12
Karageorgou *et al.* (2018) [38]; Bangladesh; means	24H recall of household meals and proportions consumed by individuals	7-day recall of household meals (n=5503)	Total population (n=22,173)	Energy, kcal	2065	2322	12
				Protein, g	50	57	13
				Carbohydrates, g	398	444	12
				Total fat, g	26	30	17
				Vitamin A RAE, μg	214	323	50

(N=22,173)	Vitamin D, µg	1.1	1.3	18
	Vitamin E, mg	4.5	5.4	20
	Thiamine, mg	0.8	0.9	25
	Riboflavin, mg	0.5	0.6	20
	Niacin, mg	14	16	13
	Vitamin B6	1.2	1.4	17
	Folate, µg	121	157	31
	Vitamin C, mg	42	65	55
	Calcium, mg	274	343	25
	Iron, mg	9.9	12	21
	Sodium, mg	4225	5855	39
	Potassium, mg	1395	1745	25
	Magnesium, mg	321	377	18
	Zinc, mg	8.6	9.8	14

Table S4. *Publications comparing apparent nutrient, energy or fortifiable food item intake estimates using HCES adult male equivalent methods to intake estimates calculated using individual-level dietary intake data for infants and children where no studies adjusted for assumed or recommended breastmilk intake (expanded to include all reported nutrients and food items)*

Reference; country; summary metric	**Individual dietary assessment data (N)**	**HCES dietary data, (n households)**	**Study sample population (n)**	**Nutrient/ food item**	**Individual intake**	**HCES AME apparent intake**	**Percentage point Difference**
I. Study compared intake estimates derived from individual-level versus HCES dietary data							
Karageorgou *et al.* (2018) [38]; Bangladesh; means	24H recall of household meals and proportions consumed by individuals (N=22,173)	7-day recall of household meals (n=5503)	Children (<5 years) (n=2807)	Energy, kcal	880	1130	28
				Protein, g	22	28	26
				Carbohydrates, g	164	216	32
				Total fat, g	13	15	10
				Vitamin A RAE, µg	108	158	47
				Vitamin D, µg	0.5	0.6	40
				Vitamin E, mg	2.0	2.6	30
				Thiamine, mg	0.3	0.4	33
				Riboflavin, mg	0.3	0.3	10
				Niacin, mg	5.7	7.8	37
				Vitamin B6	0.5	0.7	40
				Folate, µg	55	76	40
				Vitamin C, mg	18	32	80
				Calcium, mg	151	166	10
				Iron, mg	4.2	5.8	38
				Sodium, mg	1960	2887	47
				Potassium, mg	621	850	37
				Magnesium, mg	132	184	40
				Zinc, mg	3.6	4.8	31
Lividini *et al.* (2013) [40]; Rajshahi, Bangladesh; medians	2 non-consecutive days of 12-hour observed weighed food records & 12-hour dietary recall (n=477)	14-day food diary of households with children age 2-3 (n=513)	Children (2-3 years) (n=237)	Energy, kcal	905	1098	18
Lividini *et al.* (2013) [40]; Dhaka, Bangladesh; medians	2 non-consecutive days of 12-hour observed	14-day food diary of households with children age 2-3 (n=678)	Children (2-3 years) (n=226)	Energy, kcal	868	1104	21

	weighed food records & 12-hour dietary recall (n=464)						
II. Study compared consumption of fortified food vehicles derived from individual-level versus HCES dietary data							
Engle-Stone & Brown (2015) [18]; Cameroon; medians	24H individual recall (N=1794)	Combination of 3 to 7 day recalls and 15-day diary depending on sub-population, different survey sample (n=4363)	Children (12-59 months) (n=882)	Refined oil, g	11.7	6.2	-89
				Wheat flour, g	49.4	24.2	-104
				Sugar, g	19.6	7.2	-172
				Bouillon, g	0.9	1.3	31
Dary & Jariseta (2012) [11]; Kampala, Uganda; medians	24H individual recall	7-day recall of household meals (n=314)	Children (2-5 years)	Vegetable oil, g	4.9	7.0	30
				Wheat flour, g	36.2	16.0	-126
				Sugar, g	38.2	24.9	-53
				Maize flour, g	49.1	24.3	-102
				Rice, g	43.8	20.5	-114
Dary & Jariseta (2012) [11]; Southwestern Region, Uganda; medians	24H individual recall	7-day recall of household meals (n=322)	Children (2-5 years)	Vegetable oil, g	5.7	5.0	-14
				Wheat flour, g	32.4	7.5	-332
				Sugar, g	23.5	11.6	-103
				Maize flour, g	41.8	27.0	-55
				Rice, g	33.1	18.1	-83
Dary & Jariseta (2012) [11]; Northern Region, Uganda; medians	24H individual recall	7-day recall of household meals (n=321)	Children (2-5 years)	Vegetable oil, g	9.4	3.8	-147
				Wheat flour, g	26.2	3.3	-694
				Sugar, g	25.0	6.7	-273
				Maize flour, g	69.4	10.7	-549
				Rice, g	27.7	9.7	-186

Table S5. *Publications comparing apparent nutrient, energy or fortifiable food item intake estimates using HCES adult male equivalent methods to intake estimates calculated using individual-level dietary intake data for women of reproductive age (WRA)*

Reference; country; summary metric	**Individual dietary assessment data (N)**	**HCES dietary data, (n households)**	**Study sample population (n)**	**Nutrient/ food item**	**Individual intakes**	**HCES AME apparent intakes**	**Percentage point difference**
I. Study compared intake estimates derived from individual-level versus HCES dietary data							
Karageorgou *et al.* (2018) [38]; Bangladesh; means	24H recall of household meals and proportions consumed by individuals (N=22,173)	7 day recall of household meals (n=5503)	Women (n=11,671)	Energy, kcal	1965	2180	11
				Protein, g	48	53	12
				Carbohydrates, g	379	416	10
				Total fat, g	24	29	17
				Vitamin A RAE, µg	210	307	46
				Vitamin D, µg	1.1	1.2	18
				Vitamin E, mg	4.3	5.1	19
				Thiamine, mg	0.7	0.9	14
				Riboflavin, mg	0.4	0.5	25
				Niacin, mg	13.4	15	11
				Vitamin B6	1.1	1.3	18
				Folate, µg	115	148	29
				Vitamin C, mg	41	62	52
				Calcium, mg	260	324	25
				Iron, mg	9.4	11.3	20
				Sodium, mg	4096	5538	35
				Potassium, mg	1329	1646	24
				Magnesium, mg	306	354	16
				Zinc, mg	8.2	9.2	12
Lividini *et al.* (2013) [40]; Rajshahi, Bangladesh; medians	2 non-consecutive days of 12-hour observed weighed food records & 12-hour dietary recall (n=477)	14-day food diary of households with children age 2-3 (n=513)	WRA (n=240)	Energy, kcal	1984	2281	13
Lividini *et al.* (2013) [40]; Dhaka, Bangladesh; medians	2 non-consecutive days of 12-hour observed weighed food records & 12-hour dietary recall (n=464)	14-day food diary of households with children age 2-3 (n=678)	WRA (n=238)	Energy, kcal	1693	2329	27
II. Study compared consumption of fortified food vehicles derived from individual-level versus HCES dietary data							

Engle-Stone & Brown (2015) [18]; Cameroon; medians	24H individual recall (N=1794)	Combination of 3 to 7 day recalls and 15-day diary depending on sub-population, different survey sample (n=4363)	WRA (n=912)	Refined oil, g	19.6	13.3	-47
				Wheat flour, g	76.6	51.2	-50
				Sugar, g	29.2	15.5	-88
				Bouillon, g	1.9	2.7	30
Dary & Jariseta (2012) [11]; Kampala, Uganda; medians	24H individual recall	7-day recall of household meals (n=314)	WRA (15-49 years)	Vegetable oil, g	10.4	12.8	19
				Wheat flour, g	58.3	29.3	-99
				Sugar, g	55.5	45.6	-22
				Maize flour, g	115.9	44.4	-161
				Rice, g	63.0	37.5	-68
Dary & Jariseta (2012) [11]; Southwestern Region, Uganda; medians	24H individual recall	7-day recall of household meals (n=322)	WRA (15-49 years)	Vegetable oil, g	10.9	9.1	-20
				Wheat flour, g	35.3	13.7	-158
				Sugar, g	40.3	21.2	-90
				Maize flour, g	78.6	49.4	-59
				Rice, g	81.3	33.1	-146
Dary & Jariseta (2012) [11]; Northern Region, Uganda; medians	24H individual recall	7-day recall of household meals (n=321)	WRA (15-49 years)	Vegetable oil, g	18.8	7.0	-169
				Wheat flour, g	35.6	6.1	-484
				Sugar, g	39.4	12.3	-220
				Maize flour, g	130.3	19.6	-565
				Rice, g	84.4	17.7	-377

Appendix 1. *Original protocol of systematic review developed according to PRISMA guidelines*
[Original protocol attached as a separate document]

[PRISMA checklist attached as a separate document]

Appendix 2. *Search algorithms returning publications in database search*

Database	Search Algorithm
Web of Science	TOPIC: (hces) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: (household consumption and expenditure survey) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: (lsms) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("living standards measurement study") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("integrated household survey") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("household budget survey") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("living conditions monitoring survey") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("socioeconomic survey") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("national risk and vulnerability assessment") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("core welfare indicators") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("enquête" AND "auprès des ménages") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("enquête" AND "les conditions de vie") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI. TOPIC: ("enquête" AND "le budget et la consommation des ménages") Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.
PubMed	Search: “household consumption and expenditure survey” AND “food consumption” Search: “household consumption and expenditure survey” AND nutr* Search: "integrated household survey" Search: "living standards measurement study" Search: "living conditions monitoring survey" AND “food consumption” Search: "living conditions monitoring survey" AND nutr* Search: "national risk and vulnerability assessment" Search: "core welfare indicators questionnaire"
AgEcon	Query : "household consumption and expenditure survey" Query : "living standards measurement study" Query : “household budget survey” AND nutr*

	Query : “household budget survey” AND vitamin Query : “household budget survey” AND mineral Query : “household budget survey” AND micronutrient Query : “household budget survey” AND energy intake Query : “income and expenditure survey” AND nutr* Query : “income and expenditure survey” AND vitamin Query : “income and expenditure survey” AND mineral Query : “income and expenditure survey” AND micronutrient Query : “income and expenditure survey” AND energy intake Query : "living conditions monitoring survey" Query : "integrated household survey"
GARDIAN CGIAR	household consumption and expenditure survey living standards measurement study “integrated household survey” AND nutri* living conditions monitoring survey household budget survey
AGRIS	Query : "household consumption and expenditure survey" Query : "living standards measurement study" Query : “household budget survey” AND nutri* Query : “household budget survey” AND energy Query : “household budget survey” AND vitamin Query : “household budget survey” AND mineral Query : “household budget survey” AND micronutrient Query : “income and expenditure survey” AND nutri* Query : “income and expenditure survey” AND energy Query : “income and expenditure survey” AND vitamin Query : “income and expenditure survey” AND mineral Query : “income and expenditure survey” AND micronutrient Query : “integrated household survey”
JSTOR	((“household consumption and expenditure survey”) AND (nutr*)) ((("living standards measurement study") AND (food)) AND (consumption)) (("living standards measurement study") AND (nutr*)) ((("integrated household survey") AND (food)) AND (consumption)) ((("integrated household survey") AND (nutr*))) ((("integrated household survey") AND (micronutrient))) ((“living conditions monitoring survey”) AND (nutr*))

IFPRI Publications & Tools Database	household consumption and expenditure survey living standards measurement study integrated household survey living conditions monitoring survey household budget survey socioeconomic survey national risk and vulnerability assessment
Academic Search Complete	household consumption and expenditure survey integrated household survey living standards measurement study household budget survey living conditions monitoring survey household income and expenditure survey
EconLit	(household consumption and expenditure survey).mp. [mp=heading words, abstract, title, country as subject] (living standards measurement study).mp. [mp=heading words, abstract, title, country as subject] (integrated household survey).mp. [mp=heading words, abstract, title, country as subject] (living conditions monitoring survey).mp. [mp=heading words, abstract, title, country as subject] (socioeconomic survey).mp. [mp=heading words, abstract, title, country as subject] (national risk and vulnerability assessment).mp. [mp=heading words, abstract, title, country as subject] (core welfare indicators questionnaire).mp. [mp=heading words, abstract, title, country as subject]
Global Health Database	(household consumption and expenditure survey).mp. [mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes] living standards measurement study.mp. [mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes] integrated household survey.mp. [mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes] living conditions monitoring survey.mp. [mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes] (household budget survey AND nutri*).mp. [mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes] socioeconomic survey.mp. [mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes]
Global Index Medicus	search: household consumption AND expenditure survey search: tw:("living standards measurement study") search: integrated household survey search: living conditions monitoring survey search: tw:(socioeconomic survey AND (energy OR calor*)) AND (la:("en")) AND (year_cluster:[2000 TO 2020])
Scopus	TITLE-ABS-KEY (household AND consumption AND expenditure AND survey AND nutri*)

	TITLE-ABS-KEY ("living standards measurement study") TITLE-ABS-KEY (household AND budget AND survey AND nutri*) TITLE-ABS-KEY (living AND conditions AND monitoring AND survey) TITLE-ABS-KEY (integrated AND household AND survey AND nutri*)
BASE	search: "household consumption and expenditure survey" search: "living standards measurement study" AND *nutri* search: "integrated household survey" AND *nutri* search: "living conditions monitoring survey" search: household budget survey AND *nutri* search: "socioeconomic survey" AND *nutri*
Google Scholar	search: "Enquête" AND "nutrition" AND "auprès des ménages" search: "Enquête" AND "nutrition" AND "les conditions de vie" AND "auprès des ménages" search: "Enquête" AND "nutrition" AND "Suivi de la Pauvrete" search: "Enquête" AND "nutrition" AND " la Consommation et le Secteur Informel" search: "Enquête” AND "nutrition" AND "le Budget et la Consommation des Menages"

Appendix 3. *Information extracted from the included literature*

Categories	**Extracted information**
General information	• Title • Year published • Authors • Journal/publication medium • Peer review (Y/N) • Objective • Reported principal findings • Reported limitations of analysis
Question 1: What is the scope of the existing literature?	<u>Scope</u> • Country(s) of study • Name of survey • Data collection time period • Households, N • Dietary data collection method • Which nutrients were measured (or energy)? <u>Quality</u> • Recall period • Food item list, n • Survey question verb • Conversion to standard units? • Edible portions of foods? How? • Outliers identified? How? • Which food composition tables were used and in what priority?

Question 2: What metrics have been used to estimate nutrient and energy supply/apparent intake and nutrient adequacy from HCES data, and how those estimates compare across metrics?	• What nutrition metric was used?
	• Household or individual level?
	• Was energy requirement calculation necessary for metric? If yes:
	  o What was the physical activity level parameter?
	  o What was the body weight parameter?
	  o Account for pregnancy? How?
	  o Account for lactation? How?
	• Did analysis measure inadequacy?
	  o What method was used to determine inadequacy?
	  o Was dietary reference value necessary? Which was used?
	• For certain nutrients, account for bioavailability?

Question 3: How do HCES-derived estimates of apparent nutrient and energy intake compare to those estimated using individual-level dietary assessment methods? Do results differ by age group (i.e. adults, adolescents, children, infants)?	• Name of HCES
	• Data collection time period
	• Households, N
	• Individual dietary assessment methods
	  o Participants, n
	  o Members of households?
	  o Retrospective or prospective?
	  o Number of visits
	• Apparent nutrient/energy intake estimate from HCES
	• Nutrient/energy intake estimate from individual dietary assessment
	• Difference in nutrient/energy intake vs. apparent nutrient/energy intake
	• Measured inadequacy?

	• Difference in inadequacy prevalence between HCES and individual assessments
	• Disaggregated by age groups?
	    ○ Difference in nutrient/energy intake vs. apparent nutrient/energy intake by age group
	• Disaggregated by gender?
	    ○ Difference in nutrient/energy intake vs. apparent nutrient/energy intake by sex

Question 4: What types of sub-group comparative analyses have been conducted using nutrient and energy supply/apparent intake estimates from HCES data? (PROGRESS+ framework)	Disaggregation of results by: • Place of residence • Race/ethnicity • Occupation • Gender • Religion • Education • Socioeconomic status • Social capital • + (personal characteristics)

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Appendix 4

Supplementary material for Chapter 6: Modelling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys

Modeling food fortification contributions to micronutrient requirements in Malawi using Household Consumption and Expenditure Surveys

SUPPLEMENTARY MATERIAL

Table of Contents

Model Parameters

Supplementary Table 1. *Micronutrient composition for 100 grams of food items from IHS4 using food composition data from the Malawian (MWI)[1], Kenyan (KEN)[2], Lesothan (LSO)[3], Mozambican (MOZ)[4], FAO West African (WAF)[5] and United Kingdom (UK)[6] food composition tables.*

Food item	VitA *µg RAE*	Ref	Thia *mg*	Ref	Ribo *mg*	Ref	Niac *mg*	Ref	VitB6 *mg*	Ref	Fol *µg*	Ref	VitB12 *µg*	Ref	Iron *mg*	Ref	Zinc *mg*	Ref	Energy *kcal*	Ref
Maize ufa mgaiwa (normal flour)	0	MWI	0.50	MWI	0.12	MWI	1.4	MWI	0.37	MWI	25	MWI	0	MWI	3.8	MWI	1.7	MWI	374	MWI
Maiza ufa refined (refined flour)	0	MWI	0.13	MWI	0.04	MWI	0.8	MWI	0.08	MWI	10	MWI	0	MWI	1.0	MWI	0.5	MWI	367	MWI
Maize ufa madeya (bran flour)	2	MWI	0.25	MWI	0.11	MWI	2.4	MWI	0.22	MWI	18	MWI	0	MWI	2.7	MWI	3.0	MWI	373	MWI
Maize grain	0	KEN	0.35	MWI	0.10	MWI	2.1	MWI	0.20	MWI	26	MWI	0	MWI	1.4	MWI	1.6	MWI	370	MWI
Green maize	0	MWI	0.08	MWI	0.03	MWI	0.6	MWI	0.05	MWI	7	MWI	0	MWI	1.1	MWI	0.8	MWI	133	MWI
Rice	0	MWI	0.15	MWI	0.03	MWI	0.2	MWI	0.16	MWI	8	MWI	0	MWI	0.4	MWI	1.6	MWI	348	MWI
Finger millet	0	MWI	0.31	MWI	0.13	MWI	1.8	MWI	0.75	MWI	30	MWI	0	MWI	10.1	MWI	1.8	MWI	378	MWI
Sorghum	1	MWI	0.35	MWI	0.16	MWI	3.2	MWI	0.25	MWI	29	MWI	0	MWI	12.6	MWI	1.8	MWI	358	MWI
Pearl millet	0	WAF	0.20	WAF	0.20	WAF	1.9	WAF	0.32	WAF	47	WAF	0	WAF	5.4	WAF	2.4	WAF	370	WAF
Wheat flour	0	WAF	0.21	WAF	0.09	WAF	2.4	WAF	0.45	WAF	240	WAF	0	WAF	2.0	WAF	0.5	WAF	352	WAF
Bread	48	MWI	0.24	MWI	0.17	MWI	1.8	MWI	0.16	MWI	38	MWI	0.1	MWI	2.1	MWI	0.6	MWI	304	MWI
Buns, scones	32	MWI	0.11	MWI	0.17	MWI	0.3	MWI	0.04	MWI	13	MWI	0.3	MWI	1.8	MWI	0.4	MWI	224	MWI
Biscuits	40	KEN	0.09	KEN	0.03	KEN	0.7	LSO	0.05	KEN	12	KEN	0.1	KEN	1.4	KEN	0.6	KEN	460	KEN
Spaghetti, macaroni, pasta	0	KEN	0.07	KEN	0.06	KEN	1.1	WAF	0.13	KEN	18	KEN	0	KEN	1.0	KEN	0.6	KEN	354	KEN
Breakfast cereal	5	KEN	0.13	KEN	0.06	KEN	1.5	LSO	0.03	KEN	5	KEN	0	WAF	1.5	KEN	0.4	KEN	340	KEN
Cassava tubers	1	MWI	0.04	MWI	0.05	MWI	0.7	MWI	0.09	MWI	24	MWI	0	MWI	0.4	MWI	0.4	MWI	160	MWI
Cassava flour	0	WAF	0.07	MWI	0.11	MWI	1.2	MWI	0.17	MWI	46	MWI	0	MWI	0.5	MWI	0.7	WAF	348	MWI
White sweet potato	2	MWI	0.07	MWI	0.03	MWI	0.4	MWI	0.20	MWI	38	MWI	0	MWI	0.2	MWI	0.2	MWI	89	MWI
Orange sweet potato	926	MWI	0.03	MWI	0.05	MWI	1.0	MWI	0.20	MWI	11	MWI	0	MWI	0.5	MWI	0.5	MWI	81	MWI
Irish potato	0	KEN	0.16	MWI	0.01	MWI	1.4	MWI	0.21	MWI	3	MWI	0	MWI	0.7	MWI	0.3	MWI	68	MWI
Potato crisps	0	KEN	0.19	MWI	0.01	MWI	2.0	MWI	0.30	MWI	3	MWI	0	MWI	1.0	MWI	0.4	MWI	264	MWI
Plantain	38	MWI	0.05	MWI	0.04	MWI	0.5	MWI	0.20	MWI	13	MWI	0	MWI	0.8	MWI	0.1	MWI	124	MWI
Cocoyam	0	WAF	0.10	MWI	0.03	MWI	0.8	MWI	0.24	MWI	22	MWI	0	MWI	0.6	MWI	1.4	MWI	137	MWI
Beans, white	0	WAF	0.89	WAF	0.11	WAF	1.5	WAF	0.42	WAF	410	WAF	0	WAF	8.8	WAF	3.2	WAF	320	WAF
Beans, brown	0	MWI	0.54	MWI	0.22	MWI	2.1	MWI	0.40	MWI	397	MWI	0	MWI	7.7	MWI	3.3	MWI	343	MWI
Pigeon pea	8	MWI	0.61	MWI	0.18	MWI	2.7	MWI	0.27	MWI	256	MWI	0	MWI	6.1	MWI	2.2	MWI	364	MWI
Groundnut flour	0	MWI	0.86	MWI	0.14	MWI	9.5	MWI	0.58	MWI	108	MWI	0	MWI	3.8	MWI	2.8	MWI	583	MWI
Soyabean flour	1	MWI	0.70	MWI	0.08	MWI	2.0	MWI	0.82	MWI	376	MWI	0	MWI	9.5	MWI	3.5	MWI	458	MWI
Ground bean	1	WAF	0.77	WAF	0.19	WAF	2.3	WAF	0.34	WAF	480	WAF	0	WAF	10.0	WAF	1.1	WAF	322	WAF
Cowpea	3	MWI	0.72	MWI	0.15	MWI	3.1	MWI	0.36	MWI	421	MWI	0	MWI	5.4	MWI	2.8	MWI	349	MWI
Macadamia nuts	0	KEN	0.27	KEN	0.10	KEN	2.0	UK	0.28	UK	0	UK	0	KEN	2.2	KEN	1.3	KEN	696	KEN
Groundnut (shelled)	0	MWI	0.87	MWI	0.14	MWI	15.5	MWI	0.59	MWI	110	MWI	0	MWI	1.9	MWI	2.5	MWI	597	MWI
Groundnut (unshelled)	0	MWI	0.87	MWI	0.14	MWI	15.5	MWI	0.59	MWI	110	MWI	0	MWI	1.9	MWI	2.5	MWI	597	MWI
Groundnut fresh (unshelled)	0	MWI	0.47	MWI	0.08	MWI	8.4	MWI	0.32	MWI	60	MWI	0	MWI	2.1	MWI	1.4	MWI	324	MWI
Soya	1	MWI	0.71	MWI	0.08	MWI	2.0	MWI	0.83	MWI	378	MWI	0	MWI	17.3	MWI	3.9	MWI	432	MWI
Onion	0	MWI	0.03	MWI	0.01	MWI	0.1	MWI	0.12	MWI	2	MWI	0	MWI	0.5	MWI	0.4	MWI	43	MWI
Cabbage	0	KEN	0.04	MWI	0.02	MWI	0.3	MWI	0.08	MWI	15	MWI	0	MWI	0.9	MWI	0.3	MWI	32	MWI
Tanaposi/rape	579	MWI	0.07	MWI	0.10	MWI	0.6	MWI	0.26	MWI	194	MWI	0	MWI	2.8	MWI	0.4	MWI	37	MWI
Nkhwani	126	MWI	0.05	MWI	0.07	MWI	0.5	MWI	0.11	MWI	32	MWI	0	MWI	5.9	MWI	0.4	MWI	27	MWI

Chinese cabbage	27	KEN	0.02	MWI	0.02	MWI	0.5	MWI	0.05	MWI	13	MWI	0	MWI	0.3	MWI	0.6	MWI	19	MWI
Other cultivated green leafy veg.	277	MWI	0.13	MWI	0.33	MWI	0.9	MWI	0.25	MWI	118	MWI	0	MWI	5.8	MWI	0.7	MWI	52	MWI
Gathered wild green leaves	303	MWI	0.16	MWI	0.42	MWI	1.6	MWI	0.41	MWI	286	MWI	0	MWI	21.9	MWI	1.6	MWI	62	MWI
Tomato	42	MWI	0.04	MWI	0.02	MWI	0.6	MWI	0.08	MWI	15	MWI	0	MWI	0.5	MWI	0.1	MWI	26	MWI
Cucumber	0	KEN	0.03	KEN	0.02	KEN	0.2	WAF	0.03	WAF	5	KEN	0	KEN	0.7	KEN	0.2	WAF	11	KEN
Pumpkin	189	MWI	0.07	MWI	0.04	MWI	0.7	MWI	0.15	MWI	9	MWI	0	MWI	2.0	MWI	0.2	MWI	60	MWI
Okra/Therere	41	MWI	0.06	MWI	0.13	MWI	1.1	MWI	0.35	MWI	138	MWI	0	MWI	1.3	MWI	0.9	MWI	61	MWI
Tinned vegetables	16	KEN	0.12	KEN	0.03	KEN	1.0	UK	0.11	UK	23	UK	0	KEN	0.8	KEN	0.1	KEN	19	KEN
Mushroom	2	MWI	0.10	MWI	0.27	MWI	3.8	MWI	0.08	MWI	29	MWI	0	MWI	0.2	MWI	0.6	MWI	30	MWI
Eggs	67	MWI	0.13	MWI	0.40	MWI	0.1	MWI	0.04	MWI	46	MWI	1.9	MWI	1.8	MWI	1.2	MWI	148	MWI
Beef	7	KEN	0.06	MWI	0.20	MWI	6.5	MWI	0.24	MWI	7	MWI	1.5	MWI	7.5	MWI	1.8	MWI	95	MWI
Goat	0	MWI	0.18	MWI	0.29	MWI	6.1	MWI	0.40	MWI	5	MWI	1.1	MWI	2.4	MWI	3.5	MWI	165	MWI
Pork	0	MWI	0.72	MWI	0.22	MWI	3.8	MWI	0.32	MWI	2	MWI	0.8	MWI	1.4	MWI	3.6	MWI	265	MWI
Mutton	10	MWI	0.13	MWI	0.19	MWI	3.5	MWI	0.40	MWI	2	MWI	2.9	MWI	2.1	MWI	3.3	MWI	257	MWI
Chicken	7	MWI	0.09	MWI	0.06	MWI	3.7	MWI	0.27	MWI	2	MWI	0.2	MWI	1.0	MWI	1.6	MWI	129	MWI
Other poultry	11	MWI	0.23	MWI	0.24	MWI	8.0	MWI	0.51	MWI	4	MWI	0.6	MWI	2.2	MWI	2.6	MWI	121	MWI
Small animal (rabbit, mice etc.)	10	MWI	0.11	MWI	0.15	MWI	9.5	MWI	0.57	MWI	5	MWI	10.0	MWI	1.2	MWI	1.7	MWI	130	MWI
Insect (e.g. termite)	346	KEN	0.20	KEN	0.70	KEN	1.6	WAF	0.40	WAF	157	WAF	0	KEN	117	KEN	0.6	WAF	194	MWI
Tinned meat or fish	8	WAF	0.09	WAF	0.11	WAF	1.6	WAF	0.12	WAF	4	WAF	1.0	WAF	0.9	WAF	1.6	WAF	234	WAF
Fish soup/sauce	23	MWI	0.04	MWI	0.01	MWI	0.6	MWI	0.07	MWI	9	MWI	0	MWI	6.6	MWI	2.0	MWI	44	MWI
Chicken pieces	7	MWI	0.09	MWI	0.06	MWI	3.7	MWI	0.27	MWI	2	MWI	0.2	MWI	1.0	MWI	1.6	MWI	129	MWI
Sun dried fish (large)	44	MWI	0.24	MWI	0.22	MWI	4.2	MWI	0.87	MWI	21	MWI	12.0	MWI	23.6	MWI	4.6	MWI	375	MWI
Sun dried fish (medium)	44	MWI	0.24	MWI	0.22	MWI	4.2	MWI	0.87	MWI	21	MWI	12.0	MWI	23.6	MWI	4.6	MWI	375	MWI
Sun dried fish (small)	107	MWI	0.03	MWI	0.36	MWI	19.5	MWI	1.79	MWI	18	MWI	21.1	MWI	13.3	MWI	13.5	MWI	346	MWI
Fresh fish (large)	10	MWI	0.06	MWI	0.09	MWI	3.1	MWI	0.26	MWI	14	MWI	2.5	MWI	2.9	MWI	4.3	MWI	99	MWI
Fresh fish (medium)	10	MWI	0.06	MWI	0.09	MWI	3.1	MWI	0.26	MWI	14	MWI	2.5	MWI	2.9	MWI	4.3	MWI	99	MWI
Fresh fish (small)	12	WAF	0.03	WAF	0.12	WAF	2.6	WAF	0.24	WAF	15	UK	1.9	KEN	3.8	WAF	1.2	UK	126	MWI
Smoked fish (large)	414	MWI	0.29	MWI	0.32	MWI	5.6	MWI	0.88	MWI	17	MWI	9.8	MWI	100.7	MWI	4.5	MWI	394	MWI
Smoked fish (medium)	414	MWI	0.29	MWI	0.32	MWI	5.6	MWI	0.88	MWI	17	MWI	9.8	MWI	100.7	MWI	4.5	MWI	394	MWI
Smoked fish (small)	107	MWI	0.09	MWI	0.13	MWI	13.4	MWI	0.43	MWI	25	MWI	2.7	MWI	10.7	MWI	16.4	MWI	194	MWI
Mango	123	MWI	0.05	MWI	0.03	MWI	0.1	MWI	0.06	MWI	34	MWI	0	MWI	0.3	MWI	0.1	MWI	66	MWI
Banana	4	MWI	0.04	MWI	0.04	MWI	0.6	MWI	0.36	MWI	20	MWI	0	MWI	0.3	MWI	0.2	MWI	109	MWI
Citrus (naartje, orange etc)	5	WAF	0.06	MWI	0.02	MWI	0.3	MWI	0.04	MWI	24	MWI	0	MWI	0.3	MWI	0.2	MWI	51	MWI
Pineapple	6	WAF	0.08	MWI	0.02	MWI	0.3	MWI	0.06	MWI	16	MWI	0	MWI	0.3	MWI	0	MWI	58	MWI
Papaya	16	MWI	0.03	MWI	0.01	MWI	0.3	MWI	0.01	MWI	15	MWI	0	MWI	0.4	MWI	0.1	MWI	48	MWI
Guava	5	MWI	0.05	MWI	0.02	MWI	1.2	MWI	0.79	MWI	19	MWI	0	MWI	0.4	MWI	0.2	MWI	71	MWI
Avocado	6	MWI	0.06	MWI	0.14	MWI	1.7	MWI	0.32	MWI	33	MWI	0	MWI	0.7	MWI	0.3	MWI	152	MWI
Wild fruit (masau, malimbe, etc.)	15	MWI	0.13	MWI	0.09	MWI	0.9	MWI	0.09	MWI	20	MWI	0	MWI	3.0	MWI	0.8	MWI	167	MWI
Apple	1	WAF	0.02	MWI	0.06	MWI	0.2	MWI	0.03	MWI	1	MWI	0	MWI	0.3	MWI	0.1	MWI	63	MWI
Fresh milk	44	MWI	0.02	MWI	0.16	MWI	0.1	MWI	0.04	MWI	5	MWI	0.4	MWI	0.1	MWI	0.4	MWI	67	MWI
Powdered milk	329	WAF	0.3	WAF	1.20	WAF	0.8	WAF	0.25	WAF	37	WAF	1.8	WAF	0.8	WAF	3.3	WAF	493	WAF
Margarine- Blue band	850	MWI	1.3	MWI	1.70	MWI	18.0	MWI	2.00	MWI	200	MWI	1.0	MWI	0	MWI	0	MWI	724	MWI
Butter	845	KEN	0	KEN	0.05	KEN	1.1	WAF	0	WAF	5	KEN	0	KEN	0	KEN	0.1	KEN	735	KEN
Chambiko (soured milk)	17	KEN	0.02	LSO	0.15	LSO	0	WAF	0.02	WAF	7	LSO	0.2	LSO	0.1	LSO	0.6	LSO	65	LSO
Yoghurt	34	KEN	0.1	KEN	0.20	KEN	0.1	WAF	0.05	WAF	8	KEN	0.2	KEN	0.2	WAF	0.3	KEN	85	KEN
Cheese	68	KEN	0.04	KEN	0.32	KEN	0.7	WAF	0.04	WAF	21	KEN	0.9	KEN	0.3	KEN	1.1	KEN	184	KEN

Sugar	0	KEN	0	KEN	0	KEN	0	WAF	0	WAF	0	KEN	0	KENI	0	KEN	0	KEN	400	KEN
Sugar cane	0	MWI	0.03	KEN	0.04	KEN	0.1	UK	0	MWI	0	KEN	0	MWI	0.6	MWI	0.1	KEN	40	MWI
Cooking oil	0	WAF	0	WAF	0	WAF	0	WAF	0	WAF	0	WAF	0	WAF	0.1	WAF	0	WAF	900	WAF
Salt	0	KEN	0	KEN	0	KEN	0	UK	0	WAF	0	KEN	0	KEN	0.1	KEN	0.1	KEN	0	KEN
Spices	55	KEN	0.25	KEN	0.45	KEN	4.9	UK	0.21	WAF	36	KEN	0	KEN	35.5	KEN	3.7	UK	360	KEN
Yeast, baking powder, bicarbonate	0	KEN	0	KEN	0	KEN	0	WAF	0	WAF	0	WAF	0	KEN	9.7	KEN	0.9	KEN	179	KEN
Tomato sauce (bottled)	22	KEN	0	KEN	0.10	KEN	1.3	WAF	0.63	WAF	97	KEN	0	KEN	0.7	KEN	0.2	KEN	115	KEN
Hot sauce (Nali, etc)	22	KEN	0	KEN	0.10	KEN	1.3	UK	0.63	UK	97	KEN	0	KEN	0.7	KEN	0.2	KEN	115	KEN
Jam, jelly	2	WAF	0	WAF	0	WAF	0	WAF	0.03	WAF	2	WAF	0	WAF	1.0	WAF	0.2	WAF	281	WAF
Sweets, candy, chocolate	21	WAF	0.05	WAF	0.08	WAF	0.7	WAF	0.04	WAF	12	WAF	0	WAF	4.3	WAF	1.4	WAF	532	WAF
Honey	0	KEN	0	KEN	0	KEN	0	WAF	0.02	WAF	2	KEN	0	KEN	0.6	KEN	3.0	KEN	522	KEN
Maize- boiled/roasted (vendor)	0	MWI	0.08	MWI	0.03	MWI	0.6	MWI	0.05	MWI	7	MWI	0	MWI	1.1	MWI	0.8	MWI	133	MWI
Chips (vendor)	0	KEN	0.19	MWI	0.01	MWI	2.0	MWI	0.30	MWI	3	MWI	0	MWI	1.0	MWI	0.4	MWI	264	MWI
Cassava (vendor)	1	MWI	0.03	MWI	0.04	MWI	0.4	MWI	0.06	MWI	14	MWI	0	MWI	0.6	MWI	0.6	MWI	146	MWI
Eggs – boiled (vendor)	74	MWI	0.12	MWI	0.42	MWI	0.1	MWI	0.04	MWI	38	MWI	1.8	MWI	2.0	MWI	1.3	MWI	164	MWI
Chicken (vendor)	13	MWI	0.06	MWI	0.05	MWI	2.2	MWI	0.14	MWI	3	MWI	0.1	MWI	2.9	MWI	2.0	MWI	157	MWI
Meat (vendor)	55	MWI	0.12	MWI	0.22	MWI	6.9	MWI	0.37	MWI	4	MWI	1.6	MWI	5.2	MWI	3.1	MWI	351	MWI
Fish (vendor)	54	MWI	0.08	MWI	0.11	MWI	1.1	MWI	0.13	MWI	11	MWI	0.1	MWI	4.0	MWI	0	MWI	146	MWI
Mandazi (vendor)	24	MWI	0.12	MWI	0.14	MWI	0.4	MWI	0.05	MWI	11	MWI	0.3	MWI	2.0	MWI	0.3	MWI	211	MWI
Samosa (vendor)	138	KEN	0.46	KEN	0.31	WAF	3.2	UK	0.15	UK	44	UK	0.3	KEN	3.8	KEN	1.8	UK	325	KEN
Meal eaten at restaurant	13	MWI	0.06	MWI	0.05	MWI	2.2	MWI	0.14	MWI	3	MWI	0.1	MWI	2.9	MWI	2.0	MWI	157	MWI
Boiled sweet potato (vendor)	7	MWI	0.07	MWI	0.01	MWI	0.7	MWI	0.09	MWI	8	MWI	0	MWI	0.4	MWI	0.2	MWI	97	MWI
Roasted sweet potato (vendor)	2	MWI	0.06	MWI	0.03	MWI	0.4	MWI	0.18	MWI	27	MWI	0	MWI	1.0	MWI	0.8	MWI	89	MWI
Boiled groundnut (vendor)	0	MWI	0.47	MWI	0.08	MWI	8.4	MWI	0.32	MWI	60	MWI	0	MWI	2.1	MWI	1.4	MWI	324	MWI
Roasted groundnuts (vendor)	0	MWI	0.78	MWI	0.13	MWI	14.7	MWI	0.53	MWI	77	MWI	0	MWI	2.1	MWI	2.3	MWI	597	MWI
Zikondamoyo/Nkate	4	MWI	0.18	MWI	0.07	MWI	1.2	MWI	0.33	MWI	19	MWI	0	MWI	1.4	MWI	0.7	MWI	218	MWI
Cassava – roasted (vendor)	1	MWI	0.03	MWI	0.04	MWI	0.4	MWI	0.06	MWI	14	MWI	0	MWI	0.6	MWI	0.6	MWI	146	MWI
Tea	0	KEN	0	KEN	0.99	KEN	10.8	WAF	0	WAF	5	KEN	0	KEN	2.3	KEN	1.7	KEN	299	KEN
Coffee	0	KEN	0	KEN	1.00	KEN	42.9	WAF	0.03	WAF	7	KEN	0	KEN	3.9	KEN	0.7	KEN	311	KEN
Cocoa, millo	61	KEN	0.03	KEN	0.15	KEN	0.5	UK	0.11	MOZ	6	KEN	0	KEN	2.0	KEN	1.6	KEN	541	KEN
Squash (Sobo drink concentrate)	0	WAF	0.02	WAF	0.02	WAF	0.1	WAF	0.03	WAF	0	WAF	0	WAF	0.3	WAF	0	WAF	48	WAF
Fruit juice	1	MWI	0.04	MWI	0.02	MWI	0.2	MWI	0.01	MWI	21	MWI	0	MWI	0.3	MWI	0.1	MWI	83	MWI
Freezes (flavored ice)	0	WAF	0.02	WAF	0.02	WAF	0.1	WAF	0.03	WAF	0	WAF	0	WAF	0.3	WAF	0	WAF	48	WAF
Soft drinks	0	WAF	0	WAF	0	WAF	0	WAF	0	WAF	0	WAF	0	WAF	0.1	WAF	0.1	WAF	40	WAF
Chibuku (traditional beer)	0	WAF	0.01	LSO	0.03	LSO	0.1	WAF	0.05	WAF	6	LSO	0	WAF	0	LSO	0	WAF	16	WAF
Bottled water	0	MWI	0	MWI	0	MWI	0	MWI	0	MWI	0	MWI	0	MWI	0	MWI	0	MWI	0	MWI
Maheu	0	WAF	0.01	WAF	0.03	WAF	0.3	WAF	0.05	WAF	6	WAF	0	WAF	0.2	WAF	0.1	WAF	33	WAF
Bottled/canned beer	0	WAF	0.01	WAF	0.02	WAF	0.5	WAF	0.03	WAF	6	WAF	0	WAF	0	WAF	0	WAF	41	WAF
Thobwa	0	WAF	0.01	WAF	0.03	WAF	0.3	WAF	0.05	WAF	6	WAF	0	WAF	0.2	WAF	0.1	WAF	33	WAF
Masese (traditional beer)	0	WAF	0.01	WAF	0.03	WAF	0.3	WAF	0.05	WAF	6	WAF	0	WAF	0.2	WAF	0.1	WAF	33	WAF
Wine or commercial liquor	0	KEN	0	KEN	0	KEN	0.1	WAF	0.05	MWI	1	KEN	0	KEN	0.5	KEN	0.1	KEN	76	KEN
Kachasu (locally brewed liquor)	0	MWI	0.01	UK	0	UK	0	UK	0	MWI	0	MWI	0	UK	0	UK	0	UK	231	MWI

Supplementary Table 2. *Fortifiable food equivalent factors for wheat flour in wheat flour products*

Food item/product	Fortifiable food equivalent factor	Recipe	Reference
Wheat flour	1	-	-
Bread	0.75	-	[7]
Buns/scones	0.33	46g Milk, cow, whole, fresh 29g Wheat flour, white, raw 12g Chicken eggs, whole, raw 12g Sugar, white	[1]
Mandazi (beignets)	0.41	42g Wheat flour, white, raw 27g Chicken eggs, whole, raw 20g Milk, cow, whole, fresh 11g Oats, raw 7g Cooking oil	[1]

Supplementary Table 3. *Base parameters defining daily dietary micronutrient and energy requirements*

Parameters		**Data & assumptions**	**Reference(s)**
Household micronutrient supply data			
Food consumption		Data	[8]
Micronutrient composition of food		See Table S1	
Adult female equivalent factors			
Energy requirement for reference adult female (kcal)		2100	[9]
Sex of household members		Data	[8]
Age of household members		Data	[8]
Adult male body weight (kg)		65	Assumption
Adult female body weight (kg)		55.9	[10]
Energy expenditure factor from physical activity (per basal metabolic rate)		1.6	[9]
Additional energy requirement for pregnancy (kcal)		300	[11]
Additional energy requirement for lactation (kcal)		500	[12]
Energy intake from breastmilk, age 3-5 months (kcal)		434	[13,14]
Energy intake from breastmilk, age 6-8 months (kcal)		413	[14]
Energy intake from breastmilk, age 9-11 months (kcal)		379	[14]
Energy intake from breastmilk, age 12-23 months (kcal)		346	[14]
Micronutrient inadequacy thresholds (female 18-50 years)			
Vitamin A (μg RAE)	Harmonized Average Requirement	490	[15]
	Critical nutrient density (per 1000 kcal)	239	[9,15]
Thiamine (mg)	Harmonized Average Requirement	0.9	[15]
	Critical nutrient density (per 1000 kcal)	0.4	[9,15]
Riboflavin (mg)	Harmonized Average Requirement	1.3	[15]
	Critical nutrient density (per 1000 kcal)	0.6	[9,15]
Niacin (mg)	Harmonized Average Requirement	11	[15]
	Critical nutrient density (per 1000 kcal)	5.4	[9,15]
Vitamin B6 (mg)	Harmonized Average Requirement	1.3	[15]
	Critical nutrient density (per 1000 kcal)	0.6	[9,15]
Folate (μg)	Harmonized Average Requirement	250	[15]
	Critical nutrient density (per 1000 kcal)	122	[9,15]
Vitamin B12 (μg)	Harmonized Average Requirement	2	[15]
	Critical nutrient density (per 1000 kcal)	1	[9,15]
Iron (mg)	Harmonized Average Requirement	-	[16]
	Critical nutrient density (per 1000 kcal)	-	[9,16]
Zinc (mg)	Harmonized Average Requirement	10.2	[15]
	Critical nutrient density (per 1000 kcal)	5	[9,15]

Supplementary Table 4. *Standard and non-standard food consumption units recorded in Malawi's Fourth Integrated Household Survey*

Unit	**Sizes**
Standard Units	
Gram	-
Kilogram	-
Liter	-
Milliliter	-
Tablespoon	-
Teaspoon	-
Non-Standard Units	
5L Bucket (Chigoba)	-
50kg bag	-
Basin	Small, Large
Bunch	Small, Medium, Large
Cluster	Small, Medium, Large
Heap	Small, Medium, Large
Loaf	300g, 600g, 700g
No. 10 plate	Heap, flat
No. 12 plate	Heap, flat
Packet	150g, 400g, 500g, 1kg
Pail	Small, Medium, Large
Piece	Small, Medium, Large
Other (specify)	-
Sachet/tube	25g, 50g, 100g
Tin	100g, 250g, 500g, 1kg
Tina bowl	Heap, flat

Description of data cleaning and transformation procedures

Conversion of non-standard units

IHS4 food consumption data measured the quantity consumed of each food item using a list of standard and non-standard units (Supplementary Table 4). All units for all food items were converted into kilograms using regionally specific non-standard unit to kilogram conversion factors made available by the World Bank's Living Standards and Measurement Study. For food item units with missing conversion factors, kilogram conversion factors were estimated equally across all regions either using the IHS4 "Household food consumption photo aid" or by calculating the food quantity's mass using volumes of non-standard units purchased from local markets in Malawi. Food item units that were reported as "Other (specify)" which were similar to listed non-standard units were reported as their listed equivalent, and converted into kilograms as accordingly. Food item units that were reported as "Other (specify)" without equivalent listed non-standard units were disregarded due to the absence of an appropriate conversion factor.

Non-edible portions of food

We adjusted for non-edible portions of food weight included in the seven-day household recall (e.g. potato peels, maize husks, maize cobs). Proportion factors of non-edible portions for certain food items were estimated using refuse percentages from matched items of the 2019 FAO West African Food Composition Tables.[5]

Food composition table match

Each IHS4 food item was screened to identify a potential corresponding food item in the 2019 Malawi Food Composition Table (MAFOODS).[1] The screening process was done manually. We gathered information regarding each IHS4 food item, corresponding food items in MAFOODS, and classified each food item by the type of match through four categories: ‘exact match’, ‘partial match’, ‘multiple matches’, or ‘no match’.

Food items that were identified as ‘exact match’ had a one-to-one perfect match, that is identical food items and method of preparation.

Food items identified as ‘partial match’ were similar to the food consumed in MAFOODS but not perfect (e.g. “brown beans”, as reported in IHS4, was matched to “kidney beans” in MAFOODS). We made adjustments to the food composition to ensure consistency between the recalled food item processing and the match item on the food composition table (e.g. IHS4 “dried fish” matched to a fish item which adjusted composition data to reflect drying process).

Food items that were identified as ‘multiple matches’ were evaluated to identify a single, most representative item. Some IHS4 food items were listed as broad food categories (e.g. IHS4’s “Small Fresh Fish”). To find the equivalent item in MAFOODS, the median of multiple MAFOODS items was calculated to account for variability in the food composition of different varieties of the same food. All the decisions were informed by published data and experts’ opinion and recorded in the spreadsheet.

Finally, 'no match' were defined as IHS4 food items with either no equivalent in MAFOODS or had equivalents but with missing values for one or more nutrients. In this case, data from other food composition tables were used. Food composition tables were selected based on geographic proximity to Malawi and quality of the data, being, in order of preference, 2018 Kenya Food Composition Table[2], 2019 Food Composition Table for Western Africa compiled by the Food and Agriculture Organization of the United Nations [5], 2006 Lesotho Food Composition Table[3] and the 2011 Mozambique Food Composition Tables.[4] For globally traded food items and items with missing composition data from all neighboring country food composition tables, food items were matched to corresponding food items from McCance and Widdowson's food composition table for the United Kingdom. [6]

After food matching, all missing values were identified, and nutrient values and metadata were imputed from an equivalent food item using the above-mentioned food composition tables. The script used to create the final match and metadata spreadsheet used in this study is available upon request.

In total, 65% of the food items were matched to a food item reported in MAFOODS, while the rest of the items were sourced from other food composition tables. These matches were reviewed and agreed upon between two researchers. Any disagreements between the two co-authors about whether to include a publication were resolved through discussion.

Many food items were recalled by households in their raw market purchased variety (e.g. grams of dry spaghetti, bunches of uncooked green vegetables, buckets of uncooked potatoes) without providing any information on processing and cooking once obtained by the household. We choose to analyze the raw variety of these food items without making any assumptions about changes in yield or addition/loss of micronutrients during the cooking process as processing of food items may vary substantially between households. These household micronutrient supply estimates are expected to be greater than the total household micronutrient intake as some micronutrients are expected to be lost during the cooking process.

Management of outliers

Food item consumption quantities that exceed a pre-specified threshold value will be corrected and capped. Total consumption quantity of individual food items per capita per day demonstrates a non-parametric distribution with a right skew. Each food items' consumption quantity distribution will be normalized through logarithmic transformation and extreme consumption quantity values, or values greater than five standard deviations above the mean of the logarithmically transformed consumption quantities, will be defined as outliers. Outliers will be replaced with the population median consumption quantity among consumers for each food item.

Description of adult female equivalent factor calculation

For the apparent intake approach, household supply of each micronutrient will be divided by the number of adult female equivalents within the household. The subsequent steps will outline the process necessary to calculate the total number of adult female equivalents (AFE) for each household, where AFEs are based on the energy requirements of each member of the household. The following data and assumptions will be combined to estimate each household members' energy requirements as defined by Weisell & Dop.[17] All AFE base parameters, data sources, and assumptions are presented in Supplementary Table 3.

Base energy requirements

Base energy expenditure for all household members will be based on the Human Energy Requirements recommendations from the Joint FAO/WHO/UNU Expert Consultation.[9] Data describing individual household members' age and sex is collected as part of the IHS4-Module B "Household Roster." Household member's sex is described in question "B03- Sex" and age is described in question "B06_3- How old is [NAME]?".

The body weight of individual household members was not collected as part of IHS4. For females, we used data from Malawi's Demographic and Health Survey (DHS) from 2015/16 [10] describing non-pregnant females (n=7180) where the average weight across the entire country was 55.9 kg. Weights of males were not collected in the 2015/16 DHS, so we assumed energy requirements necessary for males with a weight of 65 kg as the adult male standard. This analysis assumed that all adult household members expend "moderate physical activity levels" or a factor of 1.6 basal metabolic rates.

Additional energy requirements for pregnancy

Data describing the pregnancy status of individual household members is collected as part of the IHS4-Module D "Health." Pregnancy status of household members is described in question "D04-During the past 2 weeks have you suffered from an illness or injury? (Y/N)" and "D05- What was the illness or injury?" where the categorical response "28" indicates "Pregnancy." Pregnant women will have additional energy added to their base energy requirements, where pregnant women will require an additional 300 kcal per day.[11]

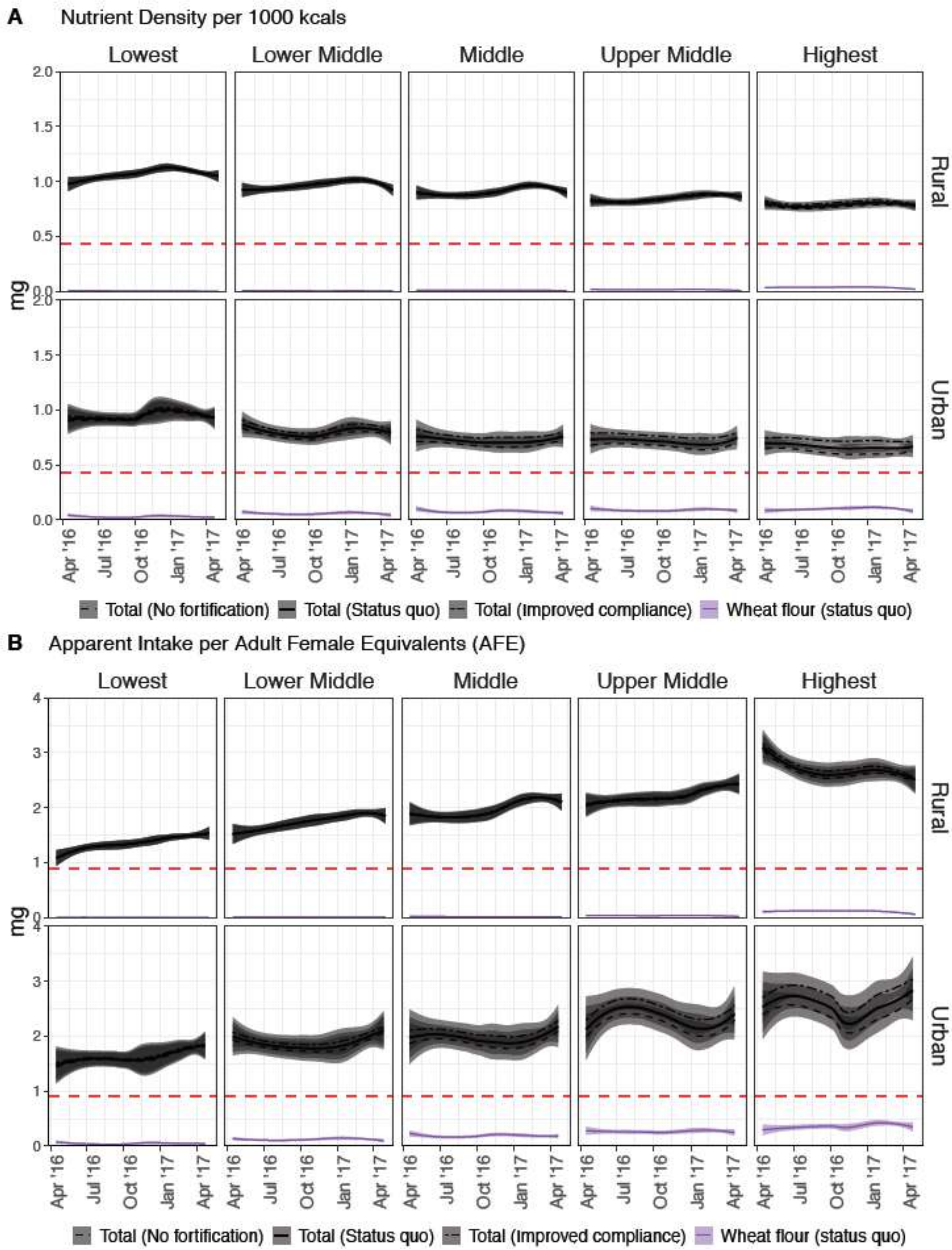
Additional energy requirements for lactation

According to Malawi's 2015/16 DHS, breastfeeding adherence was high, where 89% of infants between ages 12-23 months continued to be breastfed.[13] We assumed that all households with children below 2 years old will have a lactating mother in accordance with the Worth Health Organization recommendations for breastfeeding [14]. This is expected to be an overestimation of the total number of lactating women since there is likely to be variation in the degree of adherence to international breastfeeding guidelines, however with high breastfeeding adherence in Malawi we expected this to make little difference in estimates of apparent intake. Lactating women will have additional energy added to their base energy requirements, where lactating women will require an additional 500 kcal per day.[12]

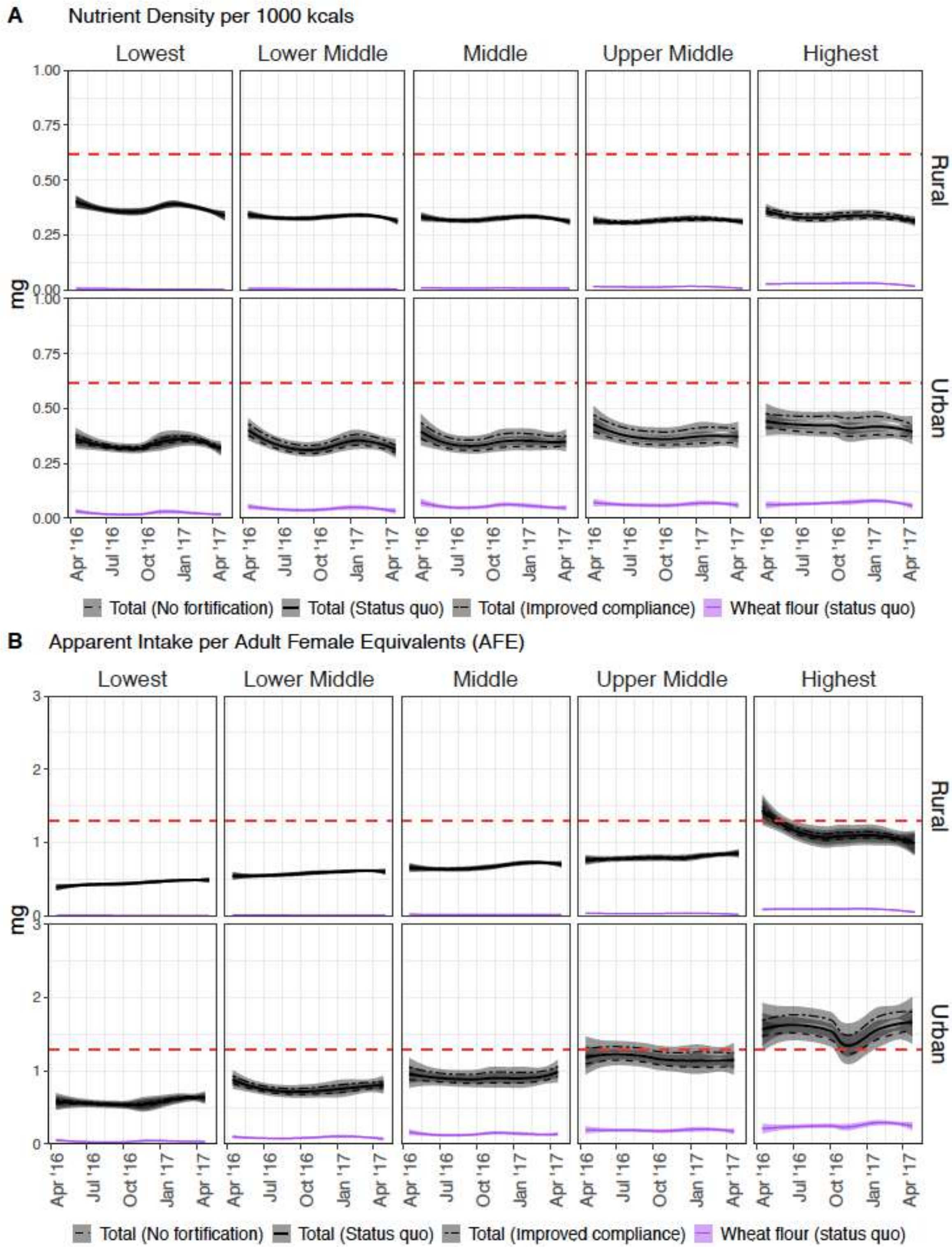
Energy contributions from breastmilk for infants under 2 years old

For infants under 2 years old, energy contributions from breastmilk were subtracted from their daily energy requirements to represent their total energy requirements from complementary foods. The total energy intake from breastmilk was age stratified for infants between 0-2 month, 3-5 months, 6-8 months, 9-11 months, and 12-23 months, which is consistent with the age stratifications from a systematic review that summarized breastmilk intake studies from developing countries. [14] For children under 6 months of age, Malawi's 2015/16 DHS data was used to provide insight into the proportion of children under 6 months that were exclusively breastfeeding, where the crude approach would be to assume that all children under 6 months were exclusively breastfeeding and didn't consume any of the family meal. Only 60% of children under 6 months in Malawi were exclusively breastfeeding, where children between 0-2 months had high exclusive breastfeeding adherence (>90%) and children between 3-6 months had lower adherence (~40%). With this, in the AFE estimates used for the HCES model, we assumed children under 2 were exclusively breastfed and did not take part in the family meal, where children aged 3-6 months did partially take part in the family meal.

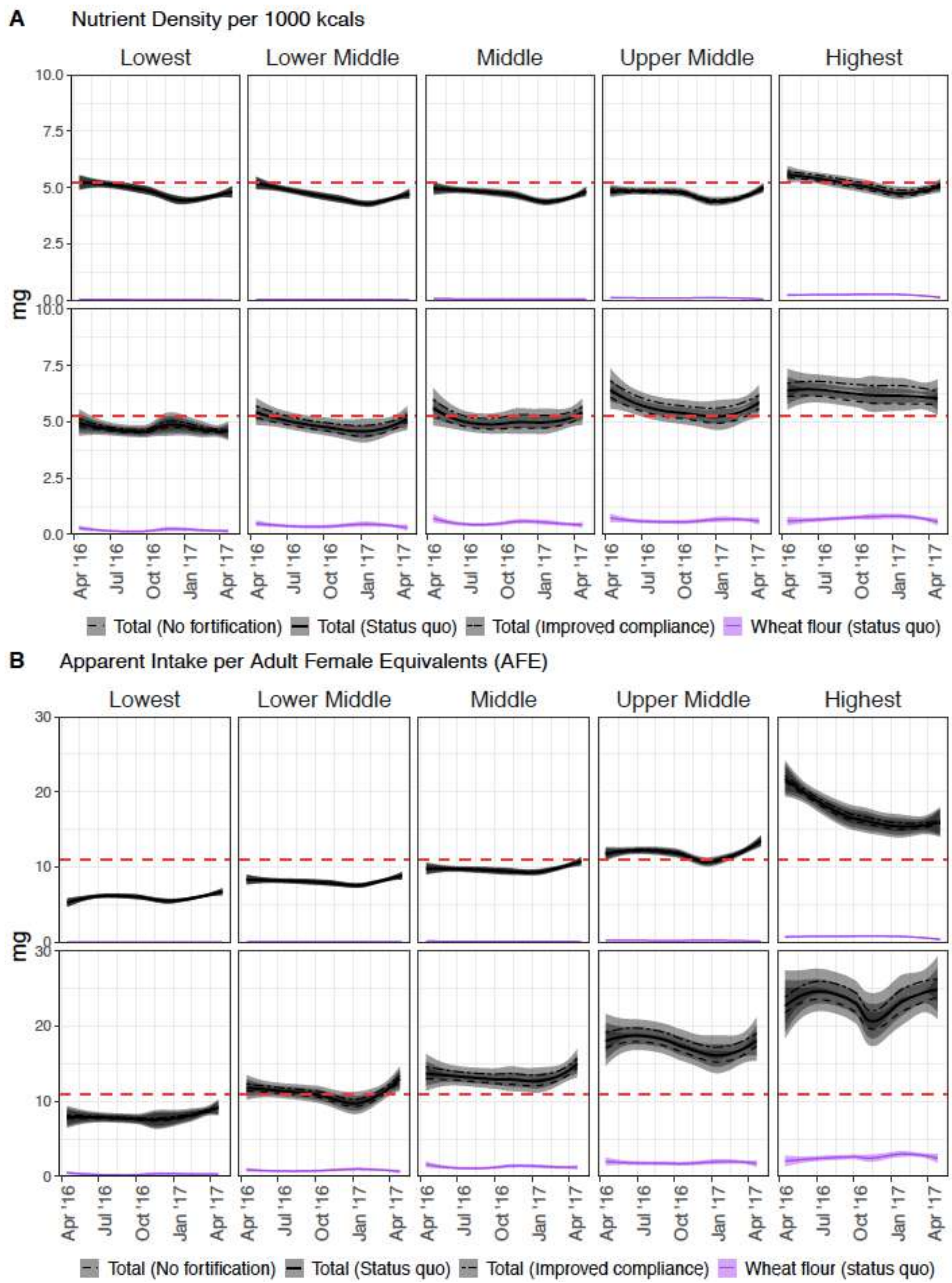
Seasonality plots and district level maps for additional micronutrients



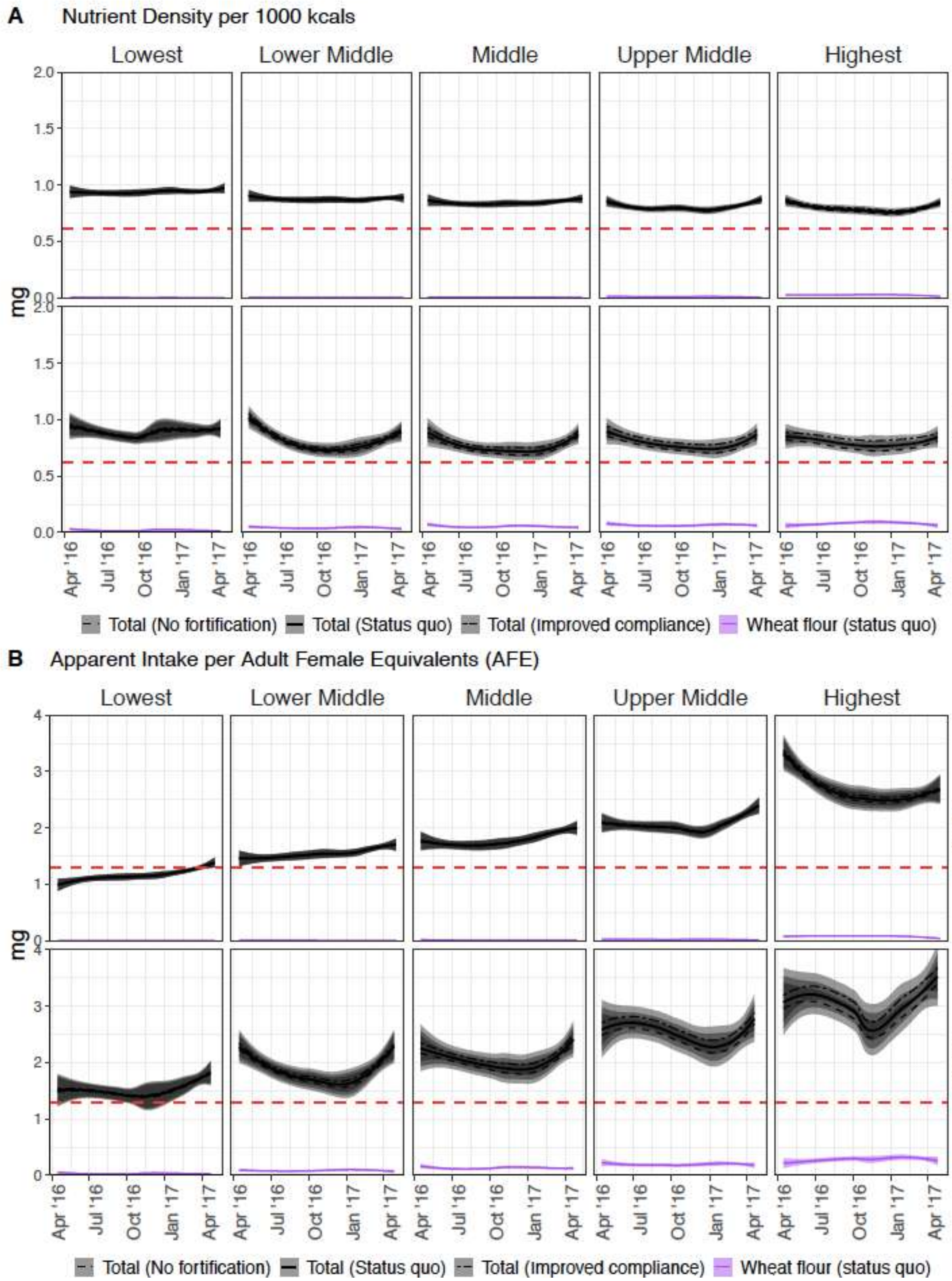
Supplementary Figure 1. *Seasonality in the (A) nutrient density and (B) apparent intake of thiamine under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residence.*



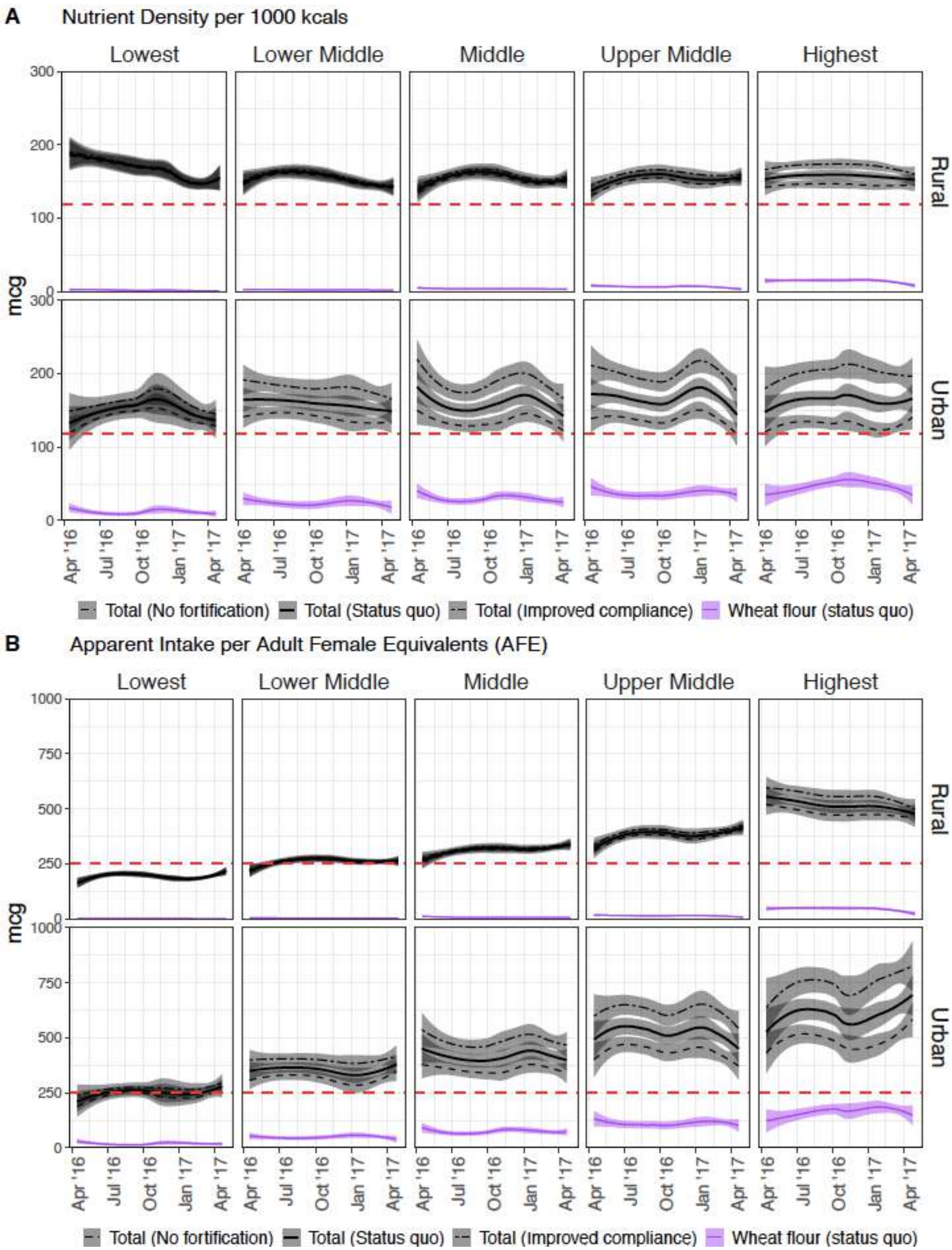
Supplementary Figure 2. *Seasonality in the (A) nutrient density and (B) apparent intake of riboflavin under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residence.*



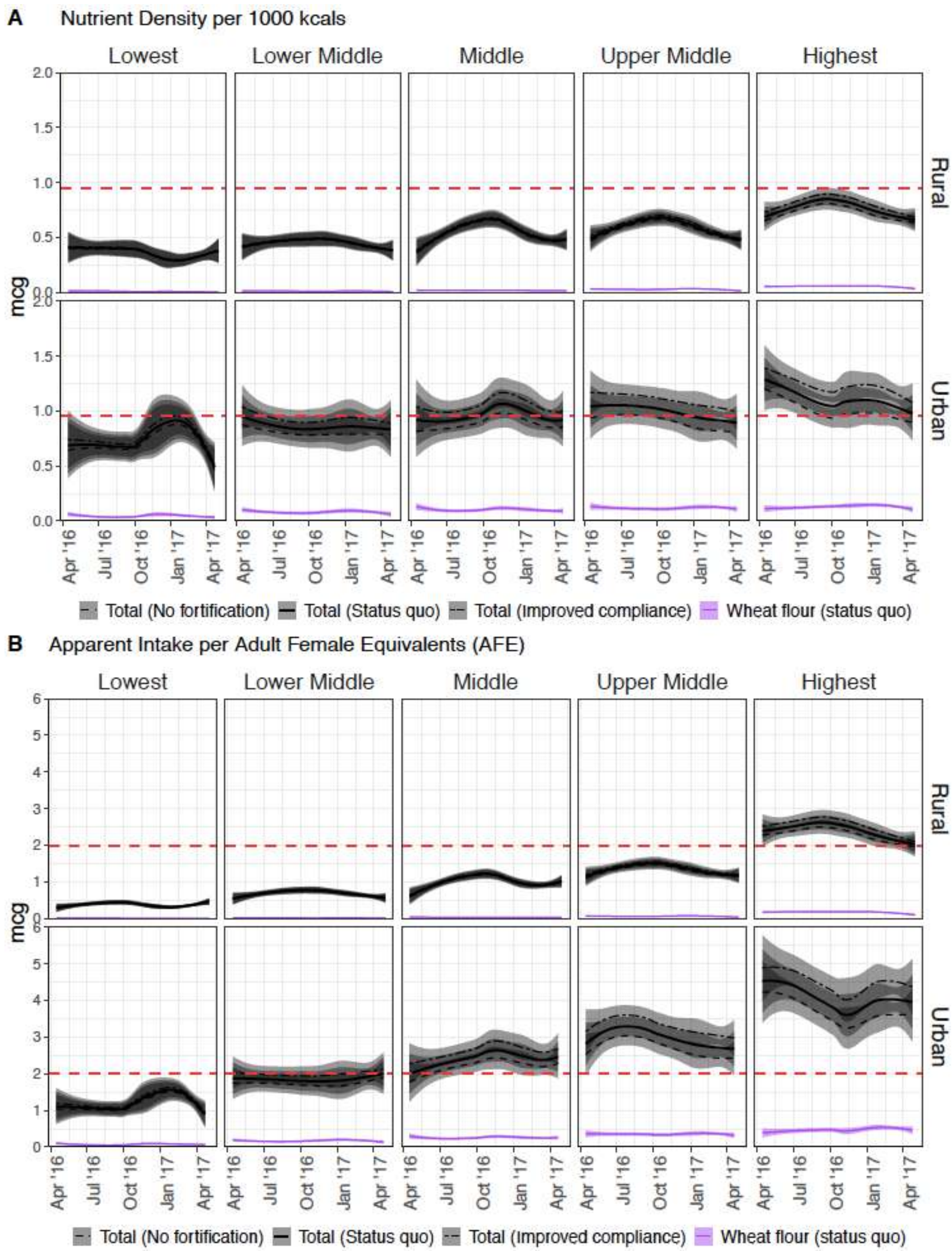
Supplementary Figure 3. *Seasonality in the (A) nutrient density and (B) apparent intake of niacin under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residence.*



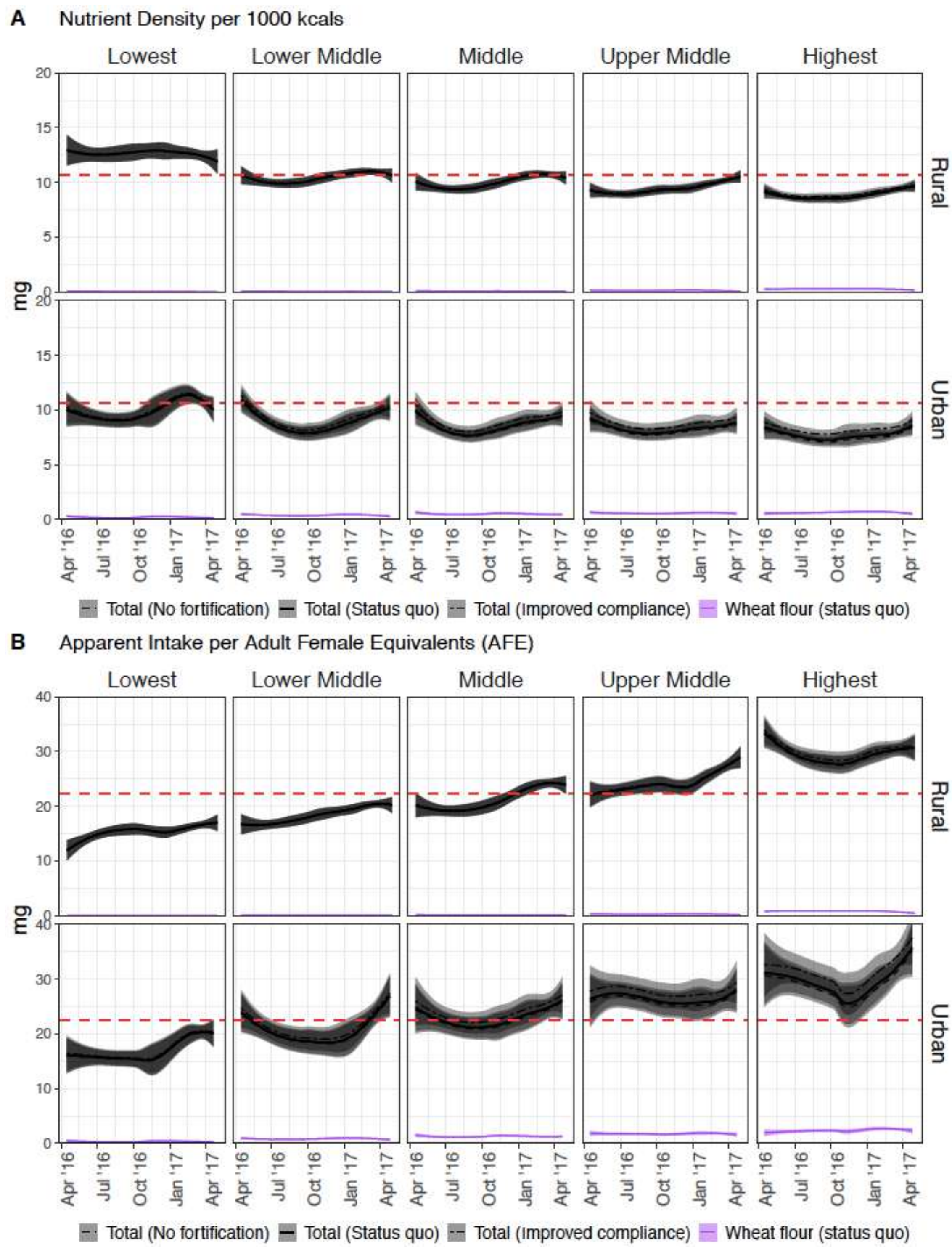
Supplementary Figure 4. *Seasonality in the (A) nutrient density and (B) apparent intake of vitamin B6 under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residence.*



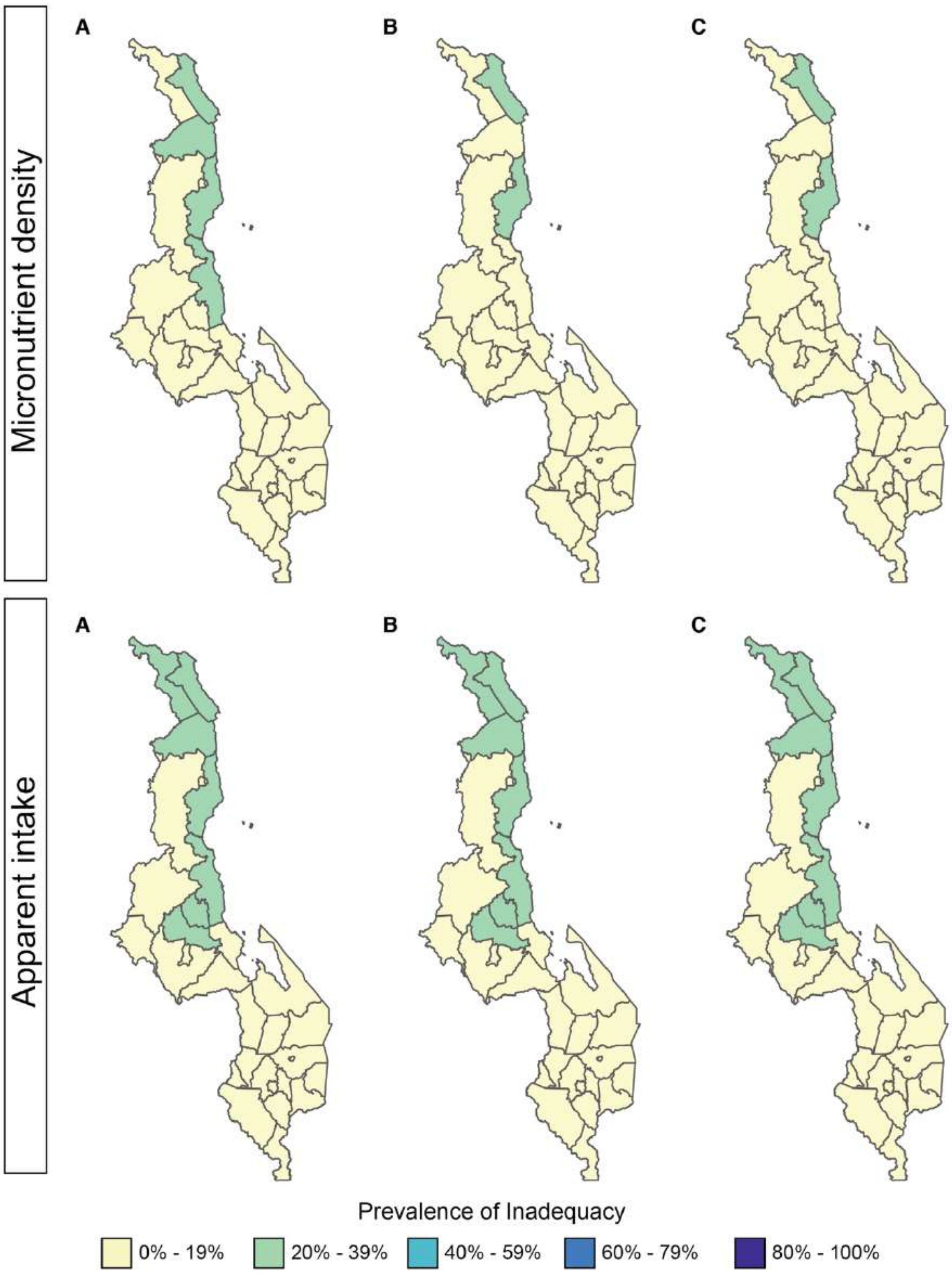
Supplementary Figure 5. *Seasonality in the (A) nutrient density and (B) apparent intake of folate under the three fortification scenarios by socioeconomic position (lowest to highest) between urban and rural residence.*



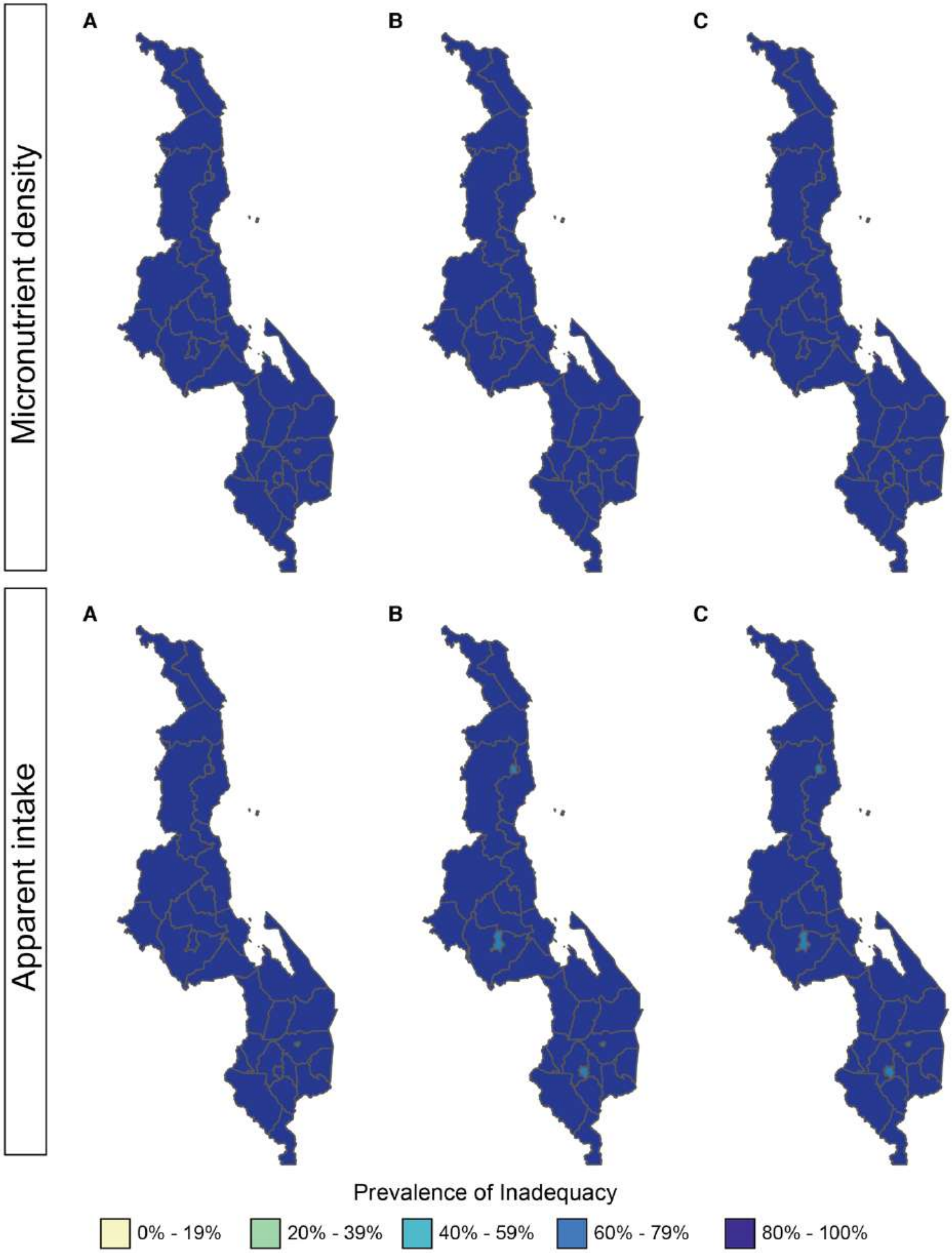
Supplementary Figure 6. *Seasonality in the (A) nutrient density and (B) apparent intake of vitamin B12 under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residence.*



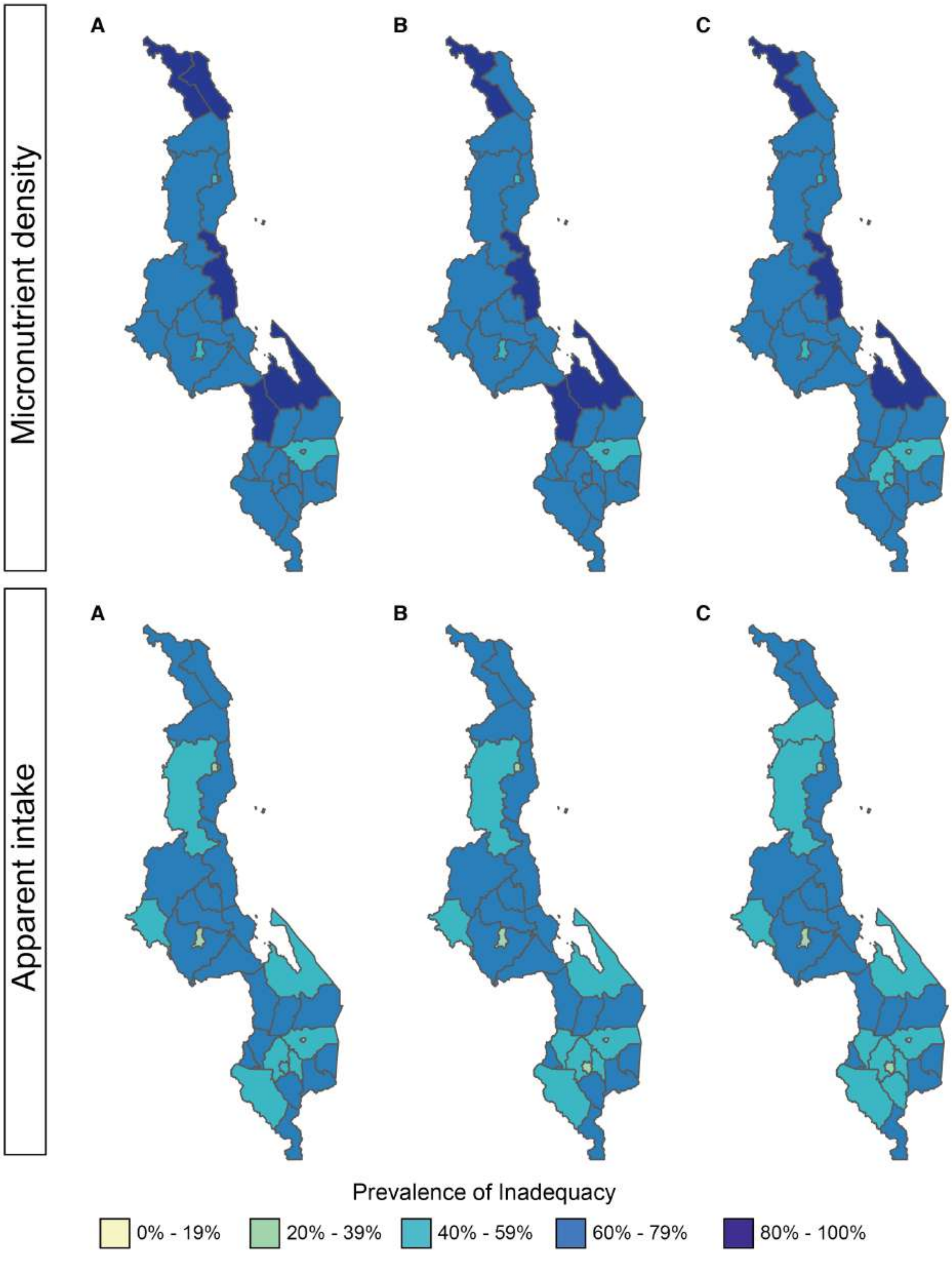
Supplementary Figure 7. *Seasonality in the (A) nutrient density and (B) apparent intake of iron under the three fortification scenarios in relation to the inadequacy threshold (red dotted line) by socioeconomic position (lowest to highest) between urban and rural residence. While the threshold for inadequacy is present, estimating dietary iron inadequacy requires the full probabilistic approach since iron requirements for menstruating women are non-parametric.*



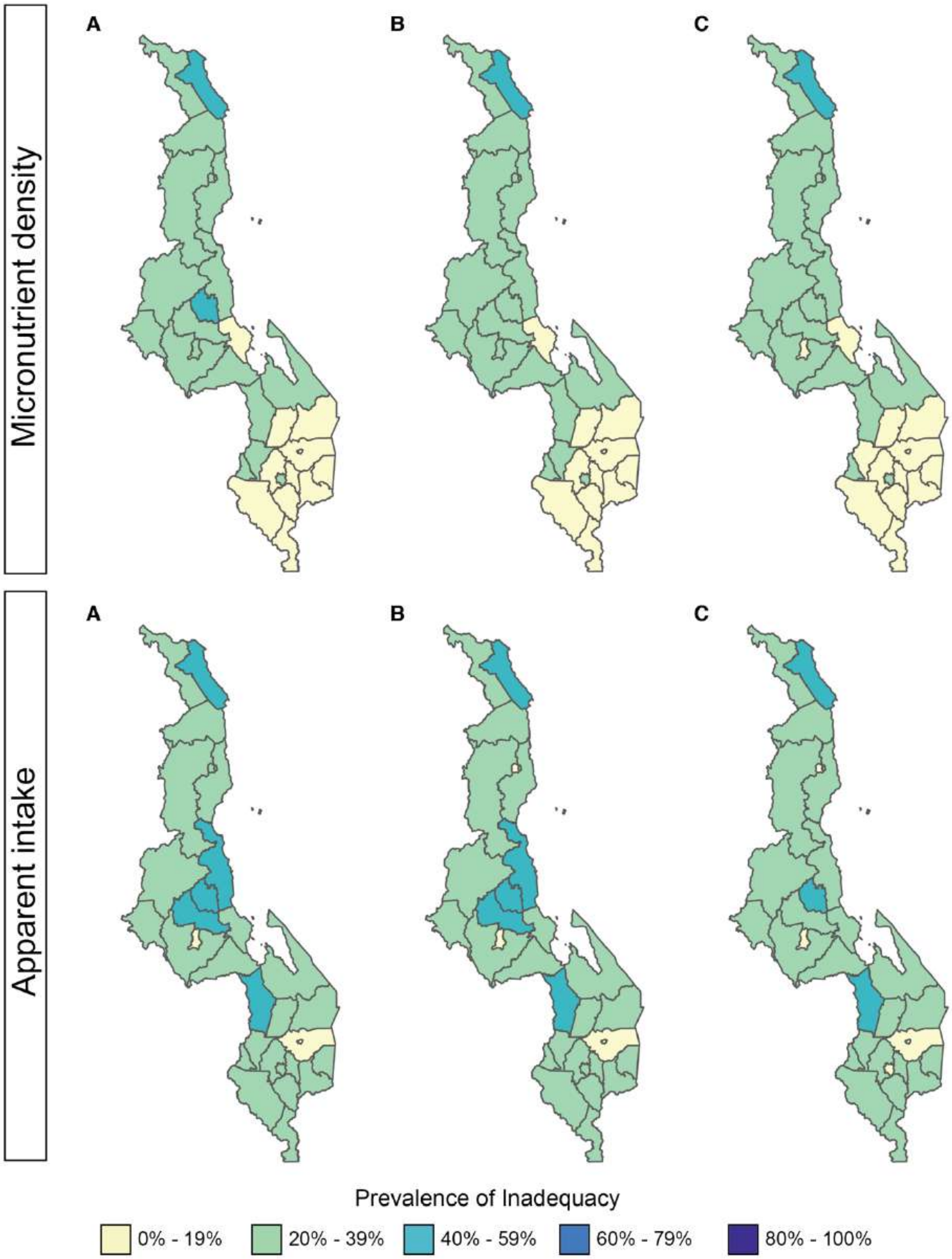
Supplementary Figure 8. Prevalence of thiamine inadequate diets estimated using the micronutrient density approach versus the apparent intake approach for the (A) 'No fortification', (B) 'Status quo', and (C) 'Improved compliance' scenarios.



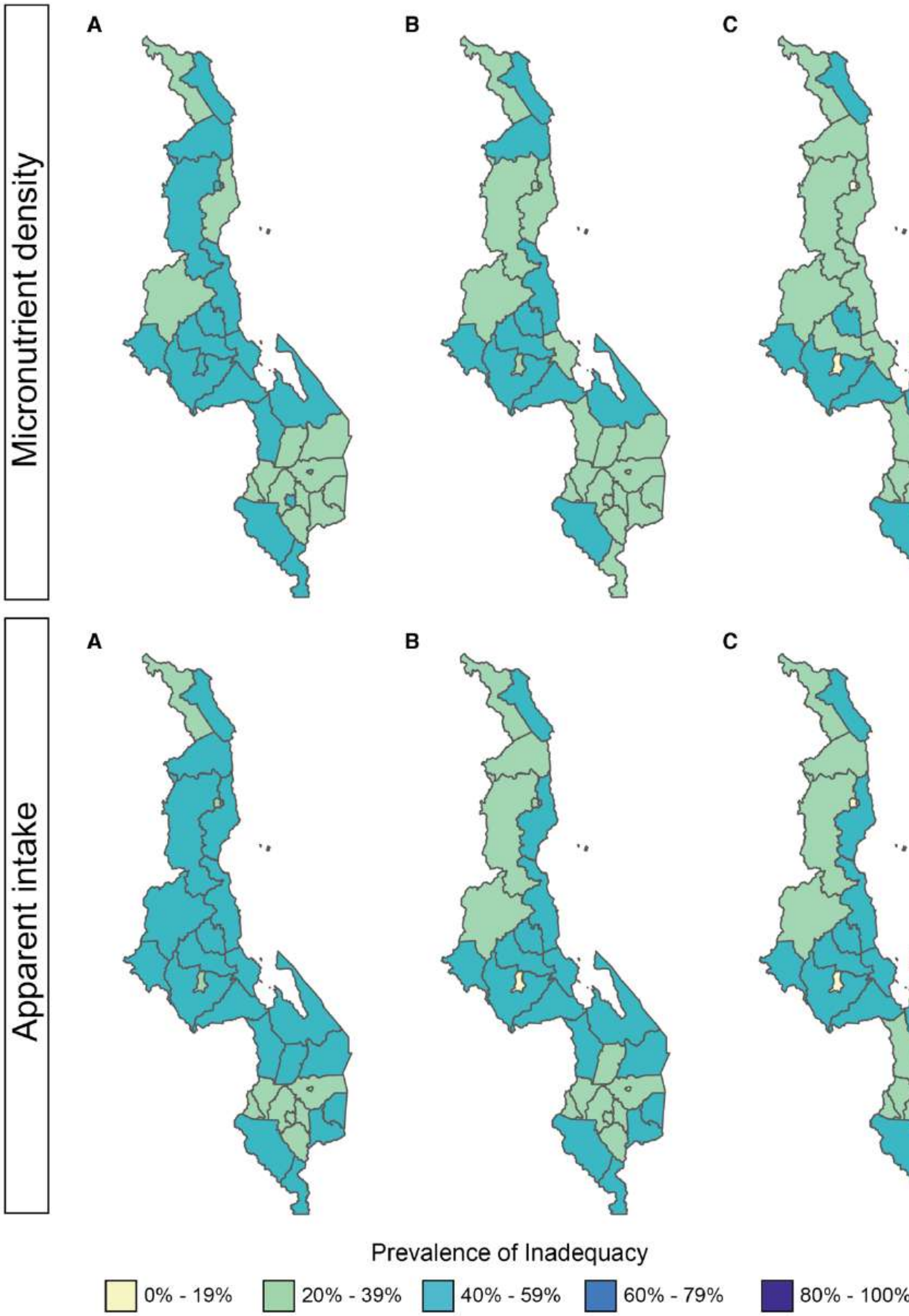
Supplementary Figure 9. Prevalence of riboflavin inadequate diets estimated using the micronutrient density approach versus the apparent intake approach for the (A) 'No fortification', (B) 'Status quo', and (C) 'Improved compliance' scenarios.



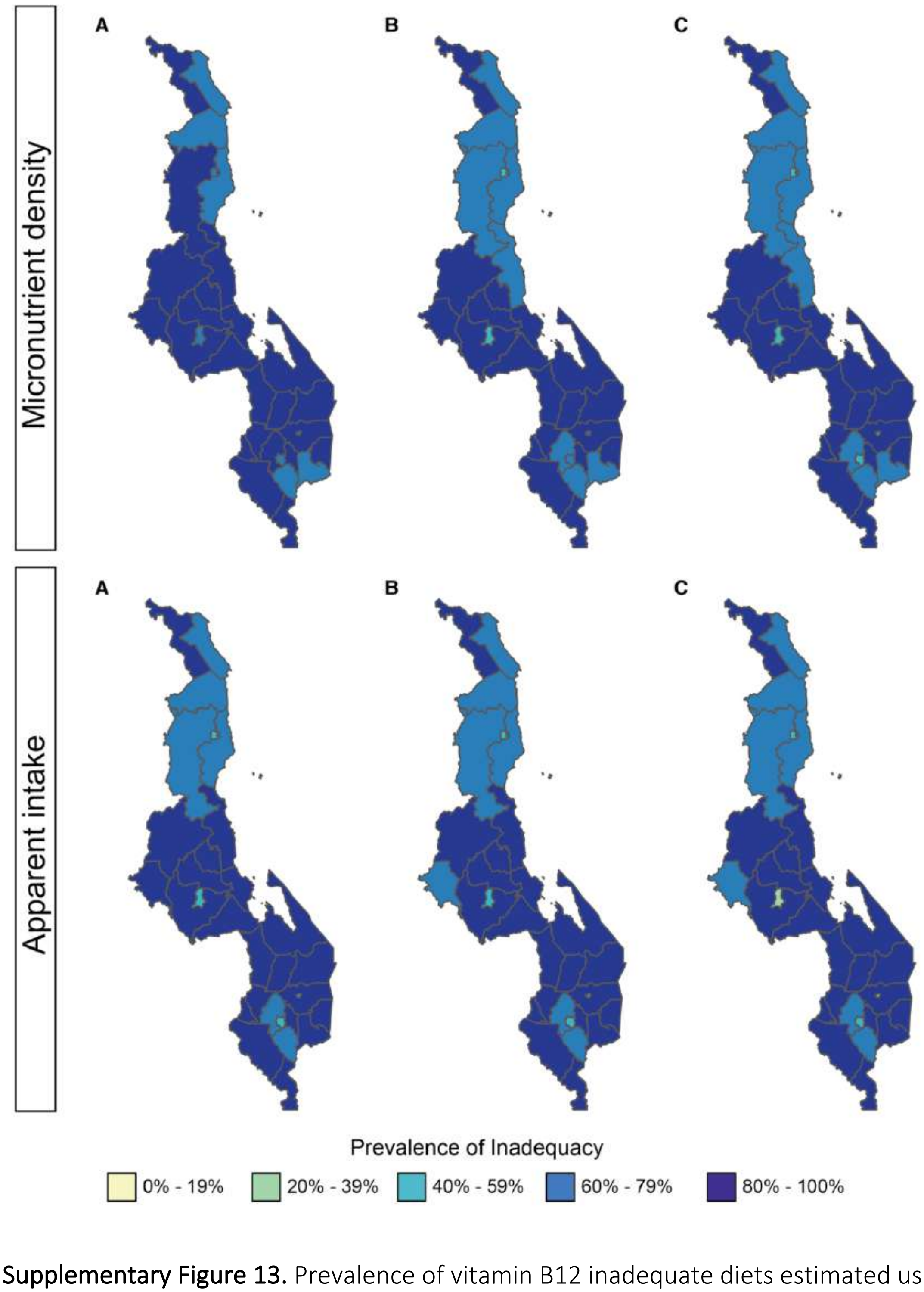
Supplementary Figure 10. Prevalence of niacin inadequate diets estimated using the micronutrient density approach versus the apparent intake approach for the (A) 'No fortification', (B) 'Status quo', and (C) 'Improved compliance' scenarios



Supplementary Figure 11. Prevalence of vitamin B6 inadequate diets estimated using the micronutrient density approach versus the apparent intake approach for the (A) 'No fortification', (B) 'Status quo', and (C) 'Improved compliance' scenarios.



Supplementary Figure 12. Prevalence of folate inadequate diets estimated using the micronutrient density approach versus the apparent intake approach for the (A) 'No fortification', (B) 'Status quo', and (C) 'Improved compliance' scenarios.



Supplementary Figure 13. Prevalence of vitamin B12 inadequate diets estimated using the micronutrient density approach versus the apparent intake approach for the (A) 'No fortification', (B) 'Status quo', and (C) 'Improved compliance' scenarios.

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Additional publication: Limited supply of protein and lysine is prevalent among the poorest households in Malawi and exacerbated by low protein quality

nutrients

Article

Limited Supply of Protein and Lysine Is Prevalent among the Poorest Households in Malawi and Exacerbated by Low Protein Quality

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Abstract: We estimated dietary supplies of total and available protein and indispensable amino acids (IAAs) and predicted the risk of deficiency in Malawi using Household Consumption and Expenditure Survey data. More than half of dietary protein was derived from cereal crops, while animal products provided only 11%. The supply of IAAs followed similar patterns to that of total proteins. In general, median protein and IAA supplies were reduced by approximately 17% after accounting for digestibility, with higher losses evident among the poorest households. At population level, 20% of households were at risk of protein deficiency due to inadequate available protein supplies. Of concern was lysine supply, which was inadequate for 33% of households at the population level and for the majority of the poorest households. The adoption of quality protein maize (QPM) has the potential to reduce the risk of protein and lysine deficiency in the most vulnerable households by up to 12% and 21%, respectively.

Keywords: protein quality; amino acids; digestibility; protein deficiency; household survey

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1. Introduction

Protein containing appropriate amounts of indispensable amino acids (IAAs) is an essential component of the human diet. Protein derived from animal products is generally regarded as high quality due to its IAA content and digestibility, and its consumption is projected to increase in low-income countries as socioeconomic status improves and the global population continues to rise [1] However, livestock production raises environmental issues due to high greenhouse gas (GHG) emissions, nitrogen pollution, and increased land degradation, mainly due to the production of crops required for animal feed [2–4]. In addition, excessive consumption of red meat is associated with an increased risk of developing cardiovascular diseases and some forms of cancer [5]. Thus, shifting diets towards more plant-based protein is often promoted on environmental sustainability and human health grounds [6]. However, in low-income countries where plant-based diets already predominate, greater consumption of animal-source foods may be required to help alleviate chronic malnutrition and micronutrient deficiencies [7,8], and associated GHG emissions may rise [9,10].

Animal and plant protein differ not only in their IAA composition but also in their digestibility, with the latter being of lower quality due to the presence of antinutrients such as phytates, tannins, trypsin, and protease inhibitors [8,11]. The digestibility of protein can be as low as 56% in some plant foods such as potatoes, compared with >85% for most animal-source foods [12]. The low protein quality of a typical plant-based diet consumed in low-income regions of the world is estimated to be the major driver of protein and IAA inadequacies. Studies using Food and Agriculture Organization (FAO) Food Balance Sheets, which report food available for human consumption at the national level, and dietary surveys indicate a high risk of deficiency of protein, particularly lysine, due to inadequate dietary supplies in low-income countries, particularly in Southeast Asia and sub-Saharan Africa where plant-based diets dominated by cereals and starchy roots are consumed [7,13–15].

According to Ghosh et al. [14], the prevalence of protein inadequacy calculated after correcting for protein quality is significantly higher than when total protein is used and can range from 20 to 90% for some of the poorest countries. Of particular concern is the strong association between available or digestible protein and IAA supply at national levels, with stunting levels in children under the age of 5 [7,14,16]. This was highlighted by Semba et al. [17], who showed a significantly lower concentration of circulating amino acids in the blood plasma of stunted children compared with non-stunted children in Malawi. The fortification of wheat flour with the amino acid lysine was found to have positive effects on diarrheal morbidity and on several nutritional and immunological biomarkers related to protein in Chinese and Syrian children, men and women [18,19]. This was attributed to improved protein utilization and a possible direct effect of lysine in the gastrointestinal tract.

While it is accepted that a largely cereal-based diet is associated with a high risk of protein and lysine deficiency, the proportion of such sources in the diet at which risk of inadequacy becomes apparent remain unclear. Arsenault and Brown [20] found that protein quality did not have a large impact on the overall prevalence of inadequate protein intake in a cohort of children aged 6–35 months from low-income countries who consumed a predominantly plant-based diet, including either breast milk or cow's milk. Although the percentage of animal protein in the diet was not clear, it can be inferred that a largely plant-based diet can provide sufficient protein and IAAs under certain circumstances. A study by De Gavelle et al. [21] reported that dietary protein quality becomes crucial when the proportion of plant protein exceeds 70%.

In 2013, the FAO recommended that protein quality be determined according to the Digestible Indispensable Amino Acid Score (DIAAS), which assesses quality according to the true ileal digestibility of each individual IAA. Although the DIAAS is now the recommended measure of protein quality, its use and adoption in practice rely on the development of a true ileal amino acid digestibility database of foods, determined preferably in humans, growing pigs, or rats, in that order. Data on the true protein and IAA ileal digestibility of foods are limited but perhaps now sufficient for evaluating the available or digestible protein and IAA supplies of many diets [22].

The objectives of this study were to characterize dietary protein supplies and deficiency risks in Malawi and to assess the impact of protein quality, corrected using ileal digestibility values, on the adequacy of dietary protein and IAA supplies across different subsections of the population. Using data from recent rounds of the Malawi-based national Integrated Household Survey (IHS), previous studies have characterized dietary micronutrient supplies and deficiency risk and modelled the effects of different interventions on alleviating deficiencies, finding important differences between socioeconomic groups [23–25]. Here, we use a similar approach to estimate the potential effects on dietary protein and lysine intakes of introducing the nutritionally enhanced quality protein maize (QPM) into the Malawian diet.

2. Methods

2.1. Estimates of Total Protein and Indispensable Amino Acid Composition

The household consumption and expenditure survey (HCES) data were obtained from the Malawi Fourth Integrated Household Survey (IHS4), conducted between April 2016 and April 2017 by the National Statistics Office of Malawi in partnership with the World Bank's Living Standards Measurement Study (LSMS) [26]. The HCES is routinely administered every 5 years, and the IHS4 covered 779 enumeration areas (EAs) in Malawi that comprised a nationally representative sample of 12,447 households. The IHS4 comprised of a single-visit 24-module questionnaire covering data on household consumption, living standards, expenditures, and other measures of social and economic welfare. In the food consumption module of the household questionnaire, participants were requested to recall the food consumed in the household over the past 7 days from a standardized list of 136 food items that are typically consumed in the Malawian diet. A comprehensive description of how nonstandard metrics recorded in the survey were transformed into standard and usable metrics is reported by Tang et al. [25].

The food items were matched for total protein, moisture, energy, and IAA content using Food Composition Tables (FCTs) (Supplementary data S1). For each food item, the composition data for protein, energy, and moisture (g/100 g edible portion (EP)) were obtained from a single FCT. Approximately 72% of these values were obtained from the Malawi FCT [27], while 26% were obtained from the South Africa FCT [28]. Food items from the South Africa FCT consisted predominantly of processed products such as biscuits, infant cereals, formulas, and beverages that were not found in the Malawi FCT. Less than 3% of food items were obtained from the West Africa FCT [29] or the USDA FoodData Central Database [30]. For foods that were ambiguously defined in the survey, the authors used local knowledge and literature to match appropriate items. For example, for a food item listed as "fish" in the IHS4, compositional data for tilapia fish (Chambo in local language) were selected as one of the most commonly consumed types of fish in Malawi. Where single matches were not deemed appropriate, several food matches were identified, and an arithmetic mean was calculated. For example, for a food item listed as "mushroom" in the IHS4, an average value of two local mushroom varieties in the Malawi FCT was determined. Amino acid data were obtained almost solely from the USDA FoodData Central Database due to very limited availability from other more geographically relevant sources. For cases where the sum of IAA composition differed by >10% with total protein content, amino acid content was scaled to total protein content. This recalculation was done for >80% of the food items. Scientific articles were used to assign amino acid data to a few food items that were missing in the USDA FoodData Central Database, e.g., infant formulas and edible insects.

2.2. Estimates of Available Protein and Indispensable Amino Acid Composition

An in-house protein and IAA digestibility database was created in which true or standardized ileal protein or IAA digestibility data were compiled from scientific articles [31]. A protein or IAA digestibility coefficient was assigned to all food items, after which available or digestible protein and IAA compositions (g/100 g EP) were calculated after applying the respective digestibility coefficients to the total protein and IAA values. For food items with missing digestibility data, an estimation was made using the closest match in the same food group. For example, in the legume and nuts food group, the digestibility of pigeon pea was estimated using values for common bean; in the roots and tubers food group, the digestibility of coco yam was estimated using digestibility values for potato. Digestibility values for processed products were estimated using the best match of the major ingredient; for example, the digestibility of pasta was estimated using digestibility values of wheat, and the digestibility of popcorn was estimated using values for maize or corn. Since data on the digestibility of fruits and vegetables are not available, a mean digestibility coefficient for each of the plant-based food items in the survey was calculated and used as an estimate. Digestibility was not corrected for fats and oils because of their minimal contributions to dietary protein and IAA intake.

2.3. Estimates of Protein and Indispensable Amino Acid Supplies and Prevalence of Sub-Optimal Supplies

Food composition data, i.e., total and available protein and IAA (g kg^{-1}, DW EP), were integrated with food consumption data (kg $household^{-1}$ day^{-1}, DW EP) to calculate the supply of nutrients at the household level. The total and available supply of nutrients for each household were expressed per adult male equivalent (AME) based on the household demographic composition and assuming that food is distributed according to the energy requirements of the individuals within the household [32]. An energy requirement of 2000 kcal day^{-1}, adult male weight of 65 kg, and a moderate physical activity level (PAL) of 1.6 were assumed. The prevalence of inadequate protein and IAA supplies were estimated by comparing household supply (g AME^{-1} day^{-1}) with the estimated average requirement (EAR) of an adult male (Table S1—Supplementary data S2) with an average body weight of 65 kg [33].The EAR is defined as the nutrient intake level that meets the needs of 50% of an age- and sex-specific population [34].

The impact of protein quality was assessed by comparing the prevalence of inadequate supplies based on total and available supply. In addition to the data being stratified according to rural/urban residences and administrative region (northern, central and southern), data were also stratified according to the socioeconomic position (SEP) of the household; households were classified into wealth quintiles on the basis of total annual-adjusted household expenditure per capita, with SEP 1 being the poorest and SEP 5 the wealthiest. The supplies of protein and IAA and the prevalence of suboptimal supplies were also compared across the five SEPs. The contributions of food groups to protein and IAA were quantified by assigning food items to the relevant food groups, i.e., cereals, legumes and nuts, animal products, vegetables, roots and tubers, dairy, fruits, and others. 'Others' included food groups with minor contribution (less than 1%) to protein and IAA supply such as fats and oils, sugars, spices and condiments. For a comprehensive insight into the consumption of animal products, this food group was further split into the following categories: poultry including eggs, red meat, and fish. The food groups supplying protein and IAAs were also assessed according to the household SEP.

2.4. Simulating the Addition of Quality Protein Maize to the Diet on Supplies and Prevalence of Sub-Optimal Supplies

The effectiveness of introducing quality protein maize (QPM) to the Malawi diet to reduce the prevalence of inadequate supplies was simulated by substituting the total and available protein and IAA compositions of currently used maize with those of a typical QPM variety using estimates derived from Prasanna et al. [35] and Yin et al. [36]. This was applied to the main IHS4 food items comprising maize as the major food ingredient i.e., 'maize *ufa mgaiwa* (normal flour)', 'maize *ufa* refined (fine flour)', 'maize *ufa madeya* (bran flour)', 'maize grain (not as *ufa*)', and 'green maize'. The total protein content of QPM is not expected to be significantly different from that of currently used maize varieties; rather the amino acid profile of QPM is modified. However, the digestibility of QPM is greater than that of currently used maize varieties, and as such, a comparison between the available protein supplies of the current scenario versus the QPM scenario was made. In terms of IAA composition, for the QPM scenario, a factor of 1.3 was applied over the current scenario to lysine composition. The QPM scenario food composition data were analyzed as described in the previous sections.

3. Results

3.1. Socioeconomic and Demographic Information of Households

Table 1 shows the demographic information of households that participated in the IHS4. A total of 12,447 randomly sampled households from the three administrative regions of Malawi (northern, central and southern) were interviewed, with 82% living in rural areas and 18% in urban areas. The number of households sampled in each region generally followed the population distribution of Malawi, with more people living in the rural areas compared with the urban areas and more people living in the southern region compared to the northern and central regions. For each region, the same proportion of households belonging to the different SEP was interviewed so that each category of SEP was equally represented. In total, each SEP comprised approximately 20% of households in the survey (Table 1). A detailed summary of the survey population is given by Tang et al. [25].

Table 1. The numbers (and percentages) of the households interviewed in IHS4 (2016–2017) by socioeconomic position and region.

Region	SEP 1	SEP 2	SEP 3	SEP 4	SEP 5	Total
Northern	399 (16%)	492 (20%)	532 (21%)	525 (21%)	543 (22%)	2491 (20%)
Central	734 (17%)	827 (20%)	862 (20%)	902 (21%)	895 (21%)	4220 (34%)
Southern	1357 (24%)	1170 (20%)	1096 (19%)	1062 (19%)	1051 (18%	5736 (46%)
Total	2490 (20%)	2489 (20%)	2490 (20%)	2489 (20%)	2489 (20%)	12,447

SEP: socioeconomic position (1 = poorest quintile, 5 = wealthiest quintile).

3.2. Food Groups Supplying Protein and Indispensable Amino Acids to the Malawian Diet

Cereal was the major food group supplying total and available protein to the Malawian diet (Figure 1A), with a mean supply of 66%, followed by legumes and nuts (15%), animal products (11%) and vegetables (4%), with other food groups contributing minor proportions. The proportion of food groups supplying protein was similar when comparing total and available supply, although there was a slight increase in the proportion of supply from animal products based on available supply. Figure 1B shows the proportions of food groups supplying protein according to household SEP. As household SEP increased, supply from cereals decreased from 78% for SEP 1 (poorest) to 54% for SEP 5 (wealthiest). The opposite was true for the proportion of supply from animal products, which increased from 5% for SEP 1 to 19% for SEP 5, and legumes and nuts, which increased from 11% for SEP 1 to 17% for SEP 5. The proportion of supply from other food sources such as vegetables, roots, and tubers, was similar across all five categories of SEP. Animal products and vegetables were equally important for the poorest households (SEP 1) as they contributed similar proportions to the protein supply (ca. 4%). The proportion of food groups supplying the majority of IAAs to the diet followed a similar trend (Table S2—Supplementary data S2). However, the supply of lysine and tryptophan from cereals was lower compared with protein, i.e., 44% and 55% respectively, vs. about 66% for protein, while the supplies of leucine and sulfur amino acids (SAA) from cereals were higher, i.e., 76% and 71%, respectively. Lysine supply showed the greatest deviation from that of protein, with legumes, nuts, and animal products supplying similar proportions (~23%). Animal products were further classified into poultry (including eggs), red meat, fish, and dairy to obtain comprehensive insights into the animal source foods most commonly consumed (Figure S1—Supplementary data S2). The most consumed animal source food in the Malawian diet was fish, which accounted for more than 50% of the animal protein consumed. Fish was the most important animal source food for the lowest SEP, while supplies of fish, red meat, and poultry were similar in the households of the highest SEP.

3.3. Total and Available Protein and Indispensable Amino Acids Supply

After accounting for digestibility, approximately 17% of proteins were not available. Losses due to digestibility ranged between 9 and 21% for individual IAAs. The median total protein supply was 80 g AME^{-1} day^{-1}, and this was reduced to 65 g AME^{-1} day^{-1} after accounting for digestibility (Table 2). When data were disaggregated according to SEP, the median total supply ranged from 48 g AME^{-1} day^{-1} for the poorest households to 120 g AME^{-1} day^{-1} for the wealthiest households. The median protein supply was reduced by 19% for households in SEP 1, compared with 16% for households in SEP 5 after accounting for digestibility. When QPM was substituted for the conventional maize varieties, losses of protein due to digestibility were reduced from 19 to 13%, and available protein supply per AME increased by 8% at the population level and by 10% for the poorest households (Table 2). The median supply of all IAAs is given in Table S3—Supplementary data S2, while that of lysine is shown in Table 3. Similar to protein, the trend in the supply of IAA followed the same pattern as that of protein, i.e., at least twofold greater supply for the wealthiest households compared with the poorest households. The median supply of lysine showed the largest deviation, with a greater reduction in supply due to digestibility in the poorest households (22%) compared with the wealthiest households (14%). If QPM is introduced into the Malawian diet, total and available lysine supply are projected to increase by 16–20%. Notably, the increase in supply was greatest for the poorest households (Table 3).

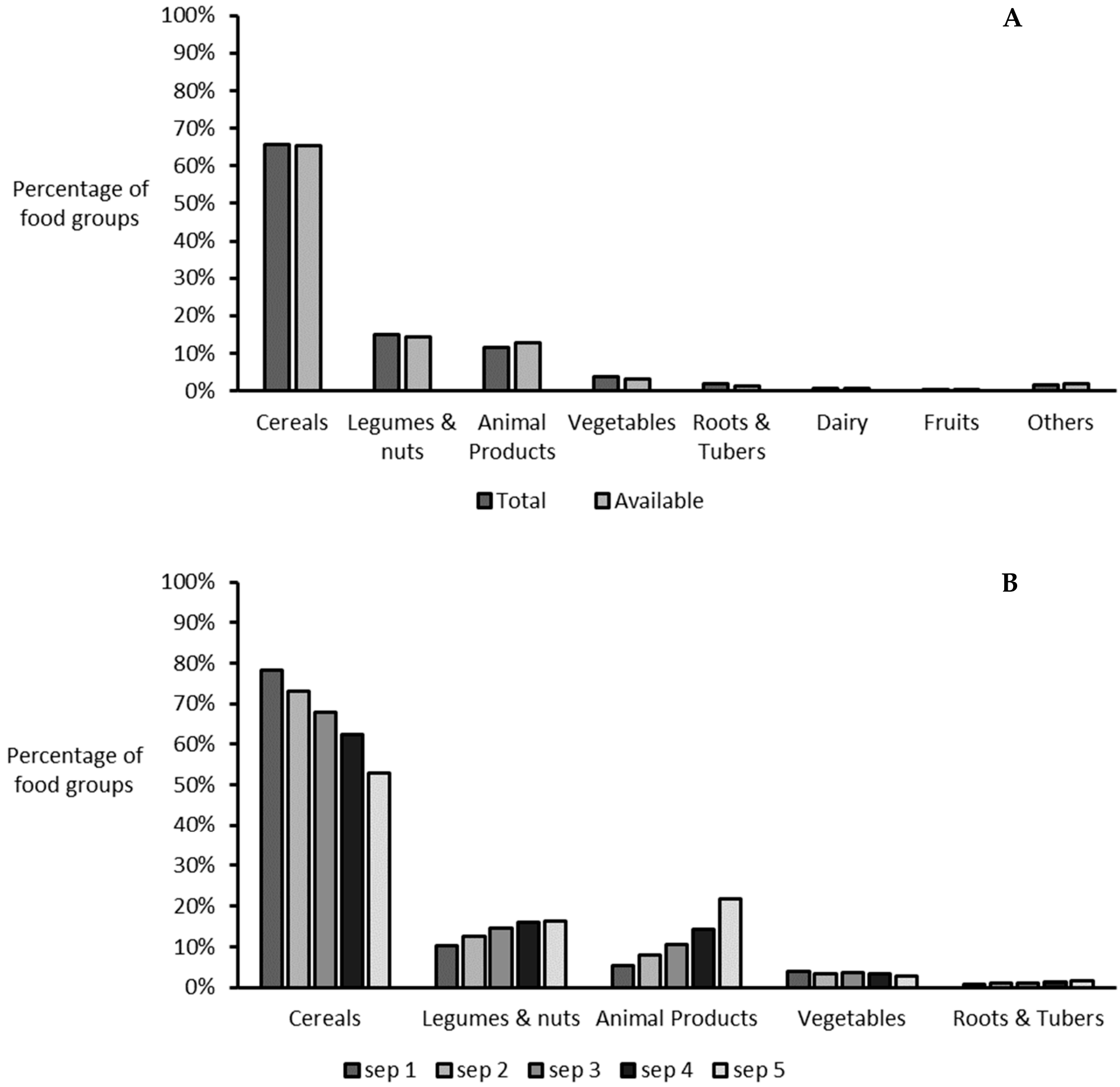

Figure 1. The food groups supplying total and available protein (**A**) and the top 5 food groups supplying total protein to the Malawian diet by household socioeconomic position (**B**). SEP: socioeconomic position (1 = poorest quintile, 5 = wealthiest quintile).

3.4. The Risk of Protein and Indispensable Amino Acid Deficiencies Due to Suboptimal Supplies

The supplies of protein and IAAs (g $AME^{-1}day^{-1}$) were compared with the EAR of an adult male with an average weight of 65 kg to determine the adequacy of supplies (Table S1—Supplementary data S2). At population level, and based on total protein supply, 12% of the population was at risk of deficiency due to inadequate dietary supplies (Table 4). When considering available protein supply, the risk of deficiency increased to 21%, meaning that at the population level, improving protein digestibility could reduce the risk of protein deficiency due to inadequate supply by up to 9%. The risk of deficiency increased according to SEP, with >50% of households in SEP 1 at risk of protein deficiency based on available supply. The importance of protein digestibility also increased as household wealth decreased, i.e., improving protein digestibility could reduce the risk of deficiency by only 1% for SEP 5 (wealthiest) compared with 19% for SEP 1 (poorest). The introduction of QPM into the Malawian diet has the potential to reduce the risk of protein deficiency from 21% to 17% at the population level, while for the most vulnerable households, risk of protein deficiency can be reduced from 58% to 51% (Table 4).

Table 2. The median total and available protein supplies (g AME^{-1} day^{-1}) by household socioeconomic position, including under a scenario with universal adoption of quality protein maize (QPM).

SEP	Total Protein	Available Protein	Available Protein QPM-Scenario
1	48	39	43
2	67	55	60
3	81	67	72
4	97	79	85
5	120	101	106
ALL	80	65	70

SEP: socioeconomic position (1 = poorest quintile, 5 = wealthiest quintile), AME: adult male equivalent, QPM: quality protein maize.

Table 3. The median total and available lysine supplies (g AME^{-1} day^{-1}) by household socioeconomic position, including under a scenario with universal adoption of quality protein maize (QPM).

SEP	Current Scenario		QPM Scenario	
	Total Supply	Available Supply	Total Supply	Available Supply
1	1.7	1.3	2.0	1.7
2	2.5	2.0	2.9	2.5
3	3.2	2.6	3.6	3.1
4	3.9	3.3	4.5	3.8
5	5.5	4.7	6.0	5.3
ALL	3.1	2.5	3.6	3.0

SEP: socioeconomic position (1 = poorest quintile, 5 = wealthiest quintile), AME: adult male equivalent, QPM: quality protein maize.

Table 4. The percentages of households at risk of protein deficiency due to inadequate dietary supply, including under a scenario with universal adoption of quality protein maize (QPM), stratified by socioeconomic position.

SEP	Current Scenario			QPM Scenario		
	Total Supply	Available Supply	Difference	Total Supply *	Available Supply	Difference
1	39	58	19	39	51	12
2	12	24	12	12	19	7
3	6	13	7	6	10	4
4	3	6	3	3	5	2
5	1	2	1	1	2	1
ALL	12	21	9	12	17	5

SEP: socioeconomic position (1 = poorest quintile, 5 = wealthiest quintile), QPM: quality protein maize.* Total protein supply under the QPM scenario is similar to current scenario as gross protein composition of QPM is not significantly different from that of traditional maize varieties.

Pertaining to IAAs, the risk of deficiency was lower than that for protein except for lysine (Table S4—Supplementary data S2). Approximately one third of the population was at risk of lysine deficiency based on available supplies (Table 5), while the majority of households in SEP 1 were at risk of lysine deficiency due to inadequate supplies. Similar to protein, digestibility was most important for the poorest households, as improving lysine digestibility could potentially reduce risk by up to 18 and 22% for SEP 1 and 2 respectively, compared with only 2% for SEP 5. If QPM is introduced into the Malawian diet, the risk of lysine deficiency can potentially be reduced by 12% at the population level and up to 21% for the poorest households (Table 5).

Table 5. The percentages of households at risk of lysine deficiency due to inadequate dietary supply including under a scenario with universal adoption of quality protein maize (QPM) stratified by socioeconomic position.

SEP	Current Scenario			QPM Scenario		
	Total Supply	Available Supply	Difference	Total Supply	Available Supply	Difference
1	63	82	19	47	64	17
2	25	47	22	14	26	12
3	10	23	13	6	11	5
4	4	9	5	3	5	2
5	1	3	2	1	1	0
ALL	21	33	12	14	21	7

SEP: socioeconomic position (1 = poorest quintile, 5 = wealthiest quintile), QPM: quality protein maize.

4. Discussion

Dietary protein and IAA supplies in Malawi varied widely and were largely associated with household wealth. Among other demographic characteristics such as geographic location and whether a household was located in a rural or urban area, household SEP was the most important attribute explaining the large variation in supplies. This is consistent with other studies in which protein and IAA supplies have been found to be strongly correlated with the gross domestic product (GDP) at country level and with household wealth when dietary surveys were used [7,14]. According to Grigg [37], "the map of protein consumption is the map of the level of economic development," and while this is evident when comparing developed and developing countries, this variability also exists among households of different SEP within a country. Indeed, high protein animal source foods are at least two times more expensive per unit protein than the energy-dense but low protein plant-based foods such as cereals and legumes [38]. In addition to the cost, the composition and quality of animal protein is superior to that of plant protein. This explain why, not only the supplies of protein and IAA was increased as household SEP increased, but also the pattern of foods providing protein also reflected the household wealth, with lower consumption of animal protein among the poorest households.

The risk of protein and lysine deficiency was high and exacerbated by poor protein quality especially among the poorest households. In general, variations in the supplies of protein and IAA were similar except for lysine, with a deviation of up to 77% from the median supply compared with protein with a deviation of up to 50%. One important factor that influences the quantity and source of protein supply in a given country is the local environmental conditions, which determine the choice of staple crop [37]. In Malawi, maize is the staple crop [39,40], and the variation in the supplies of IAAs and the subsequent risk of deficiency reflect the IAA profile of maize. For example, maize is a good source of several IAAs such as leucine, aromatic amino acids (AAA), and histidine, and this explains their lower risk of deficiency (<5%) compared with protein (21%) when considering the available supplies. On the other hand, maize is limited in lysine, as indicated by the higher risk of deficiency (33%) than that for protein. In fact, the risk of deficiency of IAAs except lysine is substantially lower (3–11%) than that for protein, suggesting that for diverse diets, protein supplies alone provide a good indication of both the protein and the IAA adequacy of a diet. As supplies were largely associated with household SEP, it is not surprising that the majority of households in the lowest SEP were at risk of both protein and lysine deficiency.

The impact of protein quality on protein and IAA supplies was more important for the poorest households than the wealthiest households. Protein quality is a measure of the digestibility and IAA profile of a protein [41]. The comparisons between total and available protein and IAA supplies show the impacts of poor digestibility, causing about 17% of protein and IAA losses across households, with the greatest nutritional significance for households in the lowest SEP. The losses in protein and IAA supplies also reflect the digestibility of the staple cereal maize, which was estimated to be about 82%. It therefore can be suggested that the risk of protein and IAA deficiencies due to inadequate supplies may be greater in regions where the protein digestibility of the staple crops is lower, particularly where diets are based on sorghum and millet varieties with digestibility of around 66–79% [31]. The effect of the other component of protein quality, which is IAA profile, is demonstrated in the greater risk of lysine deficiency than protein as mentioned previously. The risk of lysine deficiency increased exponentially according to SEP and was substantial even for the moderately wealthy households (i.e., SEP 3). Protein quality was critical at cereal protein proportions of >70% as indicated by the large increase in the risk of lysine deficiency from SEP 3 to 5. For cereal protein proportions of around 50%, the quantity of protein consumed was more important, as shown in the diets of the wealthiest households, with protein supply even exceeding requirements by a large magnitude. In agreement with De Gavelle et al. [21], the protein and IAA adequacy of a largely plant-based diet is dependent mainly upon dietary diversity. Diets with protein derived from >70% plant protein including choices of legumes, nuts, and seeds were estimated to provide sufficient protein and lysine due to the complementarity of the different food sources [21]. For example, legumes can complement the shortage of lysine in cereals, while cereals complement SAAs, which are the first limiting amino acids in legumes.

However, the main factor hindering the supply of diverse diets to vulnerable populations is poverty. In Malawi, poorer households are more likely to live in rural areas, with greater distances to markets and roads and less engagement in wage employment [25]. They are also likely to derive less benefit from large-scale food fortification programmes, including of maize flour and cooking oil, since they typically purchase processed foods less often and in smaller quantities [25,42]. In that regard, an intervention to biofortify staple crops may present a more accessible and sustainable option as vulnerable population groups are likely to be small-holder subsistence farmers. Quality protein maize (QPM) is a group of biofortified maize varieties with elevated levels of lysine and tryptophan and with crop development led by the International Maize and Wheat Improvement Center (CIMMYT) [35]. It is estimated that QPM has protein digestibility almost similar to that of casein and a balanced amino acid profile, with at least 30% more lysine compared than traditional maize varieties [35,39]. In this study, the introduction of QPM with ~10% improvement in digestibility (91% vs. 82% for maize) and a modest 30% enhancement of lysine content was simulated. The introduction of QPM could potentially augment both protein and lysine supplies and substantially reduce the risk of deficiency among vulnerable households by up to 21%. Intervention with QPM has been found to have positive effects on child growth in randomized controlled trials conducted in several developing countries [43,44]. However, QPM has not been widely adopted in sub-Saharan Africa compared with newer biofortified crop varieties, such as pro-vitamin A maize, despite its clear nutritional benefits. Nyakurwa et al. [40] highlighted some constraints to its adoption that still need to be overcome including a lack of farmer awareness and supportive government policies. Like other staple biofortified crops, government–private sector partnerships and a robust communication strategy in nutrition education campaigns are key to encourage adoption [25,40].

Although the risk of lysine deficiency can be significantly reduced if QPM is adopted in the diet, the risk remains substantial among households in the lowest SEP (up to 21% at population level and 64% for SEP 1). The risk of lysine deficiency could be reduced further if lysine enhancement levels are greater than the conservative 30% increase used in this study. The proportional increase in lysine concentrations of QPM relative to traditional maize varieties can vary greatly, ranging from 10 to 58% for some Canadian adapted cultivars [45] and from 30 to 82% for Ethiopian adapted QPM [46]. Therefore, it will be important to understand the levels of lysine enhancement that are likely to be achieved in QPM varieties adapted to the typical environmental and agronomic conditions in Malawi. While intervention with QPM can have a substantial impact on protein and IAA supplies, it is clearly not sufficient on its own and needs to be complemented with other interventions. An increase in the supply of animal source foods is especially important because the high risk of protein and lysine deficiency among households of the lowest SEP is also accompanied by a high risk of the deficiency of micronutrients including vitamin A and zinc [25]. As fish supply was almost equally available across all household SEPs, interventions increasing availability of this source of protein need to be explored.

Data from the HCES food consumption modules provide an important resource for nutritional assessment and can inform nutrition policy and programming. Although adult male equivalent (AME) factors are considered a valid proxy of apparent individual nutrient intakes within a household, giving a general picture of the status of nutrient supplies in a country [47], it is limited in its ability to identify differing risks between population age and sex groups. Considering the association between protein inadequacy and undernutrition in children [7,14], the current study would be well complemented by looking at dietary intake data from children under 5 and women of reproductive age among rural households of the lowest SEP. A more targeted study could also enable the adjustment of protein requirements for energy deficits and infections, which increase protein requirements [14] and are likely to be more prevalent among households in the lowest SEP.

5. Conclusions

Analysis of data from the Malawi Integrated Household Survey 2016–2017 (IHS4) predicted a high risk of protein and IAA deficiencies due to inadequate dietary supplies, particularly amongst those of the lowest socioeconomic status. High-quality protein sources from animal products were less available to these households, who derived the majority of their protein supply from maize, the staple crop. As a consequence, the further losses of protein and IAA supply due to protein quality disproportionately affected the poorest households compared with the wealthiest households. An improvement in protein digestibility could reduce the prevalence of inadequate protein and lysine supply by up to 20% for the poorest households but only 2% for the wealthiest households. The risk of lysine deficiency was substantial in the whole population, and evidence from other sources is needed, which if corroborated, suggests interventions need to be investigated rapidly with a focus on reaching the most vulnerable populations. An intervention involving the adoption of QPM has the potential to reduce the risk of inadequate protein supplies by up to 7% due to improved protein digestibility, while lysine deficiency risk could be reduced by up to 21%.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/nu14122430/s1, Supplementary data S1: Food composition data of food items in the IHS4. Supplementary data S2: Figure S1 Proportion of households reporting consumption of animal products in the past 7-days, by household socioeconomic position; Table S1 Estimated Average Requirements (EAR) of protein and indispensable amino acids for a 65 kg adult male, Table S2 Proportion of total protein and indispensable amino acid dietary supplies by food group, Table S3 Summary statistics of total and available indispensable amino acid dietary supplies, Table S4 Percentage of households at risk of indispensable amino acids deficiency due to inadequate dietary supply.

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Data Availability Statement: Data is contained within the article or supplementary material. Dataset on the ileal protein and amino acid digestibility of foods generated in this study can be found at: https://data.mendeley.com/datasets/gz3cx7d5f4/1—DOI:10.17632/gz3cx7d5f4.1.

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Appendix 6

Final publication of Chapter 7: Evaluating equity dimensions of infant and child vitamin A supplementation programmes using Demographic and Health Surveys from 49 countries

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Evaluating equity dimensions of infant and child vitamin A supplementation programmes using Demographic and Health Surveys from 49 countries

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ABSTRACT

Objectives Vitamin A deficiency affects an estimated 29% of all children under 5 years of age in low/middle-income countries, contributing to child mortality and exacerbating severity of infections. Biannual vitamin A supplementation (VAS) for children aged 6–59 months can be a low-cost intervention to meet vitamin A needs. This study aimed to present a framework for evaluating the equity dimensions of national VAS programmes according to determinants known to affect child nutrition and assist programming by highlighting geographical variation in coverage.

Methods We used open-source data from the Demographic and Health Survey for 49 countries to identify differences in VAS coverage between subpopulations characterised by various immediate, underlying and enabling determinants of vitamin A status and geographically. This included recent consumption of vitamin A-rich foods, access to health systems and services, administrative region of the country, place of residence (rural vs urban), socioeconomic position, caregiver educational attainment and caregiver empowerment.

Results Children who did not recently consume vitamin A-rich foods and who had poorer access to health systems and services were less likely to receive VAS in most countries despite potentially having a greater vitamin A need. Differences in coverage were also observed when disaggregated by administrative regions (88% of countries) and urban versus rural residence (35% of countries). Differences in vitamin A coverage between subpopulations characterised by other determinants of vitamin A status varied considerably between countries.

Conclusion VAS programmes are unable to reach all eligible infants and children, and subpopulation differences in VAS coverage characterised by various determinants of vitamin A status suggest that VAS programmes may not be operating equitably in many countries.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- ⇒ We used Demographic and Health Survey (DHS) data from 49 low/middle-income countries to conduct a standardised analysis of the equity dimensions of vitamin A supplementation (VAS) coverage, where consistencies in findings could be broadly applied to inform global VAS policy.
- ⇒ The covariates included in this study, guided by the 2020 UNICEF conceptual framework, covered a diverse range of social and geographical determinants with relevance to equitable VAS programming.
- ⇒ The question specific to VAS in the DHS questionnaire is dependent on a multiple month recall by the caregiver of the child, which is subject to recall bias.
- ⇒ In settings where VAS is delivered via biannual campaigns, DHS VAS coverage may be underestimated if the timing of the survey is planned immediately before a campaign.

INTRODUCTION

The UNICEF Nutrition Strategy 2020–2030 commits to a goal of protecting and promoting diets, services, and practices that support optimal nutrition, growth, and development for all children to end child malnutrition in all its forms.[1] Central to achieving this goal requires recognising the interaction between five core systems (food, health, water and sanitation, education, social protection) to improve nutrition outcomes. However, a strategy focused on working within established systems may exacerbate unequal nutrition outcomes rooted in deeper inequities that arise from already inequitable systems.[2] Therefore, when implementing policies to ensure the most vulnerable have access to services, governments should conduct regular reviews of coverage of programmes to allow for reorientation as needed.

Vitamin A deficiency affects an estimated 29% of all children under 5 years of age in low/middle-income countries,[3] contributing to child mortality and disease burden through direct clinical manifestation (eg, xerophthalmia) and susceptibility to and exacerbated adverse outcomes from infection (eg, measles, diarrhoea).[4] For children with vitamin A deficiency or who have an increased risk of mortality, high-dose vitamin A supplementation (VAS) can be a low-cost intervention to meet vitamin A needs when delivered using infrastructure from existing community-based delivery programmes.[5] Following an exhaustive review of the current evidence exploring the effect of VAS in preventing morbidity and mortality in infants and children,[4 6] in 2011, the WHO confirmed a recommendation for infants and children 6–59 months of age to receive a dose of VAS every 4–6 months in contexts where vitamin A deficiency is a public health problem.[7] Although the past two decades have seen increases in global VAS coverage,[8] stagnating VAS coverage in recent years brings into question whether current universal delivery strategies are consistently missing hard-to-reach children most in need, especially in settings with low coverage.[9] This is particularly the case as VAS programmes move away from delivery in campaigns towards routine delivery.[8]

The delivery of VAS can be integrated into routine community-based health service delivery programmes. In many countries, community-based delivery programmes, such as the national Essential Programme on Immunization (EPI), offer the most consistent contacts between the youngest children and the health system, thus creating a platform for the large-scale administration of VAS. However, in contrast to VAS administration protocols, childhood immunisation programmes typically benefit only children up to 1 year of age when the last vaccine dose is administered, and few countries have a contact point for immunisation at 6 months. Moreover, multicountry analyses of diphtheria–tetanus–pertussis (DTP) and measles-containing vaccines (MCV) identified gaps in programme coverage between geographical and socioeconomic subpopulations.[10 11] All together, these differences suggest that the services these community-based delivery programmes provide are not equitably accessible to children with the greatest needs and may affect the VAS programmes that depend on these services for delivery.

Global guidance recommends using 'two-dose coverage' as a metric for advocacy to promote national and global progress towards achieving universal VAS coverage.[12] In this context, 'coverage' is estimated as the nationally aggregated number of VAS doses administered in a country over a 6-month period (also referred to as semester) from administrative records divided by the estimated number of children aged 6–59 months in that country for that specific semester. 'Two-dose coverage' is thus established on an annual basis as the semester in a given year with lower coverage. Two-dose coverage increases the feasibility of collating national VAS programme data biannually, which is advantageous for advocacy and other such uses. From the programmatic perspective, both two-dose coverage and single-semester coverage are limited in identifying differences in coverage among subpopulations within a country. To evaluate whether national VAS programmes are missing the children with the greatest needs, global guidance recommends using indicators generated from subnational data that are readily available, easy to understand and relevant to the information needs of programme managers.[13]

There is a significant information gap in evaluating the equity dimensions of nutrition interventions, or the extent to which a community-based nutrition programme is reaching the children most in need.[2] Nationally representative household surveys, such as the Demographic and Health Surveys (DHS), can potentially provide insight into the equity dimensions of programme delivery. Since 1985, the DHS programme has conducted nationally representative cross-sectional surveys in over 90 predominantly low/middle-income countries, producing detailed, cross-sectional data on a variety of indicators describing demographics, health, economics and social welfare.[14] DHS questionnaires and variable nomenclature are consistent between all countries in the DHS programme, facilitating rapid analysis across multiple countries and survey years. DHS microdata enable the exploration of a variety of indicators to measure population health outcomes and the mechanisms influencing them in great depth.

DHS collect detailed information on the reception of VAS by infants and children; however, using such data to inform national VAS programmes is not straightforward. The aim of this study was to evaluate the equity dimensions of national VAS programmes according to determinants known to affect child nutrition and geographically using DHS data from multiple countries.

METHODS

Demographic and Health Surveys

This was a secondary data analysis using data collected as part of the DHS from various countries.[15] We reviewed DHS data from 64 countries that have been prioritised by UNICEF for support in their current national VAS programming efforts and ultimately included 49 countries in which a complete DHS was conducted since 2010, using the most recent data in countries with multiple surveys. The analysis depended on data from the Woman's Questionnaire, which contains information on the survival status of the children born to the respondent, and more detailed information on children born in the last 5 years, such as vaccination history, breastfeeding practice, recent illness and anthropometry.

The DHS protocol employs a two-stage sampling procedure.[16] In the first stage, enumeration areas are defined geographically (stratified by urban/rural residence and administrative region) using the country's most recent population census to establish the survey's primary sampling unit. In the second stage, systematic sampling identifies 20–30 households for inclusion, where selected households are visited by trained interviewers who administer the Woman's Questionnaire to women of reproductive age (15–49 years).

Our analysis included all children aged 6–59 months with available VAS history data. VAS programme participation is probed in the DHS questionnaire's *vaccination history section* by asking caregivers of children whether their child (or children) aged 6–59 months has (or have) received a vitamin A dose in the last 6 months.[17] If possible, caregivers are asked to present proof of VAS reception using a vaccination history card, and if not available, are asked to recall VAS administration from memory after probing the caregivers to describe postnatal care activities in which they and each child have participated.[18] The primary outcome of this study was defined as the percentage of children receiving VAS in the prior 6 months, or more simply, 'VAS coverage'.

Equity and geographical covariates

We stratified the primary outcome by several covariates describing various dimensions of equity, which were selected in accordance with the 2020 UNICEF Conceptual Framework on the Determinants of Maternal and Child Nutrition.[1] The framework used in this analysis was developed to guide nutrition programming by outlining three levels of determinants (ie, immediate, underlying, enabling) that contribute to preventing malnutrition in all its forms. By using this framework to guide covariate selection, this study recognises the levels and interconnectedness of various determinants affecting vitamin A status to define the underlying systems and processes that affect children with the greatest vitamin A needs. Geographical covariates were also selected as targeting geographically defined populations is more operationally feasible.

Covariates used to represent immediate and underlying child nutrition determinants included recent consumption of vitamin A-rich foods and access to healthcare systems and services. Recent consumption of vitamin A-rich foods from the DHS questionnaire is only collected for children aged 6–23 months, so this indicator refers predominantly to children who are within the age range where breast feeding is recommended.[19] Access to healthcare systems and services is measured using the proxy variable of vaccine reception. The first dose of the DTP vaccine (administered at 6 weeks of age) is one of the first vaccines given to an infant, where children who do not receive it are expected to have the lowest access to healthcare systems and services. Reception of the first dose of MCV (administered at 9 months of age) is expected to be delivered via similar platforms to VAS through both routine provisions and campaigns. Covariates serving as indicators for enabling child nutrition determinants included socioeconomic position, the caregiver's educational attainment and two women's empowerment dimensions calculated according to the Survey-based Women's Empowerment Index,[20] which measure the caregiver's social independence and decision-making autonomy. Geographical covariates included urban versus rural residence and administrative regions specific to each country. Descriptions of all covariates are available in table 1.

Statistical analysis

Percentage of children receiving VAS in the prior 6 months was stratified by each equity covariate independently for every included country. All estimates were adjusted using population sample weights provided by the DHS programme.[21] Percentages of children receiving VAS in each stratum in the prior 6 months were presented with 95% CIs, where statistically significant differences in VAS coverage were identified as those with non-overlapping 95% CIs. VAS coverage by administrative region was mapped using shapefiles downloaded from GADM (V.3.6).[22]

Data analysis was conducted in RStudio (V.3.6.1, the R Foundation for Statistical Computing). Data were accessed through the DHS programme's application programming interface on 23 November 2022 via the functions available on the *rdhs* package.[23] Survey weight adjustments and statistical analyses were conducted using the functions available on the *survey* and *srvyr* packages,[24] and additional data cleaning and management used a variety of functions from the *tidyverse* package.[25]

Patient and public involvement

As a secondary analysis of publicly available de-identified data collected as part of the DHS, patients and the public who were included as part of the study population were not involved in the design of this study.

RESULTS

Summary of included surveys and populations

In total, the birth history records of 1 465 369 women, corresponding to 608 388 children 6–59 months, were included in this study. For the survey question asking about VAS reception within the prior 6 months, the rate of response was >90% for all countries included. A summary of all included countries and the DHS data used in this study is available in online supplemental table 1.

The national VAS coverage mean among included countries was 58% and ranged from 28% to 83%, where countries with the lowest national VAS coverage were Papua New Guinea (28%), Haiti (28%), Kyrgyzstan (39%) and Guinea (40%). The percentage of children who did not recently consume vitamin A-rich foods among included countries ranged from 19% to 74%, where countries with the lowest percentage of consumption were Burkina Faso (74%), Niger (73%) and Ethiopia (70%). For vaccinations, the percentage of non-vaccinated children among included countries ranged from 1% to 48% for DTP1 and 13% to 69% for MCV1. A descriptive summary of the survey population of children aged 6–59 months for each country is provided in online supplemental table 2.

In figures 1 and 2, we present VAS coverage for all countries stratified by recent consumption of vitamin A-rich foods and access to healthcare systems and services. VAS coverage was significantly higher among children who recently consumed vitamin A-rich foods, compared with children who did not in 85% (n=41) of countries (figure 1). For access to healthcare systems and services, VAS coverage was significantly higher in children who had access to their first dose of the DTP vaccine in 47 of

Table 1 Description of study covariates used to represent immediate, underlying and enabling determinants of child nutrition and geography

Determinant	Type	Coding details
Recent consumption of vitamin A-rich foods	Immediate/underlying	Whether the following types of food were reported being consumed by the child (aged 6–23 months) in the 24 hours prior to the interview: eggs, any meat, fish, orange-fleshed pumpkin/carrot/squash/sweet potato, vitamin A-rich fruit (mango, papaya), liver/heart/organ meat, dark green leafy vegetables
Access to healthcare services and systems (DTP1 vaccine)	Immediate/underlying	Whether the child received the first dose of the DTP vaccine, administered at 6 weeks of age per international guidelines
Access to healthcare services and systems (MCV1 vaccine)	Immediate/underlying	Whether the child received the first dose of the MCV, administered at 9 months of age per international guidelines
Administrative region	Geography	Administrative region the household is located, defined by the subnational reporting area (provinces or groups of provinces) as defined by the DHS recode
Place of residence	Geography	Whether household is in an urban or rural location
Socioeconomic position	Enabling	Quintile of household wealth defined using a principal component analysis score comprised of household living conditions and durable assets (poorest=1st quintile, wealthiest=5th quintile)
Caregiver's social independence	Enabling	Women's empowerment indicator calculated as quintiles of SWPER Index. Social independence domain included data related to education, frequency of reading newspapers/magazines, and age at first childbirth and at first cohabitation (includes children with partnered caregivers) (least socially independent=1st quintile, most socially independent=5th quintile)
Caregiver's decision-making autonomy	Enabling	Women's empowerment indicator calculated as quintiles of SWPER Index. Decision-making autonomy domain included questions about involvement in household decisions and whether the respondent worked in the past 12 months (includes children with partnered caregivers) (least decision-making autonomy=1st quintile, most decision-making autonomy=5th quintile)
Caregiver's educational attainment	Enabling	Highest educational attainment of caregiver (none, primary school, secondary school or higher)

DHS, Demographic and Health Survey; DTP, diphtheria, tetanus and pertussis; MCV, measles-containing vaccine; SWPER, Survey-based Women's Empowerment.

the 49 countries compared with those who did not have access to these vaccines (figure 2A). VAS coverage was significantly higher in children who had access to their first dose of MCV in all 49 countries (figure 2B).

VAS coverage by geography and other enabling determinants

In figure 3, VAS coverage is stratified by geographical covariates of vitamin A nutritional status for all countries. For place of residence, 31% of countries (n=15) had significantly lower VAS coverage in populations residing in rural versus urban areas. In countries where VAS coverage in rural residences exceeded that of urban residences, differences in coverage were never >8%. For administrative region, regions with the lowest and highest VAS coverage in each country had significant differences in 88% of countries (n=43) with spatial structure in subnational VAS coverage visible when mapped (figure 4 for Chad, India, Nigeria, Ethiopia, Yemen; full set of country maps available in online supplemental figures 1–5).

In 73% of countries (n=36), VAS coverage was significantly higher in the wealthiest quintile of the population compared with the poorest quintile of the population, where the differences in coverage between poorest and wealthiest were greatest in Nigeria (33% difference), Cote D'Ivoire (25% difference) and the Democratic Republic of the Congo (25% difference) (online supplemental figure 6). In 37% of countries (n=18), children of caregivers who were the most socially independent had significantly higher VAS coverage compared with caregivers who were the least socially independent (online supplemental figure 7). In 20% of countries (n=10), VAS coverage in children of caregivers who were most autonomous in their decision-making was significantly higher compared with children of the least autonomous caregivers (online supplemental figure 8). Caregivers with higher educational attainment had higher VAS coverage for their children compared with caregivers with lower educational attainment in several countries (online supplemental figure 9).

DISCUSSION

This study used open-source data to identify inequities in VAS programme coverage so that strategies can be devised to improve VAS coverage among unreached populations. We found that children who likely have lower access to vitamin A-rich foods and who have impaired access to

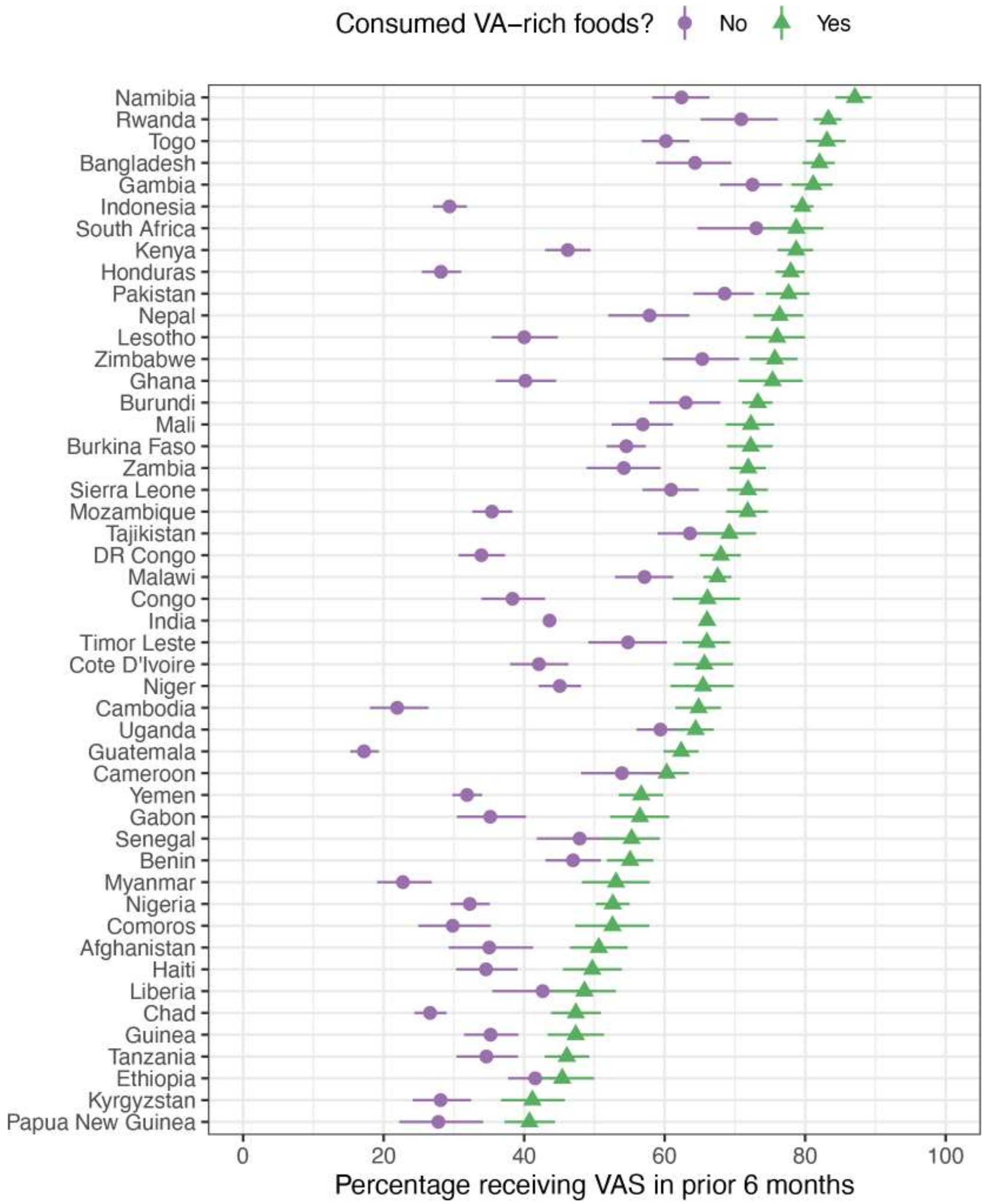

Figure 1 Vitamin A supplementation (VAS) coverage among children 6–23 months who have and have not recently consumed vitamin A (VA)-rich foods (in the 24 hours prior to the interview). Philippine Demographic and Health Survey did not collect data on child consumption of VA-rich foods.

healthcare systems and services are also less likely to receive VAS. This pattern was consistent across most countries and highlights the challenges current VAS delivery faces to reach children who are likely most in need of VAS. The analysis also shows that in some countries, children missed by VAS also reside in the poorest households, in rural areas and have caregivers who are more constrained by gender norms. Although these are the general trends, we also observed considerable variation between countries. While the use of DHS data to gain insight into VAS programmes has been conducted in some countries,[26–28] future analyses using DHS data can help inform VAS programme operations in other country contexts. National programmes can use the analysis presented here as an advocacy tool for universal coverage, or as a framework to improve targeting and prioritisation of children who are likely to be most in need of VAS delivery programmes.

The demonstrated use of DHS data to provide subnational equity perspectives can provide useful VAS programme insights. For example, this study indicated that lower VAS coverage for children who may have lower access to vitamin A-rich foods and healthcare systems and services was consistent across most countries. According to global estimates using UNICEF infant and young child feeding data, the consumption of vitamin A-rich foods by

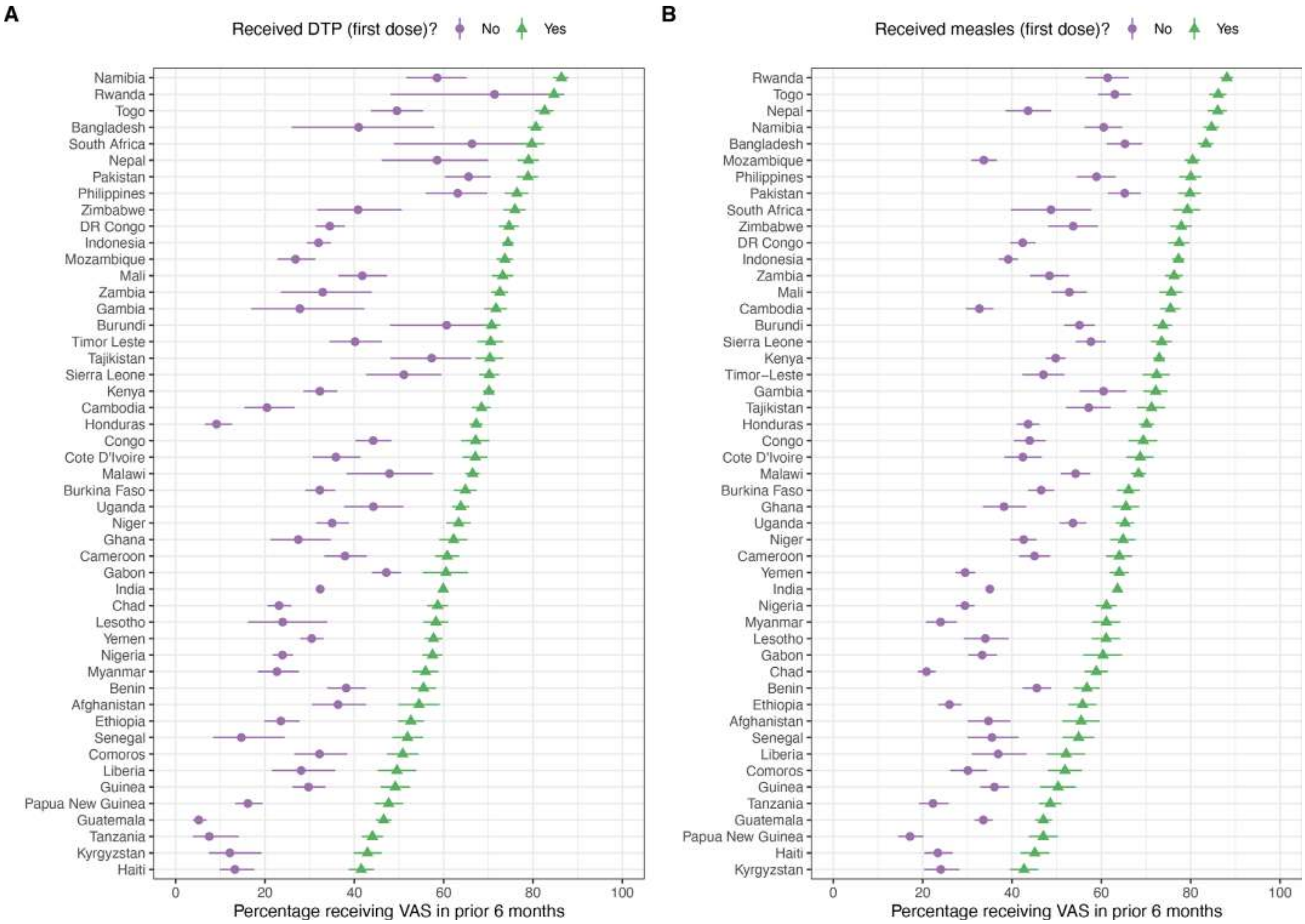

Figure 2 Vitamin A supplementation (VAS) coverage among children who have and have not received (A) the first dose of the diphtheria–tetanus–pertussis (DTP) vaccine and (B) the first dose of the measles-containing vaccine (indicator of access to healthcare systems and services).

complementary feeding children is lowest in poorer and more rural children[29] suggesting that in combination, multiple enabling determinants affecting nutrition are likely to contribute to reduced access to vitamin A-rich foods. However, this study suggests that in many countries, VAS coverage is either equal or lower in these rural and poorest populations despite likely having greater need for VAS.

To address these gaps, VAS programmes may benefit from being more aligned with routine community-based delivery programmes. In children aged 6–11 months, in countries where VAS coverage between vaccinated and unvaccinated children diverges, there is a potential opportunity to improve VAS coverage by aligning programmes more closely to the country's EPI systems. This alignment with EPI systems will require programme reforms, including the creation of a 6-month contact point in routine systems, inclusion of VAS dosing schedules on child health cards,[30] and strengthening supply chains for vaccines and vitamin A capsules to ensure concomitant availability. For older children who are not serviced by the EPI (12–59 months), there may be other established routine early childhood programmes where the routine delivery of VAS could be integrated, such as growth monitoring and promotion, counselling on breast feeding and complementary feeding, early childhood development programmes and the early detection and treatment of severe wasting.[31] Current reliance on polio vaccination campaigns to deliver VAS has presented a risk of declined VAS coverage as polio programmes cease,[32] so identifying other routine community-based delivery programmes to integrated VAS should be prioritised.

As the global vitamin A landscape evolves, it is important for national governments to consider how VAS programmes can be positioned in combination with other parallel vitamin A interventions to reduce risks of deficiency for all children. VAS has short-term benefits for children (boosting serum retinol for approximately 2 months after administration),[33] so other interventions are necessary to sustainably maintain adequate vitamin A intake through the diet. For the countries included in this study, 51% (n=25) have nationally mandated the large-scale vitamin A fortification of industrially produced food items.[34] However, poorer and rural populations—where VAS coverage is often lower—often consume small quantities of fortified food items (eg, cooking oil, sugar, wheat

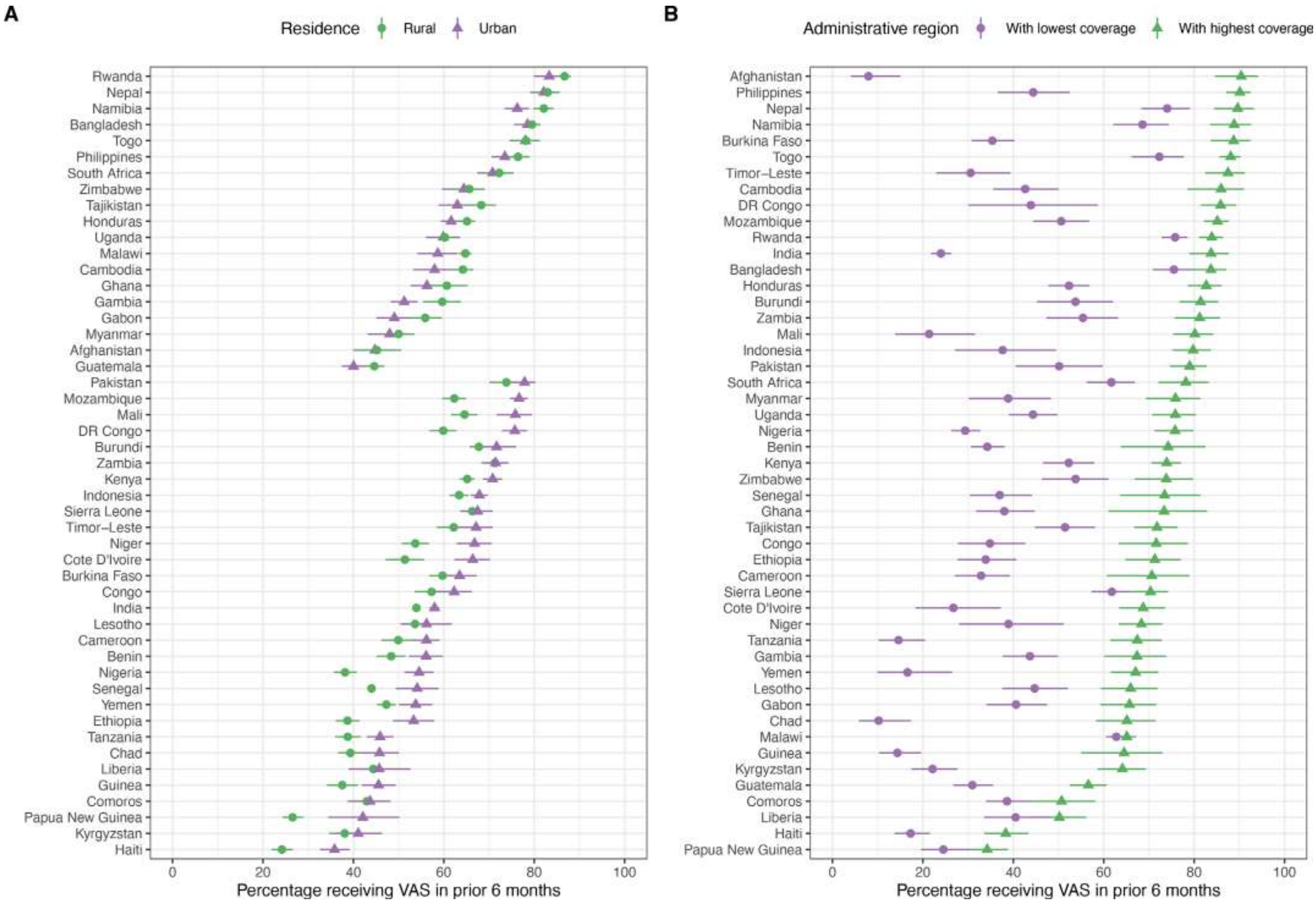

Figure 3 Vitamin A supplementation (VAS) coverage disaggregated by geography: (A) rural versus urban residence and (B) administrative regions.

flour) and may therefore derive limited benefit from industrial vitamin A fortification schemes.[35] Programmes aimed at broader improvements in dietary diversity have also been recommended,[36] but variation in diets between and within countries poses challenges when scaling up across different contexts. With multiple parallel vitamin A interventions, future studies that simultaneously consider the individual and combined contributions of all vitamin A interventions could help governments orient their national vitamin A strategies.

Evaluating equity dimensions of VAS programmes by stratifying coverage estimates using multiple variables can help identify potential gaps in national programmes' delivery strategies. This analysis drew from the DHS Household and Woman's Questionnaires to identify enabling determinants to undernutrition that could affect VAS coverage. If differences in VAS coverage are detected between populations, some of these geographical determinants (eg, place of residence, administrative regions of the country) can serve as indicators that lead to practical recommendations for programmes to adopt to bridge coverage gaps (eg, strengthening programmes in a specific region of the country or for a specific demographic). In contrast, other determinants, while useful to evaluate whether VAS programmes are broadly equitable, lack clear operational directions on how programmes can specifically target populations that are left behind (eg, socioeconomic position, caregiver's social independence, caregiver's decision-making autonomy). This study explored several different indicators made available in the DHS, and VAS programmes could benefit from further research aimed at interpreting the combination of multiple indicators in the context of a country's current VAS delivery strategy (eg, campaign vs routine delivery).

In our analysis, there are several limitations that are important to consider. First, the question specific to VAS in the DHS questionnaire is dependent on recall by the caregiver of the child. The percentage of respondents who could prove VAS reception using home-based vaccination records varied between countries, but for most countries (69%; n=34), less than half of respondents had proof of VAS reception (online supplemental figure 10). For children whose records depend solely on recall by the caregiver, recall error (eg, confusing VAS droplets with polio droplets, imprecision in the exact date of reception, confusion between multiple children) is more likely. Second, in settings where VAS is delivered via biannual campaigns, interpretation of DHS VAS coverage must cautiously consider the timing of the survey relative to the timing of the campaign (eg, VAS coverage

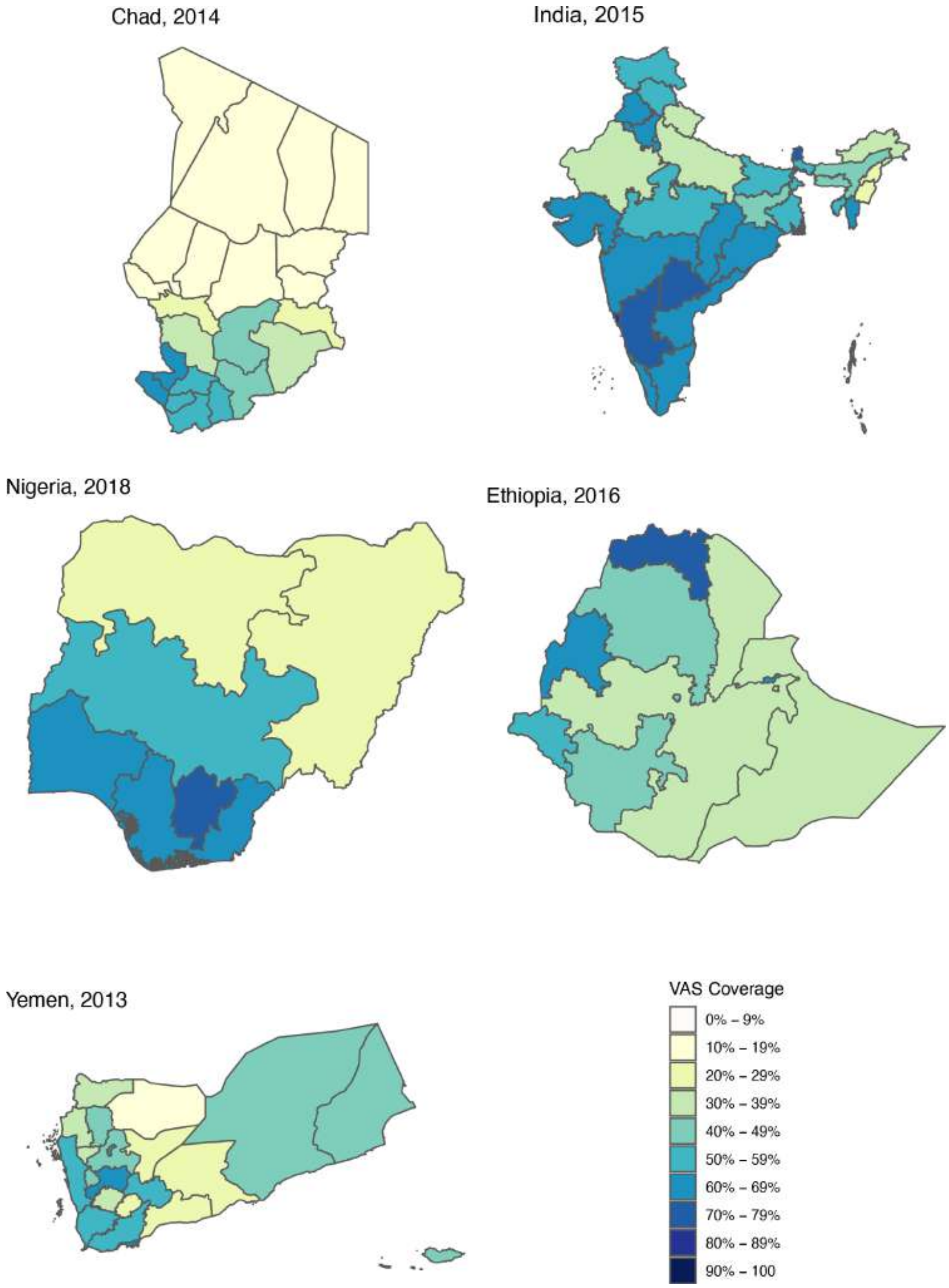

Figure 4 Vitamin A supplementation (VAS) coverage maps by administrative regions (maps of all countries available in the online supplemental material 1).

may be underestimated if the DHS was implemented immediately before the start of a new campaign). Across several settings, the characteristics of children missed by current VAS programmes remained relatively consistent, but recommendations related to specific settings would benefit from country-specific interpretation to place this information in the context of a country's current VAS policies and programmes. Third, the dietary data collected as part of the DHS only contain one dichotomous recall of whether vitamin A-rich foods were consumed in the past 24 hours by complementary feeding children. No information is available regarding food consumption quantities, weekly variation in diets or for children aged 24–59 months. With this kind of dietary data, it is not possible to understand whether VAS is being administered to children who have inadequate dietary vitamin A intake or who have intake that exceeds daily upper limits to put children at risk of toxicity. To fully understand whether VAS programmes are addressing children with the greatest vitamin A needs, VAS coverage should be estimated alongside other subnational nutritional assessment data (eg, vitamin A inadequacy from dietary assessment) to identify populations with both inadequate dietary vitamin A intake and low VAS coverage. Considering these limitations, VAS coverage data available as part of the DHS are not recommended to replace either single-semester coverage, two-dose coverage or efforts to advocate for additional repeated, representative surveys. However, DHS data analysed in parallel to these other available data can provide a more complete understanding of the VAS context in a country to inform governments on national programme performance and help characterise missed children so that strategies can be adapted to reach them.

CONCLUSION

This analysis further contributes clear and consistent evidence that VAS programmes are unable to reach all eligible infants and children. This analysis also highlighted inequity in access to VAS, as children who are likely the most in need are more often not reached by this life-saving intervention. Three decades after the WHO first recommended high-dose vitamin A supplements to infants and children aged 6–59 months, countries with high risks of vitamin A deficiency have not yet achieved the goal of universal VAS coverage. Particular attention should focus on settings with low coverage, where children who are the most in need are also more likely to be missed. While DHS data can be useful to identify variations in VAS coverage based on equity dimensions already included in the questionnaire, challenges remain for programmatic questions requiring current, context-specific data.

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