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Dietary mineral supplies in Malawi: spatial and socioeconomic assessment

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Abstract

Background: Dietary mineral deficiencies are widespread globally causing a large disease burden. However, estimates of deficiency prevalence are often only available at national scales or for small population sub-groups with limited relevance for policy makers.

Methods: This study combines food supply data from the Third Integrated Household Survey of Malawi with locally-generated food crop composition data to derive estimates of dietary mineral supplies and prevalence of inadequate intakes in Malawi.

Results: We estimate that >50 % of households in Malawi are at risk of energy, calcium (Ca), selenium (Se) and/or zinc (Zn) deficiencies due to inadequate dietary supplies, but supplies of iron (Fe), copper (Cu) and magnesium (Mg) are adequate for >80 % of households. Adequacy of iodine (I) is contingent on the use of iodised salt with <1 % of households getting adequate I supply from food alone. Hidden hunger is likely to be widespread: among households with adequate energy supply, 30, 56 and 27 % had inadequate supplies of Ca, Se and Zn, respectively. Over 80 % of the poorest households had inadequate dietary supplies of Ca and Zn compared to <30 % of the wealthiest households; >80 % of rural households living on low-pH soils had inadequate dietary Se supplies compared to 55 % on calcareous soils; concurrent inadequate supplies of Ca, Se and Zn were observed in >80 % of the poorest rural households living in areas with non-calcareous soils. Prevalence of inadequate dietary supplies was greater in rural than urban households for all nutrients except Fe.
Interventions to address dietary mineral deficiencies were assessed. For example, an agronomic biofortification strategy could reduce the prevalence of inadequate dietary Se supplies from 82 to 14 % of households living in areas with low-pH soils, including from 95 to 21 % for the poorest subset of those households. If currently-used fertiliser alone were enriched with Se then the prevalence of inadequate supplies would fall from 82 to 57 % with a cost *per* alleviated case of dietary Se deficiency of ~ US$ 0.36 year^{-1}.

Conclusions: Household surveys can provide useful insights into the prevalence and underlying causes of dietary mineral deficiencies, allowing disaggregation by spatial and socioeconomic criteria. Furthermore, impacts of potential interventions can be modelled.

Keywords: Dietary mineral deficiencies, Household survey, Malawi, Micronutrient supplies, Spatial

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Background

Food security is defined as having access to sufficient, safe and nutritious food to meet the needs of an active and healthy life [1]. Food insecurity can manifest as ‘hunger’ due to inadequate dietary energy intake, or ‘hidden hunger’, due to deficiencies of vitamins and mineral elements. Hidden hunger is widespread globally with an estimated two billion people at risk of vitamin A, iron (Fe), iodine (I) and zinc (Zn) deficiencies, causing a considerable social and economic burden particularly in low-income countries including sub-Saharan Africa [2–10]. Deficiencies of other vitamins and elements are also likely to be widespread globally, including selenium (Se) which shows significant spatial variation due to environmental factors [11–14].

The prevalence of vitamin or element deficiencies can be quantified through analysis of their concentrations in blood plasma, other tissues or urine; however, conducting wide-scale surveys can be expensive and logistically challenging. In addition, some biomarkers might not be sufficiently accurate or sensitive indicators of deficiency, particularly for mild deficiencies, e.g. for Zn [15]. In certain cases, health outcomes can be a useful proxy to measure prevalence of dietary nutrient deficiencies, for example stunting as an indicator of Zn deficiency [16]. However, such relationships can be confounded by environmental factors or multiple causes of the same health outcome and surveys of health outcomes remain expensive and logistically challenging to conduct. Thus, dietary assessment can be a useful approach whereby the mass of an element consumed or supplied in the diet is quantified, either through direct analysis of composite diets or through matching of food intake records and relevant composition data. Following conventional terminology, ‘inadequate dietary supply’ of a micronutrient puts an individual ‘at risk of deficiency’ where deficiency causes negative health outcomes. There are a number of factors that may confound the relationship between ‘dietary intakes’ and ‘nutritional sufficiency’, such as nutrient-nutrient interactions, impaired gut absorption or increased losses of vitamins and elements due to infection. For example, phytic acid (PA) is the principal form of phosphorus in cereal grains and inhibits the absorption of Fe, Mg and Zn in the human gut [17].

Previously, the prevalence of micronutrient deficiencies or inadequate dietary supplies in Malawi have been reported using different methods (*c.f.* Table 1 of Joy et al. [18] for a summary). Anthropometric measures and dietary recall matched to local or regional food composition data were used to quantify dietary supplies and deficiency prevalence of micronutrients in sub-national populations [19–25]. Global, regional or national estimates of deficiency risks were generated using food supply data captured in Food Balance Sheets (FBSs) published by the United Nations Food and Agriculture Organization [9, 13, 18, 22, 26, 27], or consumption data captured in national Household Surveys [28–30]. These studies have shown or estimated that deficiencies of calcium (Ca), I and Zn are likely to be widespread in Malawi due to inadequate dietary supplies whereas dietary supplies of copper (Cu) and magnesium (Mg) appear to be adequate for those with sufficient dietary energy intake. Some studies report generally adequate dietary supplies of Fe and low prevalence of Fe-deficiency anaemia [9, 18, 25], while others report generally inadequate dietary Fe supplies and high prevalence of Fe-deficiency anaemia [24, 30], and this requires further study. Spatial variation in crop composition due to soil type is an important determinant of dietary supplies of some elements; for example, a high prevalence of Se deficiency is likely among populations living on low-pH soils but not on calcareous soils with pH >6.5 [22].

The present study considers both environmental and socioeconomic determinants of dietary element supplies in Malawi. Household dietary energy, PA, Ca, Cu, Fe, I, Mg, Se and Zn supplies were quantified by integrating datasets for food consumption, food composition and nutrient requirements. Results were aggregated by defining household characteristics, e.g. urban/rural location, at national and Extension Planning Area (EPA) levels. The EPA is an administrative unit of the Ministry of Agriculture and Food Security. There are 186 EPAs in Malawi with mean and median land areas of 49,600 and 38,900 ha, respectively. Typically, an EPA office will have a good working knowledge of the local area and maintain contact with a high proportion of member households. Thus, EPAs provide an effective network through which agriculture-nutrition interventions can be implemented, especially given that 85 % of the population are involved in agriculture, predominantly subsistence production [31].

Methods

Food consumption

Household food consumption and socioeconomic data were derived from the Third Malawi Integrated Household Survey (IHS3) in which a nationally-representative sample of 12,271 households were interviewed during March 2010-March 2011 [28]. These data were obtained by the authors as fully anonymised secondary data from the World Bank open-data repository [32]. Author use of this open-data archive is compliant with requirements of World Bank, as specified upon data retrieval through the data portal [32]. In the first stage of household selection, Enumeration Areas (EAs) were chosen at random to represent Districts; the probability of EA selection was proportional to the number of member households.

In the second stage of selection, 16 households were selected at random to represent each EA with five replacement households in case of failure to complete the interview process. On average, EPAs were represented by 4.3 EAs (range 1–28) [33].

In the food consumption module, interviewees were asked to recall the food consumed in the household during the past 7 days from a list of 112 food items (e.g. 'Maize *ufa* refined (fine flour)', 'Dried fish', etc.). Enumerators recorded the source of the food item (i.e. 'own production', 'bought' or 'gift') and the amount consumed. Interviewees could choose from a selection of units that included standard metric measures (grams, litres etc.) and local units (small plate, large plate, small bucket, large bucket, basin etc.) to assist in estimating the quantity consumed.

There were some inexplicit food categories (e.g. 'Other cultivated green leafy vegetables'); these items were matched to a generic crop in this study (e.g. 'Cabbage leaf') unless enumerators provided a more specific description (e.g. 'Other cultivated green leafy vegetables – *Bonongwe*', meaning leaf of *Amaranthus* spp.), in which case new item codes were assigned to match more appropriate crop composition data. In total, >99 % of food records were decipherable and were included. To calculate mass consumed, local units were converted into metric units; this was done on an item-specific basis because of the variation in density of food items. The IHS3 team measured the mass of local units of common food items from 48 retail markets in Malawi and report a conversion table by region (north, central and south). However, there are still many data gaps in the published conversion table. In addition, some of the conversion factors given vary widely between regions with no apparent explanation; for example, the mass of unit 'Pail (small)' for food item 'Maize *ufa* refined (fine flour)' is reported as 1.83, 5.02 and 3.11 kg in north, central and south regions, respectively. Therefore the conversion table was re-constructed using author judgement and was applied independent of region (Additional file 1: Table S1). The inedible portions of food items (e.g. banana skin, maize cob) were estimated using author judgement (Additional file 1: Table S2). The unit/mass conversion table, inedible proportion and moisture content data (see below) were used to estimate daily household (hh) consumption of the edible portion (EP) of food items on a dry-weight (DW) basis (i.e. kg hh^{-1} d^{-1}, DW EP).

Inspection of the raw survey data revealed some implausible entries. For example, 145 households were recorded as consuming >1 kg $capita^{-1}$ d^{-1} of the food item 'Maize *ufa* refined (fine flour)'. To mitigate such potential entry errors, a maximum plausible daily consumption of each food item was imposed; this affected just 1459 (<1 %) out of a total of >197,000 food entries (Additional file 1: Table S3).

Nutrient composition

Food items in the IHS3 were matched to food crop samples from a previous national survey of plant elemental concentrations [18]. Survey samples were pooled by species and tissue, for example 'Mango_fruit', 'Cassava_leaf' or 'Cassava_root', and were assigned to one of three composition tables according to the soil type at sampling location: 'calcareous', 'non-calcareous' and 'undifferentiated' (i.e. independent of soil type; Fig. 1; Additional file 1: Table S4 and Additional file 1: Table S5) [18]. Further food composition data generated since the publication of earlier findings are included in this study and are highlighted in Additional file 1: Table S5. These include nine fish samples collected at lakeshore and inland markets, comprising both small fish (*usipa* and *kapenta*) which are typically eaten whole, and larger fish (*matemba, chambo, utake* and *mbalule*) which are typically gutted before cooking with the meat, small bones and head all consumed but larger bones discarded. The consumption of whole fish

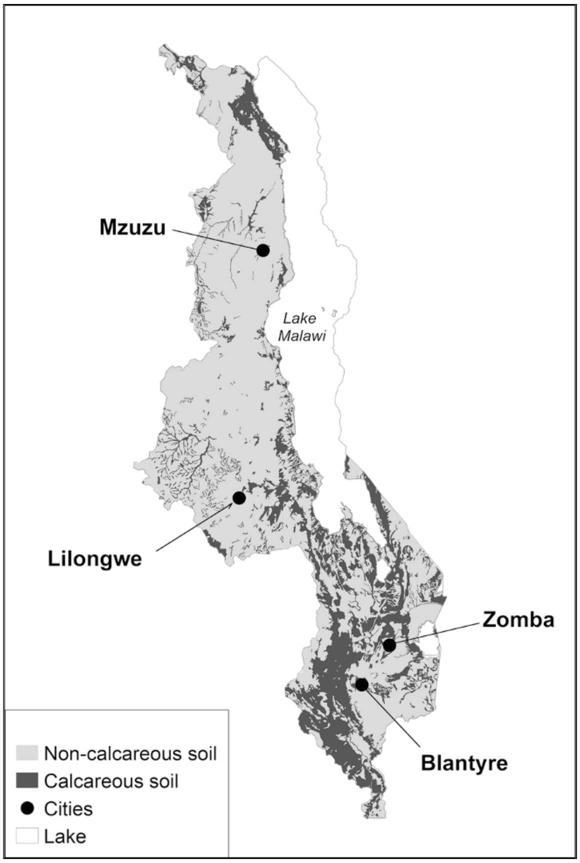

Fig. 1 Soils of Malawi. Soils are classified as calcareous or non-calcareous. Soil series mapping from [43]

including bones is likely to be a significant source of dietary Ca intake, yet the IHS3 questionnaire did not specify the size of fish consumed so mineral composition data for all fish samples were combined into one category which was not stratified by soil class. Rice samples were also not stratified by soil class as, unlike other grains or fresh crops, rice is mainly grown along the lakeshore and in the Shire River basin and is frequently traded over long distances in Malawi. For example, among rural households, 73, 15 and 12 % of rice consumption entries in IHS3 came from purchases, own production and gifts, respectively, compared to 38, 57 and 5 %, respectively, for refined maize flour. Thus for rice, the soil type at household, market or mill sampling site is unlikely to be a good predictor of the soil type on which it was grown.

The influence of outlying composition data was minimised by using median concentrations of plant/tissue groupings; however, as some sample sizes were very small (e.g. three samples of 'Pumpkin_fruit' from calcareous soils), data were screened for evidence of extraneous contamination that might make composition data unrepresentative of what is eaten. Plausible maximal elemental concentrations of plant tissues were derived from the plant nutrition literature, e.g. 500 and 100 mg kg^{-1} of Cu in leaf and seed, and 100 mg kg^{-1} of Zn in seed and fruit [34, 35]. Thus, seven and four Cu and Zn data points, respectively, were excluded. Concentrations of aluminium, titanium and vanadium in these samples did not show evidence of contamination with soil dust so elevated Cu and Zn concentrations were likely due to sample preparation methods including cutting and blending samples with metal blades and were deemed unlikely to be representative of foods eaten in Malawi (Additional file 1: Table S5). One sample of tomato fruit had a high Cu concentration (sample number 13380–0002, 190.2 mg kg^{-1} DW) but was not excluded as Cu-based fungicides are commonly used on tomato plants in Malawi, especially during the rainy season when this sample was collected, and this Cu concentration may be representative of what is eaten.

The staple dish *nsima* is prepared using maize flour (*ufa*), using either refined or whole grain. To make refined flour, grain is winnowed, de-hulled, soaked in water for ~3 d, dried in the sun and then milled. Of the 12,271 households with food consumption records, ~10,000 reported consuming maize flour of which ~6000 consumed 'Maize *ufa* refined (fine flour)' with mean consumption of 276 g $capita^{-1}$ d^{-1}. However, inadequate samples of refined flour were collected during the survey of plant crop elemental concentrations to provide reliable composition data for this important food item. Therefore, composition data for whole maize grain was used, adjusted by a standard ratio for the effects of processing on elemental concentrations. The standard ratio was calculated from paired whole grain and refined maize flour samples collected at maize mills (Additional file 1: Table S6). Consumption of whole grain maize flour, i.e. the food item 'Maize *ufa mgaiwa* (normal flour)', was recorded by ~6000 households with mean consumption of 249 g $capita^{-1}$ d^{-1}; maize grain composition data without any conversion factor was matched to this food item.

Where relevant composition data were not available (including for most animal products and for energy and PA), suitable matches were established using published food composition tables, primarily Tanzania [36] and the USA [37] (Additional file 1: Table S4). Composition data from published sources were converted to DW concentrations using matched moisture content data (Additional file 1: Table S4). The concentration of PA is greater in the bran than the endosperm of maize grain and milling and processing typically reduces PA concentrations, e.g. from 880 down to 234 mg 100 g^{-1} DW [19]. Thus, the reported PA concentration of 800 mg 100 g^{-1} edible portion of maize flour [36] is likely to represent whole grain flour. To avoid over-estimating the supply of PA from food items made with refined cereal flours, a 75 % reduction in PA concentration was assumed due to milling and processing (Additional file 1: Table S7).

Nutrient requirements

Household demographic information was used to calculate the dietary nutrient requirements of households. For calorie requirements, Dietary Energy Requirements (DERs) recommended by the FAO were used [38]. All individuals were assumed to lead a moderately active to active lifestyle with physical activity level (PAL) of 1.9 and mean body mass for adult males and females was assumed to be 70 and 65 kg, respectively (this is revisited in the Discussion). Estimated Average Requirements (EARs) and Recommended Nutrient Intakes (RNIs) for Ca, Fe, I, Mg and Zn were obtained from the World Health Organization (WHO) [39] as these data are likely to be suitable for non-U.S. population groups. The EAR and RNI define intake levels adequate for 50 and 97.5 %, respectively, of healthy individuals in an age and sex-specific population group. The WHO does not provide requirement data for Cu, so these were obtained from the Institute of Medicine [40]. The US/IOM values were also used for Se, e.g. adult EAR = 45 μg d^{-1} [41], because WHO recommendations for Se intake, e.g. adult male EAR = 28 μg d^{-1} [39], are probably too low based on recent evidence [14].

Module D of the IHS3 provides the opportunity for pregnancy of household members to be recorded under the section 'illness or injury'. Only 21 instances of pregnancy were recorded from 12,842 women aged 15–49 included in the survey. Conversely, the total fertility rate in Malawi during 2005–10 was 5.83 [42] which would translate to ~1650 instances of pregnancy; thus data capture appears to be incomplete. Lactation status was also not captured, so fertility rates by five-year age group for 2010 were used to estimate the proportion of women who were pregnant or lactating and to make an adjustment to nutrient requirements to account for their greater requirements. For example, the EARs of Zn for women aged 15–19 years are 12.0, 14.0 and 15.0 mg d^{-1} for non-pregnant, pregnant and lactating individuals, respectively [39]. In Malawi in 2010, 11 and 14 % of women aged 15–19 were estimated to be pregnant and lactating, respectively. Therefore, the adopted EAR for all 15–19 year old women in the IHS3 was 12.6 mg d^{-1}.

Data integration

Data were integrated in a database (Microsoft Access 2010, Microsoft Corporation, Redmond, WA, USA). Statistical analyses were carried out using MINITAB (Version 15, Minitab Corporation, Pennsylvania, USA), 'R' (Version 3.0.2, R Foundation for Statistical Computing, Vienna, Austria) and GenStat (Version 17, VSN International, Hemel Hempstead, UK). Spatial data management and analyses were conducted using ArcGIS (Version 10.2.1, ESRI, Redlands, CA, USA).

Food composition tables developed for 'calcareous', 'non-calcareous' or 'undifferentiated' soil types were applied to households depending on their location. Exact Geographical Position System (GPS) locations of the households are not available in the public domain to protect confidentiality of the respondents [28]. The data field which provides the greatest spatial resolution is the administrative unit Enumeration Area (EA). The IHS3 sampled 768 EAs with mean and median land areas of 1748 and 745 ha, respectively. A single GPS point is reported in the survey to represent all households within an EA. The point was formed by taking the average latitude and longitude of all households in an EA followed by a displacement (for data protection reasons) of 0–2 km in urban EAs and 0–10 km in rural area EAs to create a modified location within the original EA [28]. The modified EA point locations were overlaid with the EA polygons as *per* the 1998 Malawi population census (latest publicly available GIS data) to provide polygon spatial data for each EA; this was spatially overlaid with a soil map of Malawi [43] using the intersection function in ArcGIS to extract the proportion of each EA covered by calcareous and non-calcareous soils.

Food consumption of households in rural areas was matched to either 'calcareous' or 'non-calcareous' food composition data depending on the soils in the EA; EA soil class was assigned as 'calcareous' or 'non-calcareous' if more than two-thirds of the area was covered by one of these soil classes (Additional file 1: Table S8). Some soils are likely to be unsuitable for agricultural production, for example mountainous terrain with minimal or zero soil depth or marsh land that frequently floods, and these were omitted from the calculation of area by soil class. If there was no dominant soil class then the 'undifferentiated' food composition table was adopted. A total of 13 EAs in the survey had a land area ≥10,000 ha. These large EAs included National Parks and other sparsely populated areas and a more accurate prediction of the soil type on which households were located was determined by laying a 5 km buffer around the aggregated household EA GPS point. The soil class was then determined by calculating the proportion of calcareous and non-calcareous soils within the buffer (example map provided in Additional file 2: Figure S1). For urban EAs, the 'undifferentiated' food composition table was adopted as household location is unlikely to be a good predictor of the soil type on which their food was grown.

Households were eliminated if energy consumption was implausible, defined as >8000 or <400 kcal *per* Adult Male Equivalent (AME) d^{-1}, thus eliminating 154 out of 12,271 households to leave 12,117 households. The AME is a unit based on the ratio of energy requirement between an individual and the benchmark of an adult male aged 18–30 with a PAL of 1.75, i.e. 2800 kcal [38, 44]. For example, a household with one adult male, one adult female, a 4-year-old daughter and a 1-year-old son would have an AME value of ~3. The effect of more stringent exclusion criteria is explored in the Discussion.

Estimates of nutrient supplies and prevalence of inadequate intakes

Food consumption (kg^{-1} hh^{-1} d^{-1}, DW EP) and food composition data (mg kg^{-1}, DW EP) were combined to calculate the supply of each nutrient at the household level. While the unit of analysis remains the household, supply *per capita* was calculated for each household as this provides a tangible metric that allows comparison with previously published estimates. In addition, household demographic composition was used to calculate supply *per* AME for each household. Supply *per* AME is a preferable metric when comparing households with different age or gender compositions and is used for comparing household supplies within the present study, e.g. between poorer and wealthier households.

The contribution of food groups to nutrient supplies was quantified by assigning food items to the following groups: 'Animal products', 'Cereals', 'Fats and oils', 'Fish', 'Fruits', 'Legumes', 'Milk products', 'Roots and tubers', 'Vegetables' and 'Others' (Additional file 1: Table S4). Nutrient supplies from each food group were summed for a defined set of households, and were divided by the sum of nutrient supplies from all food groups.

The prevalence of inadequate intakes was estimated at the household level by comparing dietary element supplies with the combined EAR or RNI of all household members. Adequacy of household Zn supply was further characterised by the dietary PA:Zn molar ratio, where a value >15 is considered to provide inadequate bioavailable Zn [17].

Results

Household characteristics

Food consumption and household characteristics were recorded for 12,271 households in the IHS3 with a combined occupancy of ~56,000 individuals. A total of 154 households were found to consume unrealistic amounts of energy and were excluded from further analysis. A summary of the socioeconomic and environmental characteristics of the remaining 12,117 households is provided in Additional file 1: Table S9, with the relationships between characteristics provided in Additional file 1: Table S10 and Additional file 1: Table S11. More rural households (9944) were interviewed than urban (2173) while the number of households interviewed by expenditure quintile ranged from 1840 to 3191 in quintiles 1 (poorest) and 5 (wealthiest). Expenditure quintiles were delimited based on *per capita* consumption expenditure. Mean household size was 5.8, 5.2, 4.8, 4.3 and 3.6 for expenditure quintiles 1 to 5, respectively. Thus, although the number of interviewed households varied between expenditure quintiles, the number of individuals covered in each expenditure quintile was equivalent. The number of rural households located on non-calcareous and calcareous soils was 6523 and 2047, respectively, while 1374 were not assigned to a particular soil type. The 179 EPAs were represented by varying numbers of households, e.g. from 15 in Chileka to 431 in Ntonda, with varying socioeconomic and environmental characteristics, e.g. median expenditure quintile 1 in Dolo to 5 in seven of the EPAs (Additional file 1: Table S12).

Foods consumed

Interviewees were asked to recall foods consumed over the past 7 days. Maize is the dominant staple crop of Malawi and 11,704 households (97 %) consumed either refined or whole grain maize flour while 3815 (31 %) consumed rice (Additional file 1: Table S13). Median consumption of maize flour *per* AME was 320 g DW d^{-1}. Only 408 households consumed sorghum and 264 consumed either pearl or finger millet. 5263 households (43 %) consumed cassava (either as a boiled root or flour), 4664 consumed sweet potato (orange or white) and 2018 consumed potato (Additional file 1: Table S13).

A total of 10,529 households (87 %) consumed some form of animal product (meat, fish, eggs or milk) during the 7 day recall period, with 9286 (79 %) consuming fish. Dried fish were particularly popular with 7935 households consuming this item and median consumption *per* AME of 17 g DW d^{-1} (Additional file 1: Table S13). Fish consumption (yes/no) was related to household expenditure quintile (Pearson Chi-square = 652, df = 4, *p* <0.001; Fig. 2), with greater consumption in wealthier and urban households (Additional file 1: Table S14).

Interviews were conducted from March 2010 to March 2011 inclusive, each month was represented by ≥527 interviews. The climate of Malawi is characterised by one rainy season, generally lasting from November to February in the Southern region and December to April in the Central and Northern regions. The mid-rainy season is sometimes referred to as the ‘hunger gap’ as cereal crops have not matured and last season’s household stores are depleted. Over 75 % of households reported consuming the item ‘Green Maize’ (i.e. fresh cob, boiled) in March, but <15 % in May-December. Overall, cereal consumption showed no marked seasonal variation suggesting that stocks from the 2009 and 2010 harvests were adequate for most households or were covered by increased purchases or gifts (Fig. 2; Additional file 1: Table S15). The 2009/10 growing season was favourable in Northern and Central regions and produced a national surplus of maize [45]. However, there were prolonged dry spells in parts of the Southern region which reduced crop yields [45]. Despite this, there was no evidence of seasonal variation in cereal consumption in Southern region households covered by the IHS3 (data not shown).

Conversely, other crops showed marked seasonal variation. For example, mean consumption *per* AME of ‘Legumes’ was >87 g d^{-1} DW in May-July but <55 g d^{-1} DW in October-March. Consumption of ‘Roots and tubers’ peaked during May-September, ‘Vegetables’ during March and April and ‘Fruit’ during January and February coinciding with the availability of mangoes; there were 3226 records of mango consumption of which 79 % were in November-January. Fish is a particularly important component of dietary micronutrient supply and there was no marked seasonal variation in consumption nationally (Fig. 2; Additional file 1: Table S15). Of relevance to food fortification schemes, 11,950 (99 %), 7756 (64 %) and 7611 (63 %) of households reported consuming salt, sugar and cooking oil, respectively.

Nutrient supplies and prevalence of inadequate intakes at household levels

Energy

Nationally, median energy supplies *per capita* and *per* AME were 2114 and 2463 kcal d^{-1}, respectively, but were lower in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For

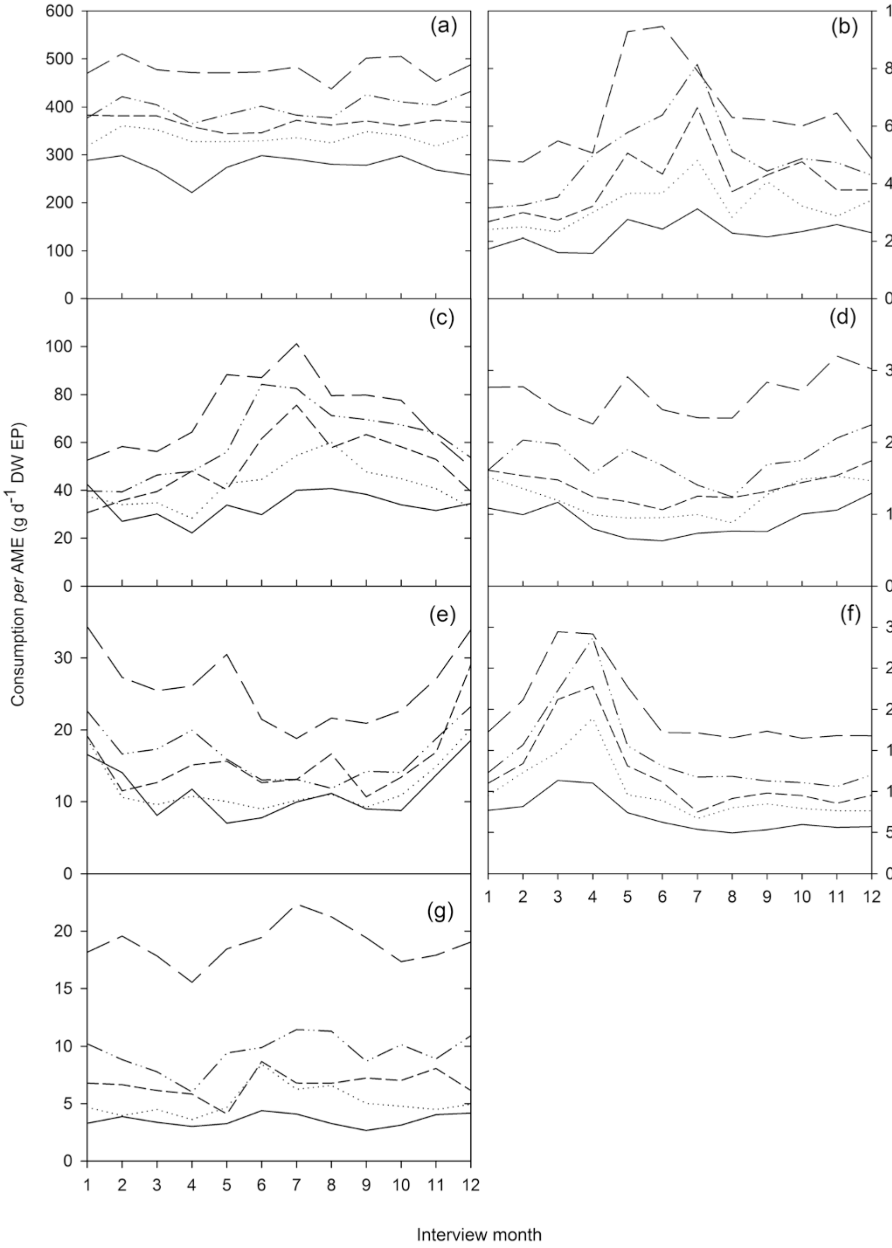

Fig. 2 Seasonal supply of food groups. Median daily supply of the food groups **a** cereals, **b** legumes, **c** roots and tubers, **d** fish, **e** fruits, **f** vegetables and **g** animal products (not including fish) *per* Adult Male Equivalent, dry-weight edible portion (AME, DW EP) by expenditure quintile and interview month (1 - January to 12 - December). Quintiles are 1 (poorest, continuous), 2 (dot), 3 (short-dash), 4 (dash-dot-dot) and 5 (wealthiest, long-dash)

comparison, the DER of an adult man with body mass 70 kg and physical activity level 1.9 is 3300 kcal d^{-1} [38]. Median household supply of energy as a proportion of sum of member DERs was 0.92 (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 57 % of households reported consumption of insufficient calories to meet the sum of member DERs (Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median energy supply *per* AME ranged from 1127 kcal d^{-1} in Kalumba (number of households, n = 16) to 3817 kcal d^{-1} in Nkhunga ($n = 125$) and was <2000 kcal d^{-1} or >4000 kcal d^{-1} in 33 of 179 EPAs (Additional file 1: Table S22 and Additional file 1: Table S23). Thus, despite data cleaning as described in the Methods and use of median household nutrient supplies during aggregation, there remains an issue with implausible dietary energy (and other nutrient) supplies. This is re-visited in the Discussion.

Household dietary energy supply was related to household socioeconomic characteristics (Fig. 3). For example,

Table 1 Nutrient supplies in rural households

Expenditure quintile	*n*	Median dietary supply									
		Energy	Ca	Cu	Fe	I	Mg	Se	Zn	PA	PA:Zn
		kcal		mg		μg	mg	μg	mg		Molar ratio
						AME^{-1} d^{-1}					
1	1783	1479	307	0.98	11.5	5.5	303	12.6	6.1	1976	35.2
2	2038	1976	510	1.40	16.0	9.3	397	18.6	7.9	2401	32.3
3	2103	2423	636	1.78	19.5	12.1	464	22.5	9.3	2680	30.7
4	2140	2870	830	2.23	23.6	16.8	548	28.8	11.5	2951	28.2
5	1880	3828	1304	3.28	30.8	26.9	741	43.3	16.1	3846	24.8
ALL	9944	2384	649	1.80	19.5	12.6	469	23.5	9.6	2764	30.2

Median energy, calcium (Ca), copper (Cu), iron (Fe), iodine (I), magnesium (Mg), selenium (Se), zinc (Zn) and phytic acid (PA) supplies per Adult Male Equivalent (AME) in rural households by household expenditure quintile (1 = poorest, 5 = highest). 'n' is the number of households. Iodine supply excludes salt

92 % of households in quintile 1 had inadequate energy supply to meet sum of member DERs compared to 28 % in quintile 5 (Additional file 1: Table S20).

The food groups 'Cereals', 'Legumes' and 'Roots and tubers' contributed 61, 10 and 9 %, respectively, of mean national dietary energy supply; other food groups contributed <6 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26).

Calcium

Nationally, median Ca supplies *per capita* and *per* AME were 602 and 704 mg d^{-1}, respectively, but were lower in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 750 mg d^{-1} [39]. Median household supplies of Ca as a proportion of sum of member EARs and RNIs were 1.0 and 0.9, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 49 and 57 % of households did not consume enough Ca to meet the sum of member EARs and RNIs, respectively (Table 3; Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median Ca supply *per* AME ranged from 210 mg d^{-1} in Kavukuku ($n = 64$) to 1896 mg d^{-1} in Chiweta ($n = 16$; Additional file 1: Table S22 and Additional file 1: Table S23).

Household dietary Ca supply varied due to household socioeconomic characteristics, soil type and proximity to Lake Malawi (Figs. 3 and 4). For example, 83 % of households in quintile 1 had inadequate Ca supply to meet sum of member EARs compared to 22 % in quintile 5 (Additional file 1: Table S20). Nationally, median Ca supply as a proportion of energy supply was 291 mg 1000 $kcal^{-1}$ and was 222 and 360 mg 1000 $kcal^{-1}$ in quintiles 1 and 5, respectively, and 368 and 274 mg 1000 $kcal^{-1}$ in urban and rural households, respectively (Additional file 1: Table S27).

The food groups 'Fish' and 'Vegetables' contributed 62 and 15 %, respectively, of national annual dietary Ca supply and adequacy of Ca supply was related to consumption of fish; other food groups contributed <7 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26). Dairy products are an important source of dietary Ca in many countries, e.g. 36 % of dietary Ca intake in the UK [46], but in the present study they contributed <2 % of national Ca supply. Median household supplies of Ca as a proportion of sum of member EARs were 1.32 and

Table 2 Nutrient supplies in urban households

Expenditure quintile	*n*	Median dietary supply									
		Energy	Ca	Cu	Fe	I	Mg	Se	Zn	PA	PA:Zn
		kcal		mg		μg	mg	μg	mg		Molar ratio
						AME^{-1} d^{-1}					
1	57	1343	425	1.09	10.4	7.0	291	15.7	6.1	1951	32.2
2	135	1784	645	1.49	12.1	11.5	327	19.7	7.7	1772	29.0
3	228	2123	751	1.60	14.4	14.2	344	21.3	8.2	1814	25.4
4	442	2404	860	1.91	16.1	18.1	390	26.1	9.6	2049	23.5
5	1311	3325	1257	2.95	21.5	31.3	540	39.4	13.9	2416	18.4
ALL	2173	2830	1021	2.30	18.2	24.1	465	32.2	11.5	2261	20.4

Median energy, calcium (Ca), copper (Cu), iron (Fe), iodine (I), magnesium (Mg), selenium (Se), zinc (Zn) and phytic acid (PA) supplies per Adult Male Equivalent (AME) in urban households by household expenditure quintile (1 = poorest, 5 = highest). 'n' is the number of households. Iodine supply excludes salt

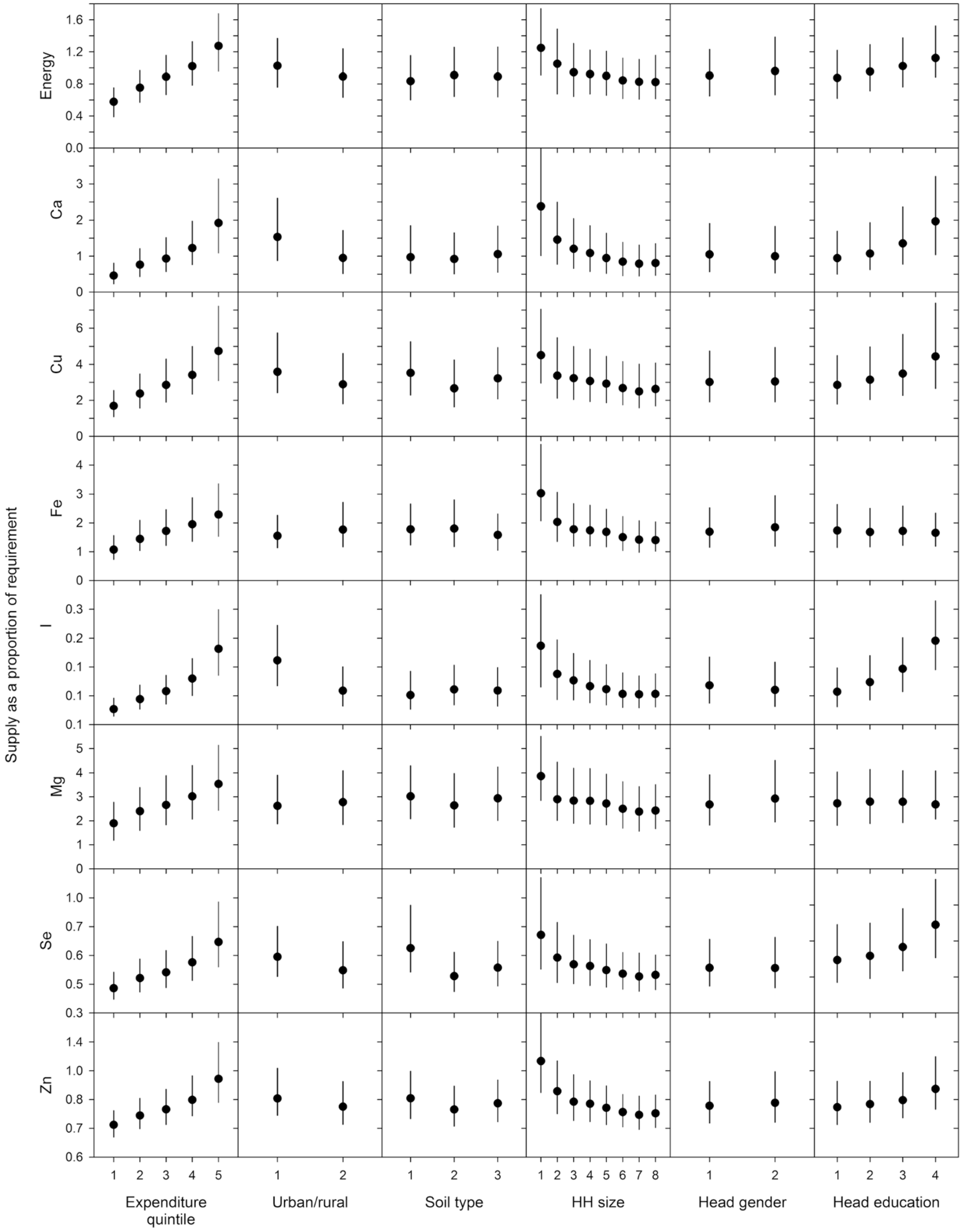

Fig. 3 (See legend on next page.)

(See figure on previous page.)

Fig. 3 Adequacy of household nutrient supplies by household characteristics. Household energy, calcium (Ca), copper (Cu), iron (Fe), iodine (I), magnesium (Mg), selenium (Se) and zinc (Zn) supplies divided by sum of member requirements. Supply of I excludes salt. Households are grouped by expenditure quintile (1 = poorest to 5 = wealthiest), urban/rural location, soil type (1 = calcareous, 2 = non-calcareous, 3 = undifferentiated), household size (capped at 8), head gender (1 = male, 2 = female) and head education (1 = none, 2 = primary school leaving certificate, 3 = junior certificate of education, 4 = Malawi school certificate of education). Points represent median values, bars represent first and third quartiles, respectively

0.37 in households that did and did not consume fish, respectively. Dietary supplies of Ca were greater in lakeshore EPAs (Fig. 4) due to greater consumption of fish.

Copper

Nationally, median Cu supplies *per capita* and *per* AME were 1.62 and 1.88 mg d^{-1}, respectively, but were lower in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 0.9 mg d^{-1} [40]. Median household supplies of Cu as a proportion of sum of member EARs and RNIs were 3.0 and 2.5, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 6 and 9 % of households were not consuming enough Cu to meet the sum of member EARs and RNIs, respectively (Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median Cu supply *per* AME ranged from 0.72 mg d^{-1} in Kalumba ($n = 16$) to 4.68 mg d^{-1} in Mbulumbuzi ($n = 47$; Additional file 1: Table S22 and Additional file 1: Table S23).

Household dietary Cu supply was related to household socioeconomic characteristics (Fig. 3). For example, 22 % of households in quintile 1 had inadequate Cu supply to meet sum of member EARs compared to <1 % in quintile 5 (Additional file 1: Table S20). Nationally, median Cu supply as a proportion of energy was 0.79 mg 1000 $kcal^{-1}$ and was 0.74 and 0.87 mg 1000 $kcal^{-1}$ in quintiles 1 and 5, respectively (Additional file 1: Table S27).

The food groups 'Cereals', 'Legumes' and 'Fish' contributed 24, 23 and 22 %, respectively, of national annual dietary Cu supply; other food groups contributed <11 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26).

Iron

Nationally, median Fe supplies *per capita* and *per* AME were 16.6 and 19.2 mg d^{-1}, respectively, and were greater in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 13.7 mg d^{-1} but 49.4 mg d^{-1} for a pregnant woman [39]. Median household supplies of Fe as a proportion of sum of member EARs and RNIs were 1.72 and 1.43, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 18 and 27 % of households were not consuming enough Fe to meet the sum of member EARs and RNIs, respectively (Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median Fe supply *per* AME ranged from 7.9 mg d^{-1} in Kalumba ($n = 16$) to 34.1 mg d^{-1} in Mbulumbuzi ($n = 47$; Additional file 1: Table S22 and Additional file 1: Table S23). Nationally, 8 % of households had Fe supplies *per* AME >45 mg d^{-1}, the tolerable upper level of intake for adults [39].

Household dietary Fe supply was related to socioeconomic characteristics (Fig. 3). For example, 45 % of households in quintile 1 had inadequate Fe supply to meet sum of member EARs compared to 7 % in quintile 5 (Additional file 1: Table S20). Adequacy of household Fe supply varied seasonally according to Fe supply from vegetables, consumption of which peak in February-April (Fig. 2). Nationally, median Fe supply as a proportion of energy was 7.5 mg 1000 $kcal^{-1}$ and showed little variation between expenditure quintiles, but was greater in rural than urban households, i.e. 7.9 *versus* 6.4 mg 1000 $kcal^{-1}$ (Additional file 1: Table S27).

The food groups 'Cereals', 'Vegetables', 'Legumes' and 'Fish' contributed 34, 29, 12 and 11 %, respectively, of national annual dietary Fe supply. Other food groups contributed <5 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26).

Iodine

The majority of dietary I supply for most households is likely to come from salt due to mandatory iodisation at >15 mg kg^{-1} in Malawi. Data for household salt consumption were captured in the IHS3 but the concentration of I in salt is highly variable depending on level of iodisation at manufacture and losses due to improper storage [47]. Not including salt, median supplies *per capita* and *per* AME were 12.2 and 14.3 μg d^{-1}, respectively, but were lower in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 150 μg d^{-1} [39]. Median household supplies of I as a proportion of sum of member EARs and RNIs were 0.13 and 0.11, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 99 and 100 % of households were not consuming enough I through food items other than salt to meet the sum of member EARs and RNIs, respectively (Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median I supply *per* AME ranged from 5.1 μg d^{-1} in Dolo ($n = 63$) to 28.1 μg d^{-1} in Ntonda ($n = 431$; Additional file 1: Table S22 and Additional file 1: Table S23).

Table 3 National prevalence of inadequate dietary calcium (Ca), iron (Fe), selenium (Se) or zinc (Zn) supplies at household level

Urban/rural	Expenditure quintile	Soil type	*n*	Ca	Fe	Se	Zn
				%			
ALL	ALL	ALL	12117	49	18	74	57
ALL	1	ALL	1840	83	45	92	88
	2		2173	65	23	86	73
	3		2331	54	14	81	64
	4		2582	38	10	72	50
	5		3191	22	7	51	28
Urban	ALL	3	2173	30	18	66	49
	1		57	72	58	93	84
	2		135	50	39	90	75
	3		228	45	30	87	76
	4		442	36	19	78	62
	5		1311	22	11	54	35
Rural	ALL	ALL	9944	52	18	75	59
	1		1783	83	45	92	88
	2		2038	66	22	86	73
	3		2103	55	12	81	62
	4		2140	39	8	70	48
	5		1880	22	4	49	23
	ALL	1	2047	51	16	55	49
		2	6523	54	18	82	62
		3	1374	48	21	75	56
	1	1	493	82	37	79	81
	2		450	62	16	67	57
	3		385	51	8	55	44
	4		379	28	5	37	30
	5		340	18	4	25	16
	1	2	1000	85	48	97	92
	2		1297	69	22	93	79
	3		1424	58	13	88	69
	4		1467	43	9	80	54
	5		1335	23	4	55	26
	1	3	290	80	48	93	86
	2		291	61	27	85	72
	3		294	40	14	78	54
	4		294	31	8	67	40
	5		205	18	4	43	18

Percentage of households with dietary supply less than sum of household member Estimated Average Requirements, by urban/rural location, expenditure quintile (1 = poorest, 5 = highest) and soil type (1 = calcareous; 2 = non-calcareous; 3 = undifferentiated)

Nationally, median consumption of salt *per* AME was 11.2 g d^{-1}, was greater in rural than urban households (median 11.4 *versus* 10.3 g d^{-1}) and was related to expenditure quintile, with median consumption of 8.5, 10.0, 10.9, 12.4 and 15.4 g d^{-1} for quintiles 1 to 5, respectively. If it is assumed that all salt was iodised at 15 mg kg^{-1} and consumed, then 17 and 27 % of households would not be consuming enough I to meet the sum of member EARs and RNIs, respectively. Further salt consumption and iodisation scenarios are explored in the Discussion section. Median I supply from foods other than salt as a proportion of energy was 5.80 μg 1000 $kcal^{-1}$ and was 3.7 and 8.1 μg 1000 $kcal^{-1}$ in quintiles 1 and 5, respectively (Additional file 1: Table S27). The food group 'Fish' supplied 49 % of I from non-salt food sources (Additional file 1: Table S26).

Magnesium

Nationally, median Mg supplies *per capita* and *per* AME were 401 and 468 mg d^{-1}, respectively, and were similar in rural and urban areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 260 mg d^{-1} [39]. Median household supplies of Mg as a proportion of sum of member EARs and RNIs were 2.74 and 2.28, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 5 and 9 % of households were not consuming enough Mg to meet the sum of member EARs and RNIs, respectively (Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median Mg supply *per* AME ranged from 182 mg d^{-1} in Kalumba ($n = 16$) to 827 mg d^{-1} in Masambanjati ($n = 32$; Additional file 1: Table S22 and Additional file 1: Table S23).

Household dietary Mg supply was related to household socioeconomic characteristics (Fig. 3). For example, 17 % of households in quintile 1 had inadequate Mg supply to meet sum of member EARs compared to 1 % in quintile 5 (Additional file 1: Table S20). Nationally, median Mg supply as a proportion of energy was 207 mg 1000 $kcal^{-1}$ and was 242 and 186 mg 1000 $kcal^{-1}$ in quintiles 1 and 5, respectively (Additional file 1: Table S27).

The food groups 'Cereals', 'Legumes' and 'Vegetables' contributed 45, 19 and 11 %, respectively, of national annual dietary Mg supply; other food groups contributed <10 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26).

Selenium

Nationally, median Se supplies *per capita* and *per* AME were 21.4 and 25.0 μg d^{-1}, respectively, but were lower in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 55 μg d^{-1} [41]. Median household supplies of Se as a proportion of sum of member EARs and RNIs were 0.63 and 0.52, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 74 and 81 % of households were not

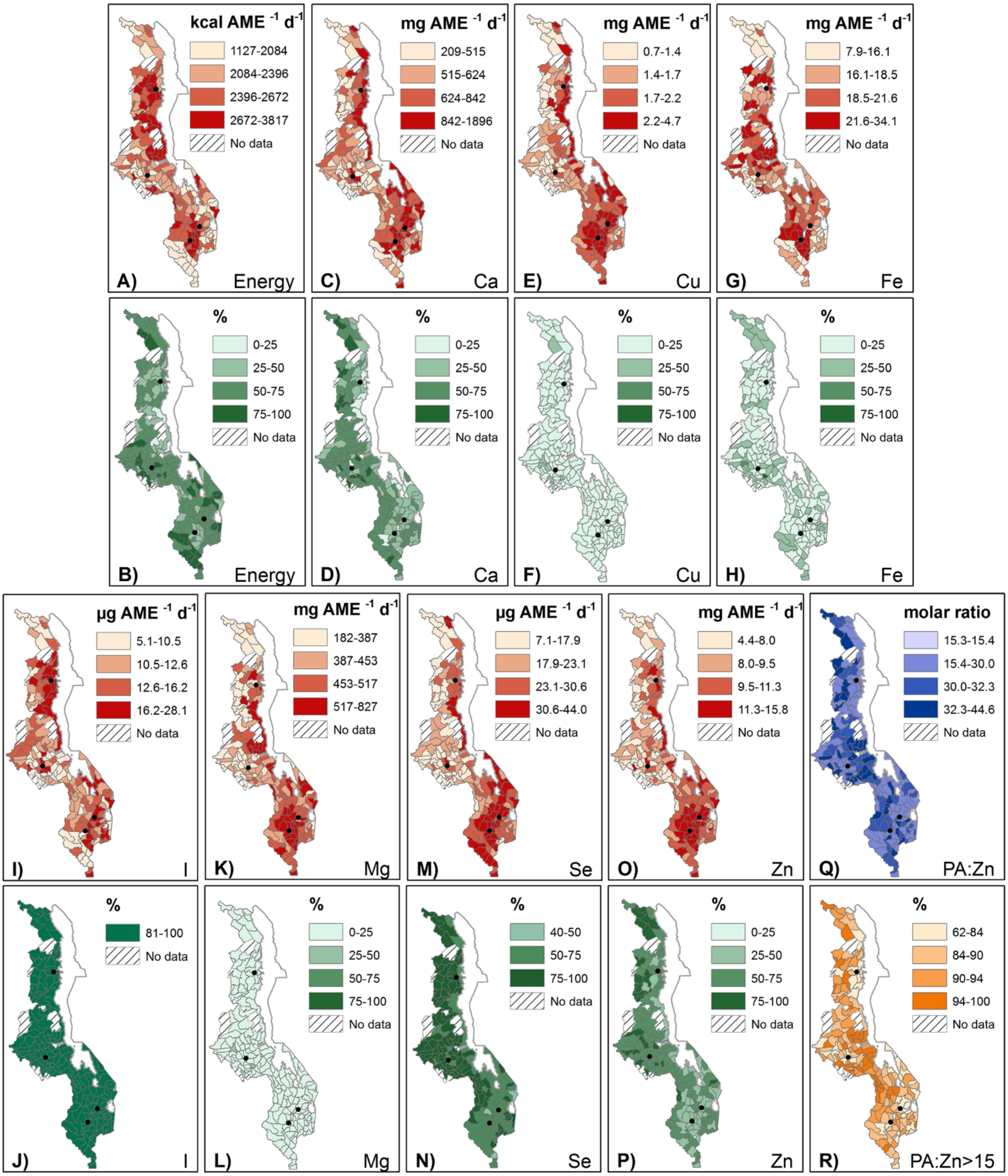

Fig. 4 Dietary nutrient supplies and deficiencies by Extension Planning Area (EPA). Median household nutrient supplies (mg AME^{-1} d^{-1}) and proportion (%) of households with inadequate dietary supplies to meet sum of member Estimated Average Requirements: **a**, **b** energy, **c**, **d** calcium (Ca), **e**, **f** copper (Cu), **g**, **h** iron (Fe), **i**, **j** iodine (I), **k**, **l** magnesium (Mg), **m**, **n** selenium (Se), **o**, **p** zinc (Zn), **q** median household phytic acid (PA):Zn molar ratio, and **r** proportion of households with PA:Zn molar ratio >15. Underlying data are presented in Additional file 1: Table S21, Additional file 1: Table S22, Additional file 1: Table S29 and Additional file 1: Table S30. Iodine supply excludes salt. EPA boundaries from the Ministry of Agriculture

consuming enough Se to meet the sum of member EARs and RNIs, respectively (Fig. 5; Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median Se supply *per* AME ranged from 7.1 μg d^{-1} in Kavukuku (*n* = 64) to 43.9 μg d^{-1} in Nampeya (*n* = 47; Additional file 1: Table S22 and Additional file 1: Table S23).

Household dietary Se supply varied due to household socioeconomic characteristics and soil type (Figs. 3, 4 and 5). For example, 55 and 82 % of households on calcareous and non-calcareous soils, respectively, had inadequate Se supply to meet sum of member EARs and there was a 92 and 51 % prevalence of inadequate supplies among households from expenditure quintiles 1 and 5, respectively (Additional file 1: Table S20). Nationally, median Se supply as a proportion of energy was 10.2 μg 1000 $kcal^{-1}$ and was 9.0 and 11.7 μg 1000 $kcal^{-1}$ in quintiles 1 and 5, respectively, and 15.6 and 8.4 μg 1000 $kcal^{-1}$ in rural households on calcareous and non-calcareous soils, respectively (Additional file 1: Table S27).

The food groups 'Fish', 'Cereals' and 'Legumes' contributed 47, 21 and 13 %, respectively, of national annual dietary Se supply; other food groups contributed <9 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26). 'Cereals' contributed 28 and 19 % of dietary Se supply among rural households on calcareous and non-calcareous soils, respectively (Additional file 1: Table S26).

Zinc

Nationally, median Zn supplies *per capita* and *per* AME were 8.5 and 10.0 mg d^{-1}, respectively, but were lower in rural areas (Tables 1 and 2; Additional file 1: Table S16 and Additional file 1: Table S17). For comparison, the RNI for an adult man is 14 mg d^{-1} [39]. Median household supplies of Zn as a proportion of sum of member EARs and RNIs were 0.90 and 0.75, respectively (Additional file 1: Table S18 and Additional file 1: Table S19). Overall, 57 and 68 % of households were not consuming enough Zn to meet the sum of member EARs and RNIs, respectively (Additional file 1: Table S20 and Additional file 1: Table S21). Among EPAs, median Zn supply *per* AME ranged from 4.4 mg d^{-1} in

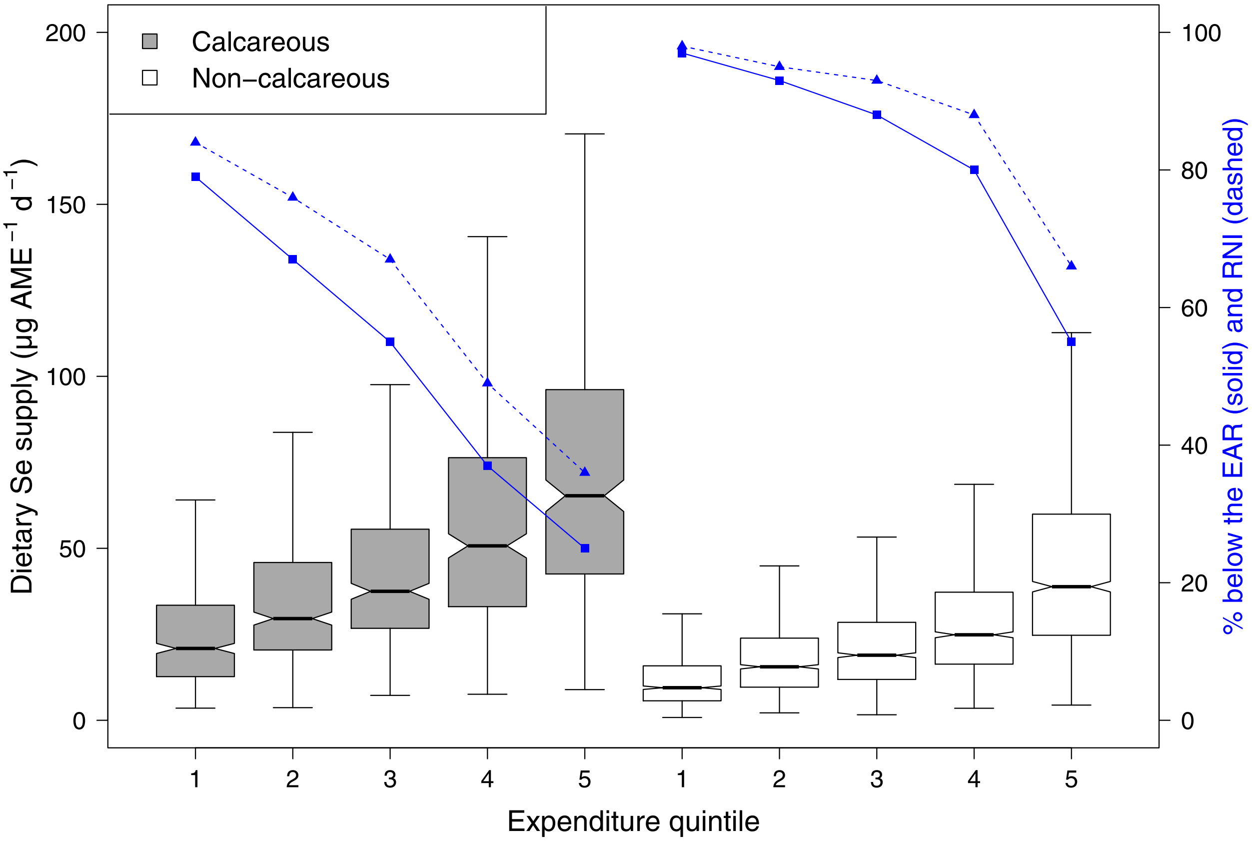

Fig. 5 Distribution of rural household dietary selenium (Se) supplies and prevalence of inadequacies. Household dietary supplies are quantified *per* Adult Male Equivalent (AME). Prevalence of inadequate supplies are quantified as percent (%) of households with dietary Se supply less than sum of household member Estimated Average Requirements (EARs) and Reference Nutrient Intakes (RNIs); the EAR and RNI for an adult male are 45 and 55 μg d^{-1} [41]. Households are aggregated by soil type (calcareous = dark grey, non-calcareous = white) and expenditure quintile (1 = poorest, 5 = wealthiest). Boxes are median, Q1 and Q3, notches estimate the median's 95% confidence interval, whiskers extend 1.5x Q1 and Q3

Kalumba ($n = 16$) to 15.8 mg d^{-1} in Masambanjati ($n = 32$; Additional file 1: Table S22 and Additional file 1: Table S23).

Household dietary Zn supply varied spatially and was related to household socioeconomic characteristics (Figs. 3 and 4). For example, 88 % of households in quintile 1 had inadequate Zn supply to meet sum of member EARs compared to 28 % in quintile 5 (Additional file 1: Table S20). Nationally, median Zn supply as a proportion of energy was 4.2 mg 1000 $kcal^{-1}$ and was 5.4 and 4.0 mg 1000 $kcal^{-1}$ for households on calcareous and non-calcareous soils, respectively (Additional file 1: Table S27).

The food groups 'Cereals', 'Fish' and 'Legumes' contributed 41, 26 and 13 %, respectively, of national annual dietary Zn supply; other food groups contributed <7 % each (Additional file 1: Table S24, Additional file 1: Table S25 and Additional file 1: Table S26). Dietary supplies of Zn were greater in lakeshore EPAs due to greater consumption of fish (Fig. 4).

Phytic acid

Nationally, median dietary PA supplies *per capita* and *per* AME were 2280 and 2460 mg d^{-1}, respectively and median dietary PA:Zn molar ratio was 29 (Additional file 1: Table S16, Additional file 1: Table S17 and Additional file 1: Table S18). Overall, 87 % of households had dietary PA:Zn molar ratios >15.0 (Additional file 1: Table S20). Household dietary PA:Zn molar ratio was related to household socioeconomic characteristics. For example, median PA:Zn molar ratios were 20 and 30 in urban and rural households, respectively, and 35 and 22 in expenditure quintiles 1 and 5, respectively (Tables 1 and 2; Additional file 1: Table S18). Among EPAs, median PA supply *per* AME ranged from 981 mg d^{-1} in Nthondo ($n = 16$) to 4580 mg d^{-1} in Masambanjati ($n = 32$) while the median PA:Zn molar ratio ranged from 15 in Chiweta ($n = 16$) to 45 in Nakachoka ($n = 32$; Additional file 1: Table S22 and Additional file 1: Table S23).

The food groups 'Cereals' and 'Legumes' contributed 65 and 28 %, respectively, of dietary PA supply (Additional file 1: Table S26) and PA:Zn molar ratio was greatest (therefore lowest bioavailability of Zn) during the harvest season of May-August (Fig. 6), mainly due to greater consumption of legumes.

Discussion

Comparison with previous estimates of dietary nutrient supplies

The present study estimated dietary mineral element supplies at household levels in Malawi by combining food supply data captured in the IHS3 [28] with locally-generated food crop composition data [18, 48]. This compares with previous efforts to quantify the prevalence of inadequate element intakes at wide scales in Malawi on the basis of national-level food supply data captured in Food Balance Sheets (FBSs) published by the FAO matched with published or local composition data [5, 9, 10, 13, 18, 22, 27, 49, 50] or food consumption from household surveys matched with published composition data [29, 30].

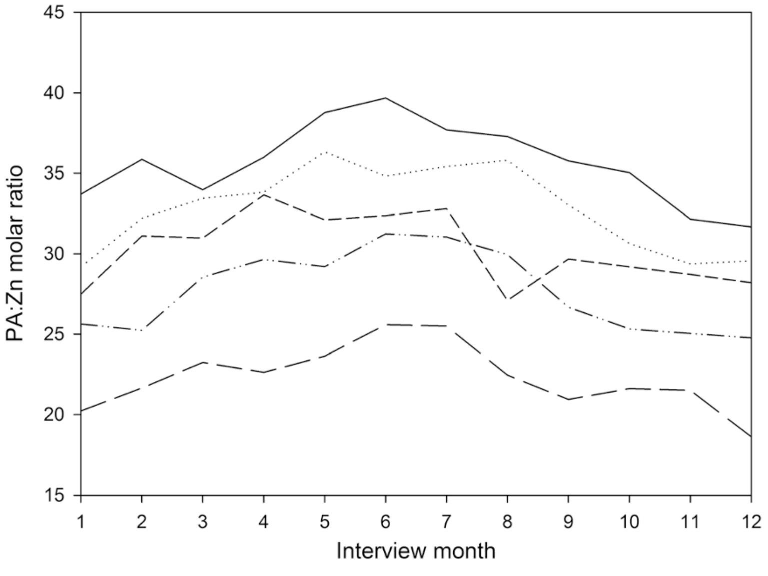

Fig. 6 Seasonal phytic acid:zinc (PA:Zn) molar ratio in the diet. Median household dietary PA:Zn molar ratio by interview month. A diet with PA:Zn molar ratio >15 is likely to supply inadequate bioavailable Zn [17]. Quintiles are 1 (poorest, continuous), 2 (dot), 3 (short-dash), 4 (dash-dot-dot) and 5 (wealthiest, long-dash)

Where appropriate, the estimated prevalence of inadequate dietary element intakes are discussed in relation to the 2010 Global Burden of Disease study, coordinated by the Institute for Health Metrics and Evaluation (IHME), in which all-cause mortality and morbidity were assigned to 67 underlying risk factors [7, 51, 52]. The Global Burden of Disease study used Disability-Adjusted Life-Years (DALYs) as a common currency to measure disease burden. A DALY is equivalent to a lost year of 'healthy life' and is the sum of years of life lost due to premature mortality and years of life lost due to a disability [53].

Energy

Previously, Joy et al. [9] estimated mean national dietary supply of energy in Malawi to be 2757 kcal *capita*$^{-1}$ d^{-1} based on FBS data while Verduzco-Gallo et al. [30] reported mean consumption of 2305 kcal *capita*$^{-1}$ d^{-1} based on the IHS3. This compares to estimated mean and median consumption of 2381 and 2115 kcal *capita*$^{-1}$ d^{-1} in the present study. Verduzco-Gallo et al. [30] reported mean consumption of 1232 kcal *capita*$^{-1}$ d^{-1} and a 37 % prevalence of inadequate energy intakes for rural households. This compares to mean and median consumption of 1258 and 1208 kcal *capita*$^{-1}$ d^{-1} and an estimated 60 % prevalence of inadequate energy intakes for rural households in the present study. The greater estimated prevalence of inadequate energy intakes in the present study is due to different assumptions regarding energy requirements: Verduzco-Gallo et al. defined 'minimum calorie requirements' based on a light physical activity level (PAL) and low body mass index [29, 38]. Thus, an adult male would be calorie deficient at intakes <2400 kcal d^{-1} compared to <3300 kcal d^{-1} in the present study where adults were assumed to lead a moderately active to active lifestyle with PAL of 1.9, consistent with expected activity given that 85 % of the population are involved in agriculture, predominantly non-mechanised [31, 38]. Inadequate energy intakes are likely to be widespread among rural households, particularly during months of field preparation and weeding when PALs of 2.25 are estimated with requirements of 3850 kcal d^{-1} for men aged 18–30 [38].

Household spending data in the IHS3 support the finding of prevalent dietary energy insufficiency in poor households. Pauw et al. [54] reported that, as the wealth of poorest rural households increased, the share of income spent on food also increased. This appears contrary to Engel's law which states that the share of household budget spent on food is inversely related to household real income [55], a remarkably consistent observation across space and time [56]. The apparent contradiction could be explained if the poorest households are calorie insufficient and additional income is used to purchase essential food.

Calcium

Previously, Broadley et al. [13], Joy et al. [9] and Kumssa et al. [10] estimated mean national dietary supplies of Ca to be 306, 592 and 259 mg *capita*$^{-1}$ d^{-1} based on FBS supply and published composition data. Subsequently, Joy et al. [18] estimated mean national dietary supplies of Ca to be 430 and 368 mg *capita*$^{-1}$ d^{-1} on calcareous and non-calcareous soils based on FBS supply and local composition data. In the present study, estimated national mean and median supplies of Ca were 924 and 602 mg *capita*$^{-1}$ d^{-1}, with median supplies of 578 and 537 mg *capita*$^{-1}$ d^{-1} for rural households on calcareous and non-calcareous soils, respectively (Additional file 1: Table S16). The main reason for the greater estimated Ca supply in the present study is fish consumption. Mean national consumption of the food item 'Freshwater Fish' is reported in the 2009 FBS as 13 g *capita*$^{-1}$ d^{-1} on a fresh-weight (FW) basis [57] which is equivalent to <3 g DW [18]. In contrast, estimated mean (± standard deviation, SD) consumption of fish in the present study is 19 ± 36 g *capita*$^{-1}$ d^{-1} DW.

Despite the greater estimated consumption of fish, estimated prevalence of inadequate Ca intakes remains high with 49 % of all households consuming less than sum of member EARs. This is due to the high inter-household variation in Ca supplies related to spatial and socio-economic factors, and low contribution of other food groups to dietary Ca supply, especially dairy products.

In the IHME Global Burden of Disease study [7], the annual disease burden in Malawi due to diets low in Ca was estimated to be 720 DALYs (100 k population)$^{-1}$ [51]. However, DALYs attributable to low dietary Ca were based only on the increased risk of prostate and colorectal cancers and not other diseases associated with inadequate dietary Ca such as rickets and osteoporosis [39], and the study is likely to underestimate the burden.

Copper

Previously, Joy et al. [9] estimated mean national dietary supply of Cu to be 3.0 mg *capita*$^{-1}$ d^{-1} based on FBS data and regional or international composition data, and subsequently, using local composition data, 2.6 and 2.0 mg *capita*$^{-1}$ d^{-1} on calcareous and non-calcareous soils, respectively [18]. In the present study, estimated median dietary Cu supply was 1.6 mg *capita*$^{-1}$ d^{-1} nationally, and 1.9 and 1.4 mg *capita*$^{-1}$ d^{-1} for rural households on calcareous and non-calcareous soils, respectively (Additional file 1: Table S16). Removal of the husk and endosperm during milling of maize grain reduces the concentration of Cu by ~80 % (Additional file 1: Table S6). These losses were accounted for in the present study, resulting in lower estimated Cu supplies.

Still, the estimated prevalence of inadequate Cu intakes is low which is consistent with previous findings [9].

Iron

Previously, Joy et al. [9] estimated mean national dietary supply of Fe to be 29.1 mg *capita*$^{-1}$ d^{-1} based on FBS data and regional or international composition data, and subsequently, using local composition data, 23.2 and 18.4 mg *capita*$^{-1}$ d^{-1} on calcareous and non-calcareous soils, respectively [18]. Verduzco-Gallo et al. [30] reported mean national dietary supplies of Fe to be 19.5 mg *capita*$^{-1}$ d^{-1} based on household survey data and regional or international composition data. In the present study, estimated national mean and median dietary Fe supplies were 20.4 and 16.6 mg *capita*$^{-1}$ d^{-1}.

The low estimated prevalence of inadequate Fe intakes is consistent with previous estimates based on FBS data [9, 18] and duplicate diet composites [23]. However, household consumption and requirement data aggregated at household level will underestimate the prevalence of Fe deficiency among adolescent and pregnant women because of their greater Fe requirements [39]. Verduzco-Gallo et al. [30] report similar median Fe supplies of 19.5 mg *capita*$^{-1}$ d^{-1}, but a 49 % prevalence of inadequate intakes on the basis of food supply data from IHS3 and this might be due to different assumptions of Fe requirement or bioavailability. Nationally, the majority of dietary Fe supply came from non-haeme sources with only 14 % from animal products including fish (Additional file 1: Table S26). Iron requirements were calculated assuming a low bioavilability (i.e. 10 %) [39]. However, a large proportion of Fe intake is likely to be attributable to inadvertent consumption of soil dust present on grains and leafy vegetables [18, 25], the bioavailability of which has not been adequately established.

Disease burden due to Fe deficiency was quantified for Malawi and other nations in the IHME Global Burden of Disease study on the basis of anaemia prevalence [7]. Thus, Fe deficiency was estimated to cause 1553 DALYs (100 k population)$^{-1}$ [51]. However, further research is required to determine whether Fe intakes are actually inadequate or whether other strategies to reduce Fe deficiency are required, for example focusing on diseases such as malaria or gut parasites that can reduce absorption and increase losses of Fe [58–60].

Iodine

Estimated dietary supplies of I are limited in their relevance and accuracy without data on I intakes from salt. However, it is clear that supply of I from foods other than salt is inadequate to meet the requirements of almost 100 % of households, with mean and median supplies of 17.7 and 12.2 μg *capita*$^{-1}$ d^{-1} (Additional file 1: Table S16). The estimated proportion of households consuming adequately iodised salt in 2010 was 62 % [61], suggesting that up to 38 % of households are likely to be consuming inadequate I to meet requirements. Estimated supplies of I from foods other than salt is much lower than the previous estimate based on FBS data and regional or international composition data of 36.2 μg *capita*$^{-1}$ d^{-1} from food sources other than salt [9] due to the use of locally generated food composition data in the present study. Scenarios of salt iodisation and consumption are explored in the section 'Interventions to improve dietary micronutrient supplies'.

The national I status of Malawi was recently defined as 'adequate' on the basis of urinary I concentrations (UIC) in school-aged children [62]. Also, the disease burden due to I deficiency has been quantified for Malawi and other nations in the IHME Global Burden of Disease study on the basis of goitre prevalence [52, 63]. Thus, a 28 % prevalence of I deficiency in Malawi was estimated to cause 82 DALYs (100 k population)$^{-1}$ [51]. However, this estimate is from a survey of goitre prevalence in school-aged children in seven districts of Malawi with endemic goitre conducted in 1996 [63, 64]; the study design bias and the use of goitre prevalence rather than UIC data is likely to over-estimate the burden of disease attributable to I deficiency, while the finding is likely to be out-dated considering that salt iodisation was only introduced as national policy in Malawi in 1995 [65, 66].

Magnesium

Previously, Broadley et al. [13], Kumssa et al. [50] and Joy et al. [9, 49] estimated mean national dietary supply of Mg to be 530–789 mg *capita*$^{-1}$ d^{-1}, based on FBS data and regional or international composition data, and subsequently, using local composition data, 712 and 632 mg *capita*$^{-1}$ d^{-1} on calcareous and non-calcareous soils, respectively [18]. Estimated supplies of Mg are lower in the present study, with national mean and median of 479 and 401 mg *capita*$^{-1}$ d^{-1}. Removal of the husk and endosperm during milling of maize grain reduces the concentration of Mg by ~80 % (Additional file 1: Table S6). These losses were accounted for in the present study but not in previous studies which used whole grain composition data. Despite lower estimated Mg supplies, the estimated prevalence of inadequate Mg supplies remains low which is consistent with previous findings [9, 13, 49], although deficiency may occur due to high dietary PA supplies [50].

Selenium

Previously, Joy et al. [9] estimated mean national dietary supply of Se to be 34 μg *capita*$^{-1}$ d^{-1} based on FBS data and regional or international composition data, and subsequently, using local composition data, 41 and 19 μg *capita*$^{-1}$ d^{-1} on calcareous and non-calcareous soils, respectively [18]. Similar estimates were found in the present study, with median Se supplies of 31 and 17 μg *capita* d^{-1} for rural households on calcareous and non-calcareous soils, respectively. Median supplies for households in expenditure quintile 5 were approximately 3–4 fold greater than those in expenditure quintile 1 on both soil types.

Using local composition data and 24 h dietary recall, Eick et al. [21] estimated mean dietary supply of Se to be 44 and 46 μg $capita^{-1}$ d^{-1} in Mangochi District among tuberculosis patients ($n = 40$) and controls ($n = 40$). In the present study, estimated median (Q1, Q3) Se supplies of rural households in Mangochi District were 39 (22, 71) μg $capita^{-1}$ d^{-1} on calcareous soils ($n = 80$) and 30 (19, 48) μg $capita^{-1}$ d^{-1} on non-calcareous soils ($n = 206$).

Hurst et al. [22] estimated median dietary Se supplies of adult women in villages on calcareous Eutric Vertisols ($n = 55$) and non-calcareous ($n = 58$) soils to be 55 and 7 μg $capita^{-1}$ d^{-1}, respectively, based on mineral analyses of weighed duplicate diet composites. In the present study, median Se consumption *per* AME was 36.4 and 20.4 μg d^{-1} on calcareous and non-calcareous soils, respectively. The greater difference in dietary Se supplies between soil types found by Hurst et al. [22] is likely to be due to the subset of calcareous and non-calcareous soils that were sampled. For example, the median Se concentration of maize grain from Eutric Vertisols was >0.3 mg kg^{-1} [22, 27], approximately 10-fold greater than the median Se concentration of maize grain samples collected nationally from areas of calcareous soils used in the present study (median = 0.03 mg kg^{-1}, $n = 50$, Additional file 1: Table S5 and Additional file 1: Table S7). Eutric Vertisols, which cover ~0.5 % of the land area of Malawi, are a subset of the calcareous soil grouping and might provide greater concentrations of phyto-available Se than other calcareous soils. The non-calcareous villages selected by Hurst et al. [22] were not in a lakeshore EPA and low fish consumption may contribute to these extremely low Se supplies.

Zinc

Previously, Wessells and Brown [5] estimated mean national dietary Zn supply to be 8.3 mg $capita^{-1}$ d^{-1} based on 2003–2007 FBS data and regional or international composition data while Joy et al. [9] used 2009 FBS data to estimate 11.8 mg $capita^{-1}$ d^{-1}, and subsequently, using locally-generated composition data, 12.0 and 10.1 mg $capita^{-1}$ d^{-1} on calcareous and non-calcareous soils, respectively [18]. Kumssa et al. [10] estimated mean Zn supply for Malawi to be 14.1 mg $capita^{-1}$ d^{-1} on the basis of 2011 FBS data and US food composition data. Verduzco-Gallo et al. [30] reported mean national dietary supplies of Zn to be 10.8 mg $capita^{-1}$ d^{-1} based on household survey data and regional or international composition data. Similar estimates were found in the present study, with mean and median Zn supplies of 10.4 and 8.5 mg $capita^{-1}$ d^{-1} for all households and a median of 9.5 and 7.8 mg $capita^{-1}$ d^{-1} for rural households on calcareous and non-calcareous soils, respectively. However, Siyame et al. [23] reported much lower dietary Zn supplies on the basis of duplicate diet composites, i.e. 6.4 and 4.8 mg $capita^{-1}$ d^{-1} for women living on calcareous and non-calcareous soils, respectively. The villages studied by Siyame et al. [23] were not in lakeshore EPAs and low fish consumption might contribute to the very low Zn supplies in both the calcareous and non-calcareous areas.

The estimated prevalence of inadequate dietary Zn supplies in the current study is 57 % nationally, and 49 and 62 % for rural households on calcareous and non-calcareous soils, respectively. A high prevalence of inadequate Zn supplies has previously been estimated using FBS data, i.e. 41 % nationally [5], 64 % nationally [9], and 31 and 57 % on calcareous and non-calcareous soils [18]; and IHS3 data, i.e. 54 % for rural households [30].

Disease burden due to Zn deficiency was quantified for Malawi and other nations in the IHME Global Burden of Disease study on the basis of dietary Zn supplies [5, 7]. Thus, a 41 % national prevalence of inadequate dietary Zn supplies was estimated to cause 791 DALYs $(100\ \text{k population})^{-1}$ [51]. By extension, disease burden is likely to be >1000 DALYs $(100\ \text{k population})^{-1}$ for rural households on non-calcareous soils where the prevalence of inadequate dietary Zn supplies was 62 % (Additional file 1: Table S20).

Phytate

Previously, Wessells and Brown [5] estimated mean national dietary PA supply to be 2584 mg $capita^{-1}$ d^{-1} with a PA:Zn molar ratio of 31 based on 2003–2007 FBS data and regional or international composition data while Joy et al. [9] used 2009 FBS data to estimate mean supply of 4510 mg $capita^{-1}$ d^{-1} and a PA:Zn of 38. Kumssa et al. [10] estimated mean PA supply of 3969 mg $capita^{-1}$ d^{-1} and a PA:Zn molar ratio of 28 based on 2011 FBS data. The present study found mean and median PA supplies of 2795 and 2281 mg $capita^{-1}$ d^{-1} with a mean PA:Zn molar ratio of 29. These estimates are closer to the Wessells and Brown [5] values owing to the adjustment in PA concentrations made due to milling.

The combination of a high prevalence of inadequate dietary Zn supplies and PA:Zn molar ratios >15 suggest that Zn deficiency is likely to be widespread in Malawi. This is consistent with anthropometric data, e.g. Gibson and Huddle [20] reported 36 and 46 % prevalence of low plasma and hair Zn concentrations, respectively, among pregnant women in a rural area, and Siyame et al. [23]

reported >90 % prevalence of Zn deficiency defined as plasma Zn <10.7 μmol L^{-1} among women living in rural areas on calcareous and non-calcareous soils. High dietary PA supplies might also increase the risks of Ca and Mg deficiencies due to inhibition of absorption [67, 68].

Inadequate supplies of multiple elements

Nationally, the prevalence of inadequate dietary supplies were greatest for Ca, Se and Zn. High dietary PA supplies are likely to increase risks of Ca and Zn deficiencies. Adequacy of dietary I supply is highly dependent on the concentration of I in salt and Fe deficiency is contingent on individuals' health, especially gut health and malaria. Thus, estimating the prevalence of I and Fe deficiencies based on food consumption data available in the IHS3 is problematic. Among rural households living on non-calcareous soils, concurrent dietary inadequacies of Ca, Se and Zn occurred in 81 % of households in expenditure quintile 1 compared to 15 % of households in expenditure quintile 5 (Table 4). Of the 5156 households nationally that had adequate energy supplies to meet requirements, 30, 56 and 27 % still had inadequate supplies of Ca, Se and Zn, respectively, to meet sum of member EARs, while 16 % had concurrent inadequate supplies of all three elements.

Table 4 Inadequate dietary supplies of multiple elements

Urban/rural	Soil type	Expenditure quintile	*n*	Households with 'x' concurrent inadequate intakes			
				0	1	2	3
				%			
Urban	3	1	57	7	4	23	67
		2	135	9	14	30	47
		3	228	11	11	36	42
		4	442	21	15	32	32
		5	1311	45	16	21	17
Rural	1	1	493	6	8	24	62
		2	450	19	16	24	41
		3	385	30	17	24	29
		4	379	52	17	16	15
		5	340	68	14	10	9
	2	1	1000	2	3	14	81
		2	1297	6	9	23	62
		3	1424	11	12	27	49
		4	1467	19	19	28	34
		5	1335	44	23	18	15
	3	1	290	3	7	18	72
		2	291	10	12	27	51
		3	294	20	19	30	31
		4	294	29	22	30	19
		5	205	54	22	14	9

Concurrent inadequate dietary supplies of calcium, selenium and zinc at household level by urban/rural location, expenditure quintile (1 = poorest, 5 = highest) and soil type (1 = calcareous; 2 = non-calcareous; 3 = undifferentiated)

Interventions to improve dietary micronutrient supplies

Strategies to improve dietary micronutrient supplies include direct supplementation, food-based interventions (such as fortification of cereal flours at the processing stage or dietary diversification), and agricultural interventions (such as biofortification of crops through breeding or application of micronutrient-enriched fertilisers). Recently, it was demonstrated that agronomic biofortification of staple cereals may be a cost-effective strategy to reduce dietary Zn deficiencies in Malawi if Zn is delivered *via* foliar sprays, although such a strategy is likely to be less cost-effective than biofortification *via* crop breeding [69]. Here, two other scenarios are explored: the iodisation of salt and agronomic biofortification of maize grain with Se.

Over 99 % of households in Malawi were not consuming adequate I through foods other than salt to meet requirements. However, the I status of Malawi has recently been defined as 'adequate' based on UIC of school-aged children [62]; thus it is likely that salt iodisation has already been a considerable success. Yet challenges remain. The WHO recommend that adults consume <5 g d^{-1} of salt to limit risk of chronic disease due to excessive sodium intakes [70, 71], yet the IHS3 data shows median salt supply *per* AME of 11.2 g d^{-1}. Even with universal coverage of salt iodised at the recommended 15 mg kg^{-1} and individual consumption of salt of 5 g d^{-1}, 93 % of households in Malawi would have inadequate I supply to meet dietary requirements. The prevalence of inadequate dietary I supply would be 24 and <1 % if salt consumption were 7.5 and 10 g $capita^{-1}$ d^{-1}, respectively. Alternatively, iodising salt at 30 mg kg^{-1} would supply adequate I to 99 % of households if individual consumption of salt was 5 g d^{-1}.

Salt iodisation programmes need close monitoring. Iodisation of table salt is mandatory in Malawi yet only 62 % of households in Malawi were consuming adequately iodised salt in 2010 [61] suggesting problems with compliance or losses due to improper storage. A recent spot survey of adult women in Malawi living on calcareous ($n = 59$) and non-calcareous soils ($n = 59$) found that the median creatinine-corrected UIC was 203 μg L^{-1}. However, there was a 14 % prevalence of I deficiency (UIC <100 μg L^{-1}) but 21 % prevalence of excess (UIC >300 μg L^{-1}) [48]. Thus, high household salt supplies or I concentration in salt might be contributing to excessive I intakes, risking hypo- and hyper-thyroidism.

An agronomic biofortification programme for Se in Malawi could be effective without major changes in farm-level infrastructure through enrichment of existing fertilisers applied to maize [72–74]. Addition of 10 g Se ha^{-1} *via* a granular NPK fertiliser to maize grown on different soils in Malawi achieved a mean concentration of 0.276 mg Se kg^{-1} in the grain [72] which is ~18-fold greater than the median Se concentration of maize grain samples from non-calcareous soils used in the present study. The approach has precedents, having largely eliminated dietary Se deficiency in Finland [75] and may be effective *via* a range of cereal crops [75–77]. Biofortification of staple crops has the potential to be highly equitable as staple foods are consumed on a daily basis by most low-income households and individuals with low status within the household. For example, 98 % of all households in IHS3 and 94 % of those in expenditure quintile 1 reported consuming maize. Furthermore, alternative options to increase dietary element supplies are limited in subsistence contexts. For example, Fiedler et al. [78] showed that flour fortification during milling currently has limited reach in Zambia as few households purchase maize flour from large, centralised milling factories and those that do are generally wealthier with greater baseline Zn intakes.

Application of Se increases its concentration in all fractions of the grain including the endosperm [79], although concentration is likely to be greater in the bran and embryo and previously it was demonstrated that refined maize flour has ~ half the concentration of Se than the whole grain (Additional file 1: Table S6). Thus, if all maize grown on non-calcareous soils received 10 g Se ha^{-1}, the median concentration of 'Maize *ufa* refined (fine flour)' would likely be ~0.138 mg Se kg^{-1} and maize products would supply ~37 μg Se *capita*$^{-1}$ d^{-1} compared to ~4 μg Se *capita*$^{-1}$ d^{-1} without biofortification. The prevalence of inadequate dietary Se supplies among rural households on non-calcareous soils would fall from 82 to 14 %. However, the efficacy will depend on fertiliser use. Currently, maize production in Malawi requires ~140 kt of fertiliser nitrogen (N) to cover the ~2800 kha of production [69]. Usage is ~50 kt (i.e. 36 % of requirement) of which ~35 kt is subsidised under the Farm Input Subsidy Programme (FISP) [80]. Thus, the efficacy of a biofortification scenario is likely to be ~36 % of the universal application modelled above, i.e. reducing prevalence of inadequate dietary Se supplies from 82 to 57 %.

Agronomic biofortification with Se in areas where dietary deficiency occurs is likely to be highly cost-effective. If maize production in Malawi is assumed to be evenly distributed across different soil types then there are ~2000 kha of maize production on non-calcareous soils [69]. Application of 10 g ha^{-1} of Se would therefore cost US$ ~2 million $year^{-1}$, assuming exogenous Se costs US$ 100 kg^{-1} (other programmatic costs not included). Thus, for application of Se at 10 g ha^{-1}, a percentage point drop in national dietary Se deficiency prevalence would cost ~ US$ 27,000 yr^{-1}. If the Se status of individuals is assumed to be the same as their respective household status, then the cost *per* alleviated case of dietary Se deficiency would be ~ US$ 0.36 $year^{-1}$. The WHO TUL of intake for Se is 400 μg d^{-1} for adults and excessive Se intake may be defined as household supply *per* AME >400 μg d^{-1}. With universal application of 10 g ha^{-1} of Se on non-calcareous soils, 13 out of 12,117 households (~0.1 %) would be expected to have excessive Se intake. The actual risk of excessive intakes is likely to be lower as all of these 13 households reported consuming >4000 kcal *per* AME d^{-1} which is implausibly high over a long period. Cost-effectiveness could be improved if Se-enriched fertiliser was distributed through the FISP scheme due to the greater prevalence of inadequate dietary Se supplies among poorer households. Furthermore, the modelled scenarios are likely to underestimate efficacy due to increases in the Se concentration of legumes intercropped with maize and of livestock products fed on maize stover or grain receiving Se-enriched fertiliser. Alfthan et al. [75] reported an increase in the contribution of animal products to human dietary Se intakes in Finland following a national policy of agronomic biofortification with Se; milk products from 'conventional' production had ~2-fold greater Se concentration than from 'organic' production. There may also be benefits to livestock productivity and health [81] which are not captured in the current study.

Use of household surveys to estimate the prevalence of inadequate dietary element supplies in Malawi

There are three main potential sources of dietary survey data: individual-level recall, household-level surveys and national-level FBSs. Individual-level 24 h diet recall is considered the 'gold standard' for dietary assessment by nutritionists, but the approach is often prohibitively expensive to conduct at large scales e.g. nationally [82] and only small-scale surveys have been conducted in Malawi. Household surveys and FBSs are routinely conducted/compiled allowing longitudinal assessment of diets at national, e.g. [30], or international scales, e.g. [10, 49]. The main advantage of household surveys over FBSs is that they provide insights into the distribution of element supplies at sub-national levels. In the present study, there was a positive skew in the distribution of household supplies of all nutrients (Fig. 7). Thus, 68 % of households had *per capita* supplies of Ca less than the mean of all households, i.e. 924 mg *capita*$^{-1}$ d^{-1}. Estimates of dietary element supplies derived from FBSs have previously assumed a normal distribution of individual-level dietary supplies centred on mean *per capita* availability of an element in the national food supply; a 'cut-point' is set as

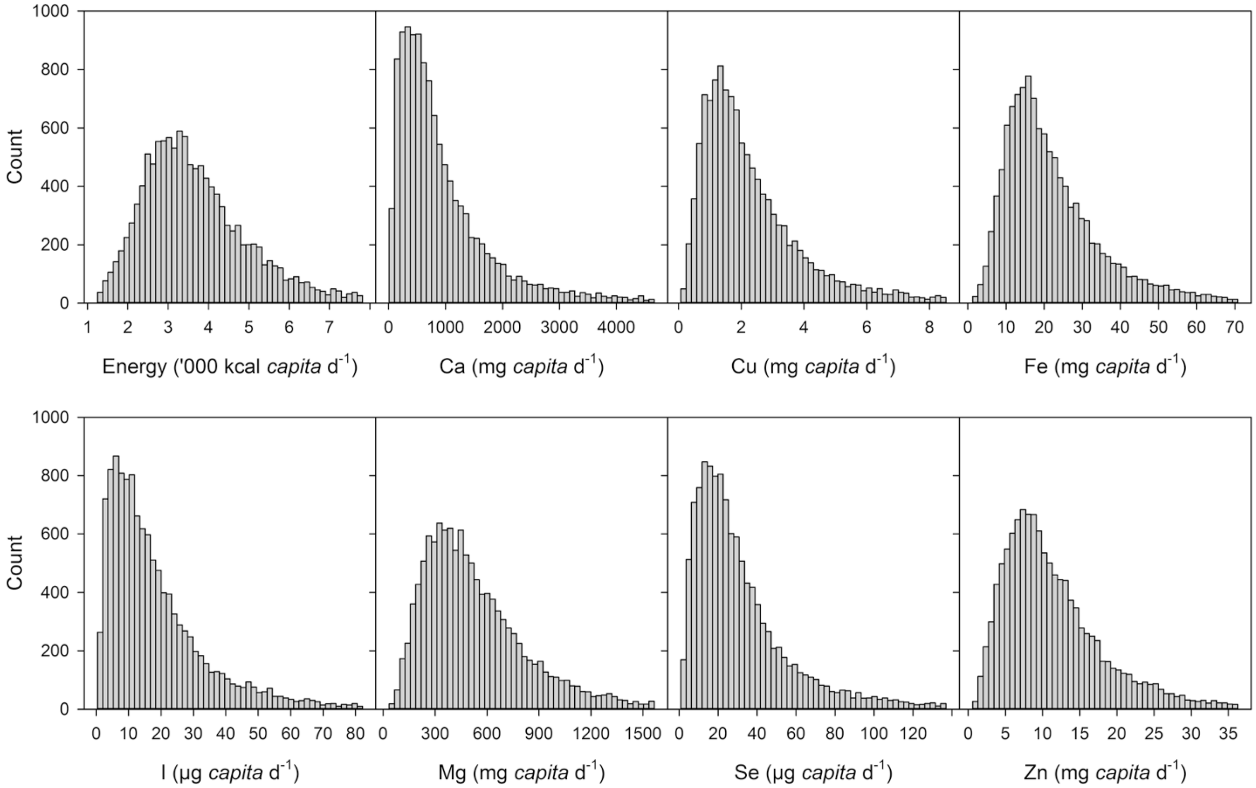

Fig. 7 Distribution of household nutrient supplies. Dietary supplies of energy, calcium (Ca), copper (Cu), iron (Fe), iodine (I), magnesium (Mg), selenium (Se) and zinc (Zn). Iodine supply excludes salt

the national mean EAR and prevalence of inadequate supplies is assumed to equal the proportion of the population with intakes below this level [5, 9]. If the positive skew in household level supplies also occurred at individual level, then the FBS approach is likely to underestimate the prevalence of inadequate dietary supplies.

There are three further advantages of deriving food consumption data from the IHS3 compared to the Malawi FBS. First, a greater variety of food items or break down of major food items are reported than the standard 94 edible items in the FBS, for example common indigenous vegetables, or refined and whole grain maize flour, and this allows more accurate matching of crop composition data. Second, FBSs generally rely on crop or livestock production data which may be restricted to commercialised major food crops; for example, sweet potato supply is not recorded in the most recent FBS [57]. Third, IHS3 gives insights into seasonality of supplies.

National-level estimates of inadequate dietary supplies derived from the analysis of FBSs might spur policy makers to intervene or support further research. However, inter-household and seasonal variation in food choice and dietary micronutrient intakes are likely to be required for effective policy making. For example, agronomic biofortification appears to be a promising strategy to address dietary Se deficiency in Malawi [22, 72–74]. A policy maker might question whether an intervention needs to reach wealthy households with their greater calorie intakes and more diverse diets. Despite greater consumption of nutrient-dense foods including fish, 55 % of households in expenditure quintile 5 on non-calcareous soils had inadequate Se supplies to meet sum of member EARs. Thus, enriching subsidised fertiliser used by poorer households would not be sufficient in eliminating dietary Se deficiency. Valid concerns of potential toxicity might also be raised given the relatively narrow range between ‘inadequate’ and ‘excessive’ intakes of Se [40]; but in the present study, it was estimated that ~0.1 % of the population would have excessive intakes if application of Se at 10 g ha^{-1} were universal on non-calcareous soils. And this figure is likely to be lower if households with unrealistically high calorie intakes are removed. Similarly, Fiedler et al. [78] used household survey data to address concerns over the effectiveness and safety of potential food fortification schemes in Zambia. However, close monitoring of fertiliser enrichment and distribution to appropriate areas would be required, similar to management considerations in the salt iodisation strategy.

Caveats

Dietary recall at household level

Dietary recall provides a proxy for food consumption and is subject to error. Recall error can occur when interviewees forget instances of food consumption ('recall loss') or include items which were consumed prior to the recall period ('telescoping errors'). These types of error are likely to be greater for longer recall periods. Furthermore, the ability of one household member to accurately report the consumption of all household members is questionable, and this might account for some of the association between decreasing dietary energy supplies with increasing household size (Fig. 3). Under- or over-reporting of food consumption can also be intentional. For example, respondents in the UK and US national dietary surveys were estimated to under-report their individual calorie intakes by up to 41 % [83, 84]. This occurred in a society in which being overweight is generally perceived as undesirable, yet in the UK 71 and 58 % of men and women, respectively, have a Body Mass Index >25 [46].

Social pressures in Malawi are likely to differ to those in the UK or US. For example, being overweight is generally perceived as healthy and socially desirable [85] and it is interesting to note the high reported calorie consumption of the wealthiest expenditure quintile, i.e. mean and median consumption *per* AME of 3837 and 3618 kcal d^{-1} compared to a requirement of 3300 kcal d^{-1} for adult males with a PAL of 1.9. Also, many wealthy individuals, particularly in urban areas, are unlikely to require such high calorie intakes due to lower PALs. For example, an adult male with a sedentary or light activity level would require 2500-3000 kcal d^{-1} [38].

In addition to recall errors, there are likely to be numerous reporting errors introduced by enumerators. The capping of food item consumption at maximum plausible levels is likely to have reduced, though not eliminated, the influence of such errors. Local units are a convenient way to report quantities consumed in an interview process but may encourage inaccurate reporting. For example, ~80 % of households that recorded consumption of the food item 'Maize *ufa* refined (fine flour)' expressed the quantity consumed in units of small, medium or large pails. The accuracy of these units is subject to the interpretation of the interviewees and enumerators, as well as the conversion to metric units applied by the authors of the present study.

One quick way to assess the validity of food consumption data reported in the IHS3 is to look at the plausibility of dietary energy supplies. As reported in the Results, there were both implausibly low and high calorie intakes when households were aggregated at the EPA level. The energy requirement of an adult male with PAL of 1.9 and body mass of 70 kg is ~3300 kcal d^{-1} [38], yet 21 % of households reported consumption *per* AME of <1650 kcal d^{-1}, i.e. half the requirement, and 8 % reported >4950 kcal d^{-1}, i.e. double the requirement, and these levels are highly unlikely to be sustainable for periods of more than a few days. If these households were excluded, the estimated national prevalence of inadequate dietary energy, Ca, Cu, Fe, I, Mg, Se and Zn supplies from foods other than salt would be 50, 44, 2, 10, 100, 1, 72 and 51 %, respectively, compared to 57, 49, 6, 18, 99, 5, 74 and 57 % prior to removal of households with 'implausible' dietary energy intakes. Thus, the results of the present study are reasonably robust against recall or reporting errors at a national scale and demonstrated some regional variation that could not be identified using national-level food supply data, e.g. greater Ca supplies in lakeshore EPAs. However, taking Ca as an example, removing households with implausible energy intakes would increase or decrease the prevalence of inadequate dietary supplies by >25 % in 94 of 149 EPAs which suggests that further research is required to improve the accuracy of household survey food consumption data before intervention policies can be designed at the highly disaggregated level of the EPA.

Comparison between food supply in FBS and IHS3 reveals some consistencies and discrepancies. For example, mean national consumption of maize is reported as 365 g $capita^{-1}$ d^{-1} FW in the 2009 FBS [57], equivalent to 327 g $capita^{-1}$ d^{-1} DW [18]; this compares to mean (± SD) consumption of maize products (i.e. item codes 101–105 and 820) of 320 (± 203) g $capita^{-1}$ d^{-1} DW in the household survey. However, mean consumption of freshwater fish differs by ~7-fold between the two food supply datasets (*cf.* discussion on Ca supplies). The original source of FBS fish supply data in Malawi is not publicly available which prevents further investigation of this discrepancy.

The present study estimated dietary element supplies and prevalence of inadequate supplies at the household level due to the availability of data in the IHS3. However, intra-household variation in foods consumed is not captured. Energy requirement ratios of household members could be used to estimate distribution of foods within the household and hence the prevalence of inadequate supplies at the individual level. However, the reliability of this approach is questionable as it requires the assumption that all members within a household consume the same mixture of food items [86].

Estimating dietary supplies at household level is likely to underestimate the prevalence of inadequate intakes at individual levels because poorer, rural households are more likely to have inadequate dietary element supplies and to have larger household size (Tables 1 and 2; Additional file 1: Table S9 and Additional file 1: Table S10). If all individuals living in households with supplies less than sum of member EARs were assumed to have inadequate intakes, then the prevalence of dietary energy, Ca, Cu, Fe, I, Mg, Se and Zn deficiencies among individuals would be 61, 53, 7, 20, 99, 6, 77 and 63 %, respectively, compared to 57, 49, 6, 18, 99, 5, 74 and 57 % among households.

Food composition

As with food supply data, there is an accuracy-cost trade-off in the use of food composition data and *caveats* regarding composition data were discussed previously [18]. In the present study, households were assigned to 'calcareous', 'non-calcareous' and 'undifferentiated' soil types on the basis of their location. This is likely to improve the relevance of matched food composition data. A national-scale food crop survey can only capture some of the variation in crop composition due to soil factors or varietal differences. However, locally-generated data remain preferable to the use of regionally or internationally collated datasets, particularly for elements such as Se where plant uptake is under strong geochemical control. However, it is inevitable that some households were misclassified due to GPS location being aggregated at EA level and displaced to ensure confidentiality or due to the resolution of soil maps.

Nutrient requirements

Nutrient requirements for age and sex categories are reported by a number of different public health bodies. In the present study, requirements were derived from FAO [38], WHO [39], and IOM [40, 41] as described in the Methods. However, aggregated requirement values cannot fully capture inter-individual variation in requirements, e.g. due to different body sizes, activity levels, presence of infection, consumption of promoters or inhibitors of nutrient absorption etc. A preference for conservative (i.e. high) requirement values might overestimate the prevalence of nutrient deificiencies.

Drinking water

Drinking water can contribute significantly to dietary element intakes but this was not quantified in the present study; consequently, the prevalence of inadequate dietary supplies may be overestimated. For example, an *ad hoc* survey of borehole waters ($n = 19$) revealed mean and median Ca concentration of 39.2 and 22.2 mg L^{-1} (range 3.2-209.3), I concentration of 15.4 and 12.6 μg L^{-1} (range 1.0-54.2) and Mg concentration of 31.4 and 24.8 mg L^{-1} (range 0.9-95.2; Additional file 1: Table S28). Mean concentrations of Cu, Fe, Se and Zn were 1.9, 0.3, 0.2 and 8.4 μg L^{-1} which is insignificant compared to dietary food intakes. A wider survey would be required to assess the contribution of drinking water to dietary element supplies, although this does illustrate the potential of some drinking waters to contribute significantly to dietary Ca, Mg and I supplies as seen in other contexts, e.g. [87, 88].

Conclusions

Prevalence of dietary element supplies and deficiencies were quantified for Malawi by combining food consumption data captured in the most recent household survey (IHS3) with locally-generated food composition data, stratified by soil type. We estimate that 57 % of households had inadequate dietary energy supplies for requirements of an active lifestyle, while >50 % of households had inadequate dietary supplies of Ca, Se or Zn to meet requirements but <20 % had inadequate dietary supplies of Cu, Fe and Mg. Among households with adequate energy supply, 30, 56 and 27 % still had inadequate supplies of Ca, Se and Zn to meet requirements. Supply of I from foods other than salt is inadequate for >99 % of households. Access to essential nutrients varied due to socioeconomic and environmental factors. For example, the median supply of Ca in rural households in the wealthiest and poorest expenditure quintiles was 1157 and 255 mg *capita*$^{-1}$ d^{-1}, respectively; the difference was largely driven by the consumption of fish with a median supply of Ca from fish of 737 and 246 mg *capita*$^{-1}$ d^{-1} in the wealthiest and poorest expenditure quintiles, respectively. The median supply of Se among rural households in areas of calcareous and non-calcareous soil was 30.7 and 17.3 μg *capita*$^{-1}$ d^{-1}, respectively; the difference was driven by food composition, with median Se concentration of 0.0138 and 0.0071 mg kg^{-1} in refined maize flour from calcareous and non-calcareous soils, respectively.

Nationally, cereals supplied >60 % of dietary energy, >40 % of Mg and Zn, >30 % of Fe and >20 % of Se, but <5 % of Ca. Fish was an essential source of micronutrients for many households, partly due to the preference for eating whole small fish (*usipa*) including bones. Overall, 77 % of households recorded fish consumption during 7 days preceding their interview, and fish supplied 62, 47 and 26 % of national dietary Ca, Se and Zn supplies. However, consumption of fish varies with greater access for wealthier households and those living in lakeshore EPAs.

Two strategies to increase dietary element supplies were modelled. We show that iodisation of salt at 15–30 mg kg^{-1} can ensure that the majority of households have adequate I supplies due to near universal consumption of salt, including in poorer, rural households. However, mean household salt supplies of 11.2 g *per* AME were greater than the WHO maximum recommended intake of 5 g *capita*$^{-1}$ d^{-1} and close monitoring of iodisation levels at production is required to avoid excessive I intakes. Agronomic biofortification with 10 g Se ha^{-1} of maize has the potential to reduce the prevalence of inadequate dietary Se supplies from 82 to 14 % of households living on non-calcareous soils, and from 95 to 21 % for the poorest subset of those households. However, if only those fertilisers currently in use were enriched, the prevalence of inadequate Se intakes among all households living on non-calcareous soils would fall from 82 to 57 % The cost *per* alleviated case of dietary Se deficiency would be ~ US\$ 0.36 year^{-1}, representing a highly cost-effective strategy.

Household surveys provide a valuable resource for assessing national diets, although the accuracy of food consumption data remains an issue: instances of implausibly high or low reported energy intakes suggest reporting errors, possibly due to purposeful under- and over-reporting. Also, there are unresolved discrepancies between national-level FBS and household survey datasets, for example the ~7-fold greater estimated consumption of fish based on IHS3. The present study used food crop composition data generated for Malawi and demonstrated significant variation in dietary supplies of some elements depending on soil properties. However, locally-generated food crop composition data stratified by soil type are not available for many countries. Thus, work to improve the accuracy and spatial resolution of food crop composition data is required to extend the methodology to other countries, particularly for elements where plant uptake is under strong geochemical control.

Additional files

Additional file 1: Tables S1 to S30 Joy et al. Tables S1 – S30 provide: supporting information regarding the integration of food supply and composition datasets; summaries of results by household environmental and socioeconomic factors; and summaries of results by Extension Planning Area (EPA). (XLSX 995 kb)

Additional file 2: Figure S1. Assignment of Enumeration Areas (EAs) to soil types. Soil type was assigned as 'calcareous' or 'non-calcareous' if more than two-thirds of the EA area was covered by one of these soil classes, except for large EAs (≥10,000 ha) for which soil type was assigned by laying a 5 km buffer around the modified household GPS point location. Soil series data from [43] and EPA boundaries from Ministry of Agriculture. (TIFF 748 kb)

Abbreviations

AME: adult male equivalent; Ca: calcium; Cu: copper; DALY: disability-adjusted life-year; DER: dietary energy requirement; DW: dry-weight; EA: Enumeration Area; EAR: estimated average requirement; EP: edible portion; EPA: Extension Planning Area; FAO: Food and Agriculture Organization of the United Nations; FBS: Food Balance Sheet; Fe: iron; FISP: farm input subsidy scheme; GPS: Geographical Position System; I: iodine; IHME: Institute of Health Metrics and Evaluation; IHS3: Third Integrated Household Survey of Malawi; IOM: Institute of Medicine; Mg: magnesium; N: nitrogen; PA: phytic acid; PAL: physical activity level; RNI: recommended nutrient intake; Se: selenium; UIC: urinary iodine concentration; WHO: World Health Organization; YLD: years of life lost due to disability; Zn: zinc.

Competing interests

Funding has previously been received by MRB, ADCC and SDY from Yara Fertilisers for Se-related research in UK and Malawi (2003–2011), but no industry funds were used in this study. The authors declare no other competing interests.

Authors' contribution

EJMJ, ELA, MRB and DBK conceived the study. EJMJ and DBK compiled the food supply data. EJMJ, MJW, ELA, SDY and ADCC generated the food composition data. EJMJ, DBK and ELA integrated the datasets. EJMJ and DBK drafted the manuscript and figures/tables, with input from all authors. All authors read and approved the final manuscript.

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