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Selenium deficiency risks in sub-Saharan African food systems and their geospatial linkages

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Selenium (Se) is an essential element for human health. However, our knowledge of the prevalence of Se deficiency is less than for other micronutrients of public health concern such as iodine, iron and zinc, especially in sub-Saharan Africa (SSA). Studies of food systems in SSA, in particular in Malawi, have revealed that human Se deficiency risks are widespread and influenced strongly by geography. Direct evidence of Se deficiency risks includes nationally representative data of Se concentrations in blood plasma and urine as population biomarkers of Se status. Long-range geospatial variation in Se deficiency risks has been linked to soil characteristics and their effects on the Se concentration of food crops. Selenium deficiency risks are also linked to socio-economic status including access to animal source foods. This review highlights the need for geospatially-resolved data on the movement of Se and other micronutrients in food systems which span agriculture–nutrition–health disciplinary domains (defined as a *GeoNutrition* approach). Given that similar drivers of deficiency risks for Se, and other micronutrients, are likely to occur in other countries in SSA and elsewhere, micronutrient surveillance programmes should be designed accordingly.

Hidden hunger: Malnutrition: Micronutrient surveillance

Biological role of selenium

Selenium (Se) is an essential trace element with many roles in human health. An important group of Se-containing compounds which are required for optimal health are the selenoproteins[(1)]. There are twenty-five genes expressing selenoproteins in the human genome, including iodothyronine deiodinases, thioredoxin reductases, glutathione

Abbreviations: EPA, extension planning area; Se, Selenium; SSA, sub-Saharan Africa.
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peroxidases and other selenoproteins such as selenoprotein P[1]. These selenoproteins play important roles in thyroid function, redox homeostasis and antioxidant defence. Se deficiency has been linked with a range of negative health outcomes including reduced immune responses and lower $CD4^+$ T cell counts, increased disease progression and increased mortality among individuals infected with HIV-1[1–4].

Establishing optimal dietary selenium requirements from biomarkers of selenium status

Establishing optimal dietary Se requirements is challenging; these can vary according to age and physiological status of individuals[1]. Furthermore, only small amounts of Se are required at an individual level and the corresponding low concentrations of Se in tissues, used as biomarkers of Se status, are technically challenging to measure accurately. Approximately 50 % of an individual's Se circulates in the blood system and this Se pool is responsive to short-to-medium term Se intake (days-to-weeks). Whole-blood or plasma/serum Se concentration is therefore an informative biomarker of Se status at individual and population levels[1]. Plasma Se concentrations of 87 and 65 μg/l are typically used as thresholds for the optimal activities of the selenoproteins glutathione peroxidase 3 and iodothyronine deiodinase, respectively, in adults[5].

A plasma Se concentration of about 100 μg/l corresponds to a habitual Se intake of about 1 μg/kg body mass/d[1]. Notably, the optimal plasma activity of other selenoproteins (e.g. selenoprotein P) occurs at greater plasma Se concentrations (>120 μg/l) than for glutathione peroxidase 3 and iodothyronine deiodinase; however, the significance of this for human health has not yet been established[6]. The tolerable upper limit for Se has been defined for adults and adolescents as 400 μg/capita/d based on potential adverse effects[7].

The use of blood Se concentration as a biomarker of Se status requires invasive sampling; there can be sensitivities regarding the use of blood samples (e.g. for HIV testing) and suspicions about blood sampling originating in cultural beliefs, e.g. vampirism or 'blood sucking' and witchcraft in some countries[8]. Urine Se concentration is an alternative potential biomarker of Se status[1,8,9]. Most excreted Se is in a urinary selenosugar[10]; however, the concentration of Se in urine is strongly influenced by intra- and inter-individual variation in hydration and urinary flow rates, amongst many other factors[10]. Toenail and hair Se concentrations are other potential biomarkers of Se status, which are potentially less invasive than blood Se concentration, and can indicate longer-term Se status[1,11]. However, toenails and hair are prone to contamination from extrinsic sources of Se (e.g. dust, hair cleaning products) as well as having their own potential cultural sensitivities. Thus, whilst measurements of urine, toenail and hair Se concentrations can provide useful information, these are less useful than blood Se concentration for assessing population-level Se status.

Evidence of widespread dietary selenium deficiency risks in Africa

Data on the concentration of Se in blood as reported for populations in African countries were obtained from a literature review. Search terms were individual African country names, together with *selenium* and *plasma* or *serum* or *blood* (conducted August 2017, Web of Science, Clarivate Analytics). There were fifty-four publications in which the Se concentration of whole-blood (*n* 4), plasma (*n* 21) or serum (*n* 29) was reported (Supplementary Table 1). Whilst plasma Se concentration has been reported to represent 81 % of whole-blood Se concentration and 94 % of serum Se concentration[12], the original data values were used in this summary without adjustments. This search was not considered to be exhaustive, but likely to be representative.

Studies from nineteen countries are represented in this literature summary: Algeria (*n* 2 studies), Côte d'Ivoire (*n* 2), Democratic Republic of Congo (*n* 8), Egypt (*n* 6), Ethiopia (*n* 6), Ghana (*n* 2), Kenya (*n* 1), Malawi (*n* 8), Morocco (*n* 2), Mozambique (*n* 1), Niger (*n* 1), Nigeria (*n* 4), Rwanda (*n* 1), Senegal (*n* 1), South Africa (*n* 3), Sudan (*n* 3), Tanzania (*n* 2), Uganda (*n* 1) and Zambia (*n* 1). From across these studies, we were able to identify blood Se concentration data for a total of 131 distinct groups of people for which an average (mean and/or median) and a dispersion measure of blood Se concentration was reported. Many of the cited studies presented data for case and control groups, the former comprising individuals presenting clinical symptoms (e.g. tuberculosis, HIV), typically in a hospital setting, the latter being drawn from apparently healthy individuals often living or working in the vicinity of the hospital.

The average blood Se concentration data for these 131 groups, and citation details, are provided in Supplementary Table 1. Among these studies, eighty-four of the 131 groups have average blood Se concentrations below the threshold for optimal glutathione peroxidase 3 activity (87 μg/l); sixty-four groups are also below the threshold for optimal iodothyronine deiodinase activity (65 μg/l). These data indicate that Se deficiency risks are potentially high for groups in many settings in Africa. Strong caveats are needed to avoid these summary data being over-interpreted. These include (1) the small number of studies included, (2) not using analytical quality control as inclusion criteria, (3) biases in the original study designs (i.e. explicit case–control comparisons of people experiencing ill-health with healthy controls).

Evidence of geospatial variation in selenium deficiency risks in sub-Saharan Africa

Geospatial variation in Se status has not been studied widely in sub-Saharan Africa (SSA). We identified studies from four countries, in which groups of people were selected according to explicit geospatial criteria: Democratic Republic of Congo[13–20], Ethiopia[21–24], Côte d'Ivoire[25,26] and Malawi[27]. In all four countries, there is evidence of geospatial variation in Se status.

In the Democratic Republic of Congo, Ngo *et al*. compared the Se status of groups of pregnant women (about 20 weeks' gestation, *n* 505 in total), from seven discrete locations[18]. Serum Se concentration varied from 40 to 111 µg/l between these groups with evidence of geospatial determinants of Se status. This is one of several studies in the Democratic Republic of Congo to have explored geospatial links between Se and iodine nutrition and potentially associated health disorders[13–20]. In Côte d'Ivoire, adult plasma Se concentration was reported to be 3–5-fold greater among adults in Abidjan, than in the mountainous Glanlé Region of west Côte d'Ivoire[25,26].

In Ethiopia, Gashu and coworkers have reported geospatial variation in Se deficiency, based on surveys of the serum Se status of about 600 children aged about 5 years in the Amhara Region[21–24]. Serum Se concentration ranged from 11 to 291 µg/l; 49 % were below 70 µg/l. Plasma Se concentration was lower in rural villages in the west of Amhara (West Gojjam, East Gojjam, South Gonder zones) than in the east of Amhara Region (North Wollo, South Wollo and Waghemera zones). Given that the consumption of animal-source foods was limited across the region, Gashu and coworkers hypothesised that Se deficiency risks were likely to be due to soil and/or landscape features influencing the Se concentration of the crop[21]. Based on dietary assessments, Gashu and coworkers concluded that the grain Se concentration of the two dominant cereal crops, teff and wheat, would likely be the primary drivers of differences in Se status; for example, teff had been eaten by 76 % of children in the 24 h prior to the dietary assessments[22].

Evidence of widespread dietary selenium deficiency risks and geospatial linkages in Malawi

The most comprehensive geospatial data on the Se status of a population in SSA are from Malawi. A high prevalence of Se deficiency was predicted in Malawi, based on plasma Se concentration ranges of <54 µg/l among a population of adults (*n* 779) living in rural areas of Zomba District[27,28]. These data were consistent with an earlier report of small dietary Se intakes (15–21 µg/capita/daily) among children living in Zomba[29]. Subsequent national-scale estimates of Se intake, based on predicted maize grain Se concentrations arising due to variation in soil properties[30], strengthened the case that Se deficiency was likely to be widespread.

In a cross-sectional study, designed explicitly to compare the Se status of women living in two locations with contrasting soil types and maize grain Se concentrations, marked differences in the Se status of blood plasma and casual urine were observed[31]. Plasma Se concentration in Zombwe extension planning area (EPA) (median 53·7 µg/l, SD 9·7, range 32·3–78·4, *n* 60) was less than half that seen in Mikalango EPA (median 117 µg/l, SD 22·5, range 82·6–204, *n* 60) which had been selected as a site because of the local Vertisol soil types used for local crop production, which had previously been linked with much higher grain Se concentrations[30]. Casual (spot) urine Se concentration in Zombwe EPA (median 7·3 µg/l, SD 2·0, range 4·1–13·3, *n* 59) was one-third that of Mikalango EPA (median 25·3 µg/l, SD 18·9, range 12·4–106, *n* 56). These data strengthened the case that Se deficiency was likely to be very widespread in Malawi based upon the relative extent of corresponding soil types in Malawi[30,31]. The higher plasma Se concentration of people living in areas where Vertisols are prevalent in Malawi (Chikwawa District, which includes Mikalango EPA) has been shown to be consistent with a high erythrocyte Se concentration[32]. Erythrocyte Se concentration is unlikely to be affected by the systemic inflammatory response, which can cause a decrease in plasma Se concentration that is independent of Se status[32].

To the authors' knowledge, Malawi is the only country in Africa to have reported Se status using a nationally representative survey of the population[33]. Blood plasma Se concentration was used as a population-level biomarker, from samples collected during the Malawi Micronutrient Survey and Demographic and Health Survey of 2015–16. The study comprised 2761 people, including preschool children (aged 6–59 months), women of reproductive age (aged 15–49 years), school-aged children (aged 5–14 years) and men (aged 20–54 years). Across all demographic groups, the mean and median plasma Se concentrations were 73·2 and 68·2 µg/l, respectively (SD 33·9 µg/l; range 9·9–374 µg/l). Plasma Se concentration increased with age, ranging from a median of 57·7 µg/l in preschool children to 78·4 and 81·9 µg/l in adult women and men, respectively[33].

As predicted from the earlier, localised studies[27,28,31], widespread Se deficiency risks and geospatial linkages were evident[33]. For example, 62·5 and 29·6 % of women of reproductive age (*n* 802) had plasma Se concentrations below the thresholds for the optimal activity of the glutathione peroxidase 3 (87 µg/l) and iodothyronine deiodinase (65 µg/l), respectively (Fig. 1). Geostatistical modelling and prediction showed that Se status of people shows marked spatial variation, with higher blood concentrations in areas where particular soils are commonly found (Vertisols) and near Lake Malawi where more fish is likely to be consumed[33].

Phiri *et al*. reported similar geospatial patterns in urine Se concentration, based on casual (spot) urine samples (*n* 1406) taken from the same sample of women of reproductive age (*n* 741) and school-aged children (*n* 665) during the 2015–16 Malawi Demographic and Health Survey[8]. Thus, between-cluster (enumeration area) variation in urine Se concentration corresponded with variation in plasma Se concentration (Fig. 1). There was a stronger geospatial correlation between urine and plasma Se concentrations, at the enumeration area scale, when urine Se concentration data were adjusted for individual hydration status (e.g. using specific gravity) than when uncorrected urine Se concentration data were used. The limitations of urine Se concentration as an individual-level biomarker of Se status were evident in that urine Se concentration was not associated with variation in plasma Se concentration between households within a

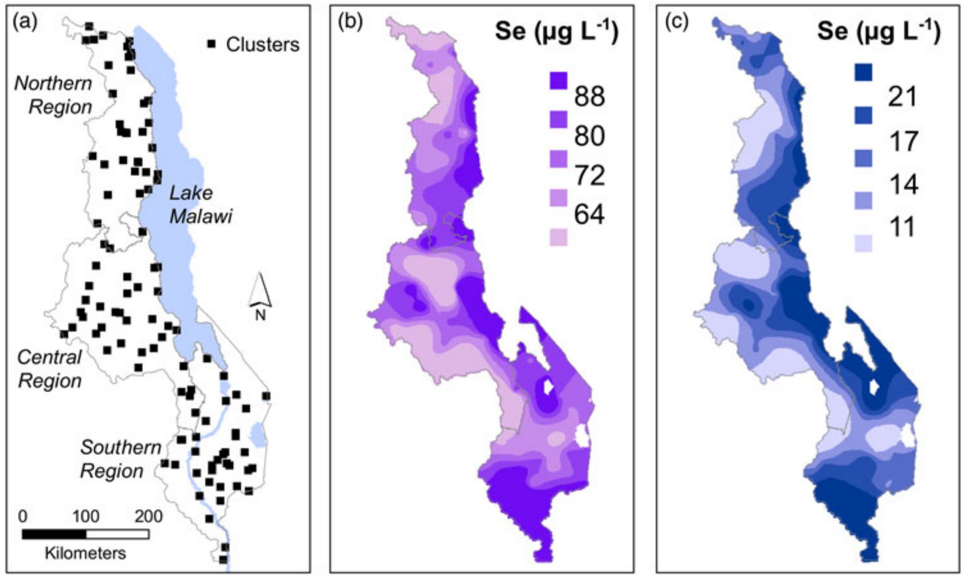

Fig. 1. (a) Enumeration area cluster locations from the nationally representative micronutrient survey of Malawi, (b) predicted plasma selenium (Se) concentration (adapted from Phiri *et al.*[33]), and (c) urine Se concentration unadjusted for hydration status. Data are for women of reproductive age (15-49 years). Reproduced with minor changes from Phiri *et al.*[8]; https://doi.org/10.1016/j.envint.2019.105218; Attribution-Non Commercial-No Derivatives 4·0 International (CC BY-NC-ND 4·0) License (https://creativecommons.org/licenses/by-nc-nd/4.0/).

cluster, nor between individuals within a household. Nevertheless, Phiri *et al.* concluded that urine Se concentration has potential value as a non-intrusive method for population-level surveillance of Se status, especially if urine samples are already being collected for other purposes, e.g. iodine surveillance[8].

Variation in dietary selenium supply and intake in sub-Saharan Africa

Selenium status correlates strongly with the intake of Se from dietary sources[1]. Selenium intakes ranging from 3 to 7000 μg/capita/d have been reported globally due to differing dietary preferences and the levels of plant-available Se in the soil on which crops are grown[1,34–36]. Intake of Se from water and air is usually insignificant, except where local natural or anthropogenic factors arise[34]. Assessments of dietary Se intake can therefore be made from the direct compositional analysis of duplicate portions of diets, or by secondary analysis of food composition data multiplied by food consumption/expenditure/supply data which are available from various sources[37–39].

Among forty-six countries across all of Africa, Joy *et al.* reported mean and median national Se supplies of 50 and 55 μg/capita/d, using FAO food supply and regional food composition tables and population-weighted data[37] (Fig. 2). National Se supply ranged from 23 (Liberia) to 93 μg/capita/d (Burkina Faso). These data represent a single data point for each country with an assumed normal distribution, which was then used to estimate the prevalence of Se deficiency[37]. The estimated risk of Se deficiency was 28 % across Africa. Greater risks of Se deficiency were estimated to occur in Eastern (52 %) and Middle (49 %) regions, followed by Southern (26 %), Northern (12 %) and Western (6 %) regions. The critical importance of secondary data quality, and inferred Se supply data for individual countries, is discussed in Joy *et al.* For example, such analyses are highly sensitive to food Se concentration data, especially for frequently consumed food items, and such concentration data often do not have supporting information on analytical quality control[37].

In the continental-scale analysis of Joy *et al.*[37], dietary Se supply in Malawi was estimated to be 34 μg/capita/d compared to a population-weighted estimated average requirement for Se of 37 μg/capita/d. The estimated average requirement is defined as the quantity of intake that meets the requirements of 50 % of an age- and sex-specific population group. A Se deficiency risk of 64 % was estimated based on the estimated average requirement cut-point method[40]. Data from Joy *et al.*[37] were consistent with a subsequent secondary data analysis, by Joy *et al.*, in which median dietary Se supply in Malawi was estimated to be 21 μg Se/capita/d (25 μg Se/d per adult male equivalent)[39]. An estimated 74 % of households had inadequate dietary Se supply to meet the sum of household members' estimated average requirements[39]. Joy *et al.* assessed dietary Se supply in Malawi using food composition data, derived from national-scale convenience sampling[30,38,39], which were combined with household food consumption data (and socio-economic data) from the Third Malawi Integrated Household Survey. The Third Malawi Integrated Household Survey was a nationally-representative sample

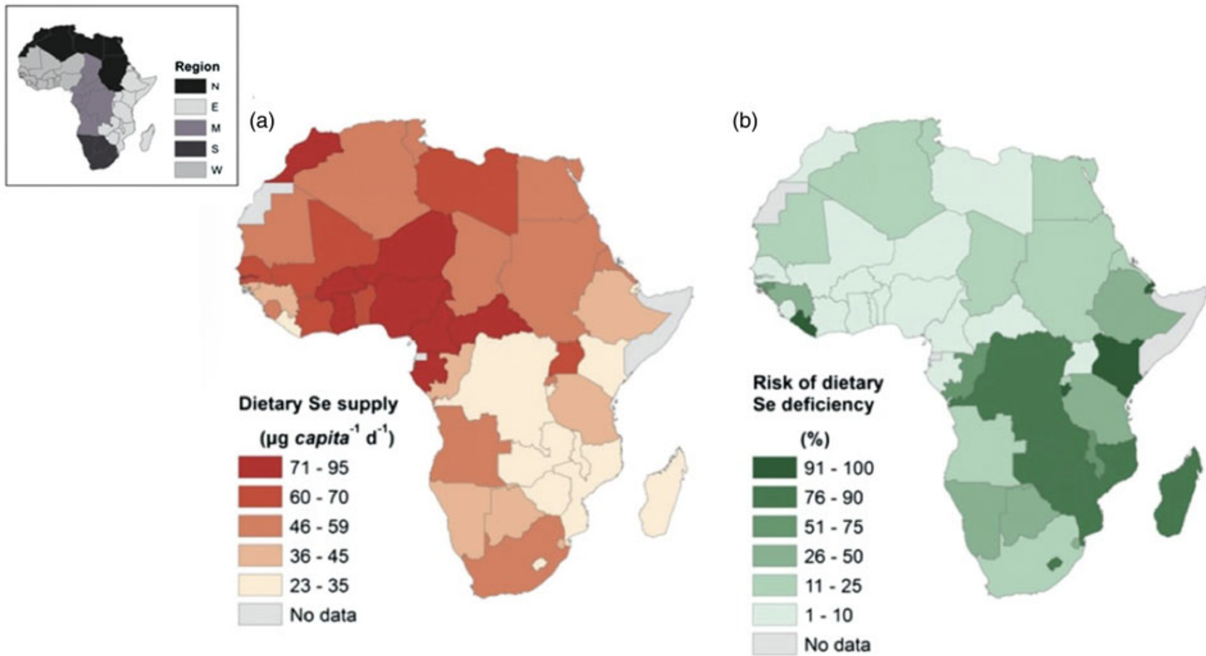

Fig. 2. (a) Dietary selenium supply and (b) deficiency risk for forty-six African countries. Inset: sub-regions of Africa (http://unstats.un.org/unsd/methods/m49/m49regin.htm). Reproduced unchanged from Joy *et al.*[37]; https://doi.org/10.1111/ppl.12144; Creative Commons Attribution 4·0 International License (http://creativecommons.org/licenses/by/4.0/).

of >12 000 households interviewed from March 2010 to March 2011. In the Third Malawi Integrated Household Survey food consumption module, participants were asked to recall the types and amounts of food consumed in the household during the past 7 d, from a list of 112 food items, and also whether this was sourced from home production, purchased or gifted[39]. Data were integrated at an EPA level to provide information for 179 disaggregated spatial units.

In Malawi, >50 % of dietary energy was derived from maize[39]. Other cereals, including rice, sorghum, pearl millet and finger millet, each contributed <5 % of energy intake, whilst legumes and root and tuber crops such as cassava and sweet potato each contributed about 10 % of national energy supply[39]. All animal source foods combined, including meat, milk and eggs, represented <10 % of overall energy intake.

At an EPA level, the median Se supply per adult male equivalent ranged from 7 µg/d in Kavukuku in northern Malawi (*n* 64 households) to 44 µg/d in Nampeya in southern Malawi (*n* 47 households; Fig. 3). The food groups, fish, cereals and legumes contributed 47, 21 and 13 %, respectively, of national annual dietary Se supply, with all of the other food groups each contributing <9 %. Se supply was positively correlated with household socio-economic status, with the risk of Se deficiency substantially greater in lower-expenditure households[39].

Outside of Malawi, there are few reports of geospatial variation in dietary Se supply or intake within countries in SSA, either from food consumption/composition surveys or from duplicate dietary analyses. In Burundi, using duplicate diet analyses and questionnaires, mean intakes of 17 µg/capita/d were reported among adults

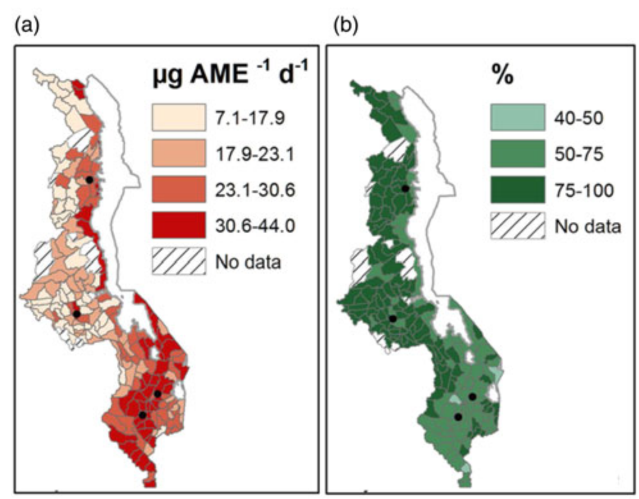

Fig. 3. (a) Dietary selenium (Se) supply and (b) deficiency risk by extension planning area for Malawi. Median household Se supply (µg/AME/d; AME = adult male equivalent) and the proportion (%) of households with inadequate dietary Se supply to meet the sum of member estimated average requirements. Reproduced unchanged from Joy *et al.*[39]; https://doi.org/10.1186/s40795-015-0036-4; Creative Commons Attribution 4·0 International License (http://creativecommons.org/licenses/by/4.0/).

living in rural areas, compared to 82 and 38 µg/capita/d among urban middle-class men and mothers, respectively, and 67 and 64 µg/capita/d in hospital and university institutional settings, respectively[41]. Access to fish, based on increased purchasing power, was associated with increased Se intake in urban settings. These observations are consistent with small Se intakes (15–21 μg/capita/d) reported among children living in Zomba District, in rural southern Malawi[29], as compared to larger intakes (44–46 μg/capita/d) in Mangochi District, adjacent to the southern end of Lake Malawi, where fish consumption was greater[42].

Linkages between dietary selenium supply and intake, food crop composition and soil type in Malawi

Geospatially-resolved food composition data from Malawi[30,38,39] provide strong evidence of links between soil type and food crop Se composition, consistent with observations from an earlier analysis of soils and maize grain[30]. Chilimba *et al.* sampled seventy-three sites in 2009 and reported a median maize grain Se concentration of 16 μg/kg[30]. This value was less than reported in earlier food composition data from Malawi[29]. However, a single large maize grain Se concentration of 533 μg/kg was noted from a crop growing on a Vertisol soil (pH 7·9), in Mikalango EPA, in the south of Malawi[30]. This observation led to the additional sampling of Vertisol sites in 2010, with large maize grain Se concentrations 173–413 μg/kg reported subsequently at thirteen sites in Mangoti, Dolo and Mikalango EPA, where soil pH values ranged from 7·0 to 8·0[30].

Across the full data set of Chilimba *et al.*, there was a weak positive correlation between grain Se concentration and potentially plant-available soil Se concentration, but no correlation between grain Se concentration and total soil Se concentration[30]. There was a stronger positive correlation between grain Se concentration and soil pH above pH 6·5. Inorganic Se, selenate (Se^{6+}) and selenite (Se^{4+}), is usually categorised into three soil fractions: fixed, adsorbed (phosphate-extractable) and soluble Se. Fixed Se, which is bonded to soil minerals and soil organic matter, is likely to be unavailable for plant uptake. Chilimba *et al.*[30] proposed that the correlation between grain Se concentration and soil pH was linked to decreasing adsorption of inorganic selenate and selenite on iron/manganese oxides at increasing pH. Chilimba *et al.*[30] also noted that the chemical stability of selenate, which is taken up more rapidly than selenite by plants under most soil conditions, is greater in the soil solution at higher soil pH values. Recent studies have similarly shown that fertiliser-applied selenate is more bioavailable in Vertisols than in acidic soils such as Oxisols and Alfisols[43].

Vertisols represent about 0·5 % of the total land area of Malawi[30,43] although they are agriculturally significant, e.g. they represent about 11 % of the cultivated arable soils of Blantyre agricultural development division, which is one of the eight agricultural development divisions covering Malawi[44]. Vertisols form from Ca- and Mg-rich parent materials, such as limestones and basalts, and in topographic depressions where leached elements collect from higher elevations[43]. Vertisols have a predominantly 2:1 clay mineralogy, whereas the acidic Oxisols and moderately acidic Alfisols, which dominate most arable systems in Malawi, are characterised by larger concentrations of hydrous oxides of aluminium, iron and manganese, which can adsorb inorganic Se anions much more strongly than the Vertisols[43]. The cycling of Se between organic and inorganic forms is also likely to have a strong influence on crop Se uptake and it is noteworthy that Vertisols have a variable, but generally much larger, soil organic matter content than the Alfisols and Oxisols.

Beyond these studies in Malawi, there are only limited data on linkages between soil type and food crop composition elsewhere in SSA. However, there is circumstantial evidence to support the hypotheses: (1) that many soils in SSA will provide inadequate Se to food crops for optimal human health, especially where access to animal source foods is limited, and (2) that soil factors including pH, organic matter content and soil mineralogy directly influence crop Se concentration.

In South Africa, Courtman *et al.* reported evidence of longer-range geospatial variation in the Se concentration of maize grain, sampled from maize silos, in the context of poor livestock-feed quality linked to a (widely-recognised) high prevalence of Se deficiency among livestock[45]. Of the 896 grain samples taken from 231 silos, 46 % had <12 μg/kg, 76 % had <25 μg/kg and 88 % of samples had <40 μg/kg. Courtman *et al.* discussed these data in the context of previously published maps of total soil Se concentration and soil pH for South Africa; however, they were not able to identify a direct link between soil and grain properties in their study[45].

In the central Kenya Highlands, Ngigi *et al.* reported low Se concentrations in maize grain (range 11–48 μg/kg) and bean (range 18–48 μg/kg) from three sites of moderately acidic soils (pH 5·8–6·2)[46]. These data contrast with larger Se concentrations reported in maize grain (median 182 μg/kg; seventeen sites) and bean (median 150 μg/kg; four sites) from more alkaline soils (median pH 7·9) in a separate study in the south of Kenya[47].

In western Kenya and north-eastern Tanzania, maize grain and bean seed Se concentrations were greater in calcareous than non-calcareous soils in both countries[48]. In Kenya, median maize grain Se concentrations were 37 and 27 μg/kg and median bean seed Se concentrations were 63 and 34 μg/kg, in the calcareous (median pH 7·1) and non-calcareous (median pH 5·3) soils, respectively[48]. In Tanzania, median maize grain Se concentrations were 223 and 159 μg/kg and median bean seed Se concentrations were 256 and 138 μg/kg, in the calcareous (median pH 7·0) and non-calcareous (median pH 5·8) soils, respectively[48].

Knowledge gaps in selenium in sub-Saharan African food systems

Evidence of Se or other micronutrient deficiency linkages across the agriculture–nutrition–health domains remains scarce in SSA. Elsewhere, case studies of linkages between soil, crop, livestock and human Se status have been reviewed extensively[1–4,34–36]. For example, in China, a detailed geochemical analysis of areas with a

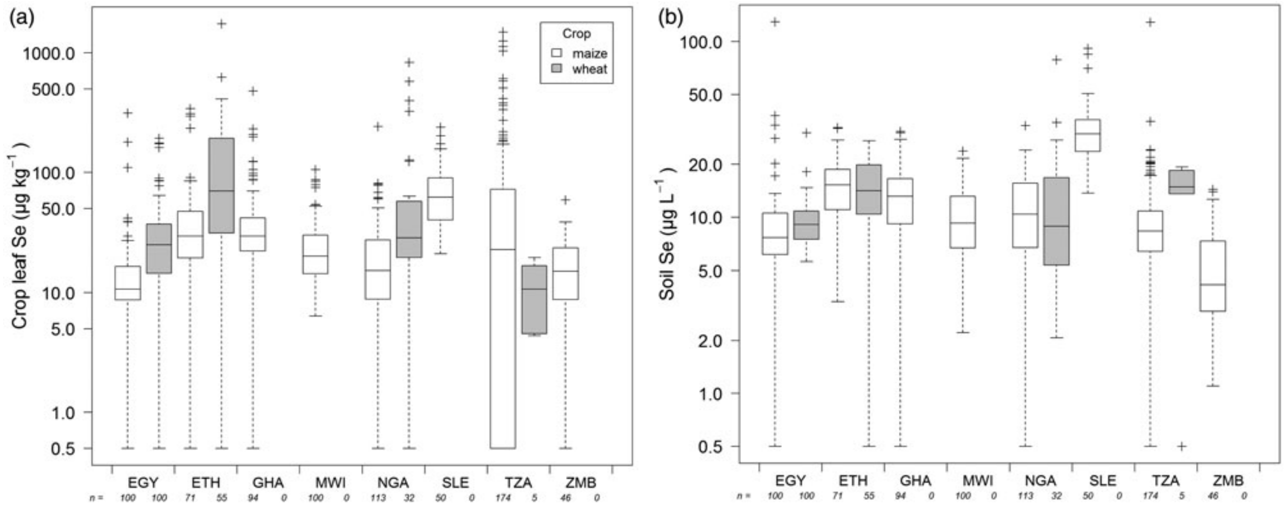

Fig. 4. Summary selenium (Se) concentration data from Sillanpää and Jansson[57] for (a) maize (white boxes) and wheat (grey boxes) leaves, (b) topsoil using acid ammonium acetate-EDTA universal extraction: Egypt (EGY), Ethiopia (ETH), Ghana (GHA), Malawi (MWI), Nigeria (NGA), Sierra Leone (SLE), Tanzania (TZA), Zambia (ZMB). Boxes represent upper and lower quartiles; whiskers are the 95 %-iles; medians are indicated within the boxes.

high incidence of Keshan disease in the late 1990s showed that the incidence was negatively correlated with water-soluble soil Se[36]. In New Zealand, increased Se intake and status correlated with the imports of Australian wheat that contained a larger concentration of Se[5,49,50]. In the UK and other countries in northern Europe, decreased Se intake and status is likely to have occurred since the mid-1970s as a consequence of altered trade leading to reductions in the imports of wheat from the USA and Canada[1–4,34–36]. This is because the grain Se concentration of wheat grown in the USA and Canada is more than ten times greater than that grown in the UK, due to the prevalence of soils containing large concentrations of plant-available Se in North American wheat-growing areas. There is no evidence of soil Se depletion due to more intensive cropping over the past century in the UK[51]. From nationally-aggregated data, polished rice from the USA and India had grain Se concentration >30 times greater than the rice sourced from Egypt[52]. In Algeria, wheat grain Se concentration from eight different areas ranged from 21 to 153 μg/kg, and correlated positively with total soil Se concentration[53]. In Finland, linkages between the supply of Se into the soil via Se-enriched fertilisers, its subsequent uptake into crops, and the Se intake and status among populations are conclusive[34,54].

In a global-scale modelling study, Jones *et al*. projected that total soil Se concentration, and thereby crop Se concentration and dietary Se intakes, will likely decrease under moderate climate-change scenarios by the years 2080–2099[55]. Decreases in total soil Se concentration, driven by complex climate–soil interactions, have been estimated to be especially pronounced in areas currently under agricultural production in southern Africa[55]. This model was developed from a compilation of fifteen data sets of total soil Se concentration (*n* 33 241). Soil data for Africa comprised: data from Chilimba *et al*.[30] and Joy *et al*.[38] for Malawi (*n* 276); data reproduced by Courtman *et al*.[45] for the South Africa maize study described earlier (*n* 148); and data from Maskall and Thornton[56] from a soil micronutrient survey of Lake Nakuru National Park, Kenya, characterised by a low total soil Se concentration (*n* 123).

In a global-scale surveillance study, Sillanpää and Jansson reported the Se status of soils and co-located plants in thirty countries, including eight in Africa[57]. Soil and plant samples were collected during an earlier survey of micronutrients which, unlike Se, are essential for plant growth, such as zinc[58,59]. Topsoil Se concentration was reported using an acid ammonium acetate-EDTA universal extraction[60]. The Se concentration of the leaf tissues of maize and wheat was used as an indicator tissue, rather than edible crop portions. Given that Se is translocated efficiently by plants, leaf Se concentration is expected to be a good proxy for relative grain Se concentration and for other food crops, including roots, tubers, leaves, fruit and therefore dietary Se intake[61]. The data are also expected to be a good proxy for Se concentrations in livestock forages. Across the global dataset (*n* 3644), a positive correlation between soil pH and plant Se concentration, and a negative correlation between soil organic carbon and plant Se concentration were reported[57].

Six countries in SSA had data represented which could be georeferenced digitally, based on original hard copy maps[57–59]. These were Ethiopia (*n* 126 locations), Malawi (*n* 100), Nigeria (*n* 145), Sierra Leone (*n* 50), Tanzania (*n* 179) and Zambia (*n* 46). Data for Ghana were not georeferenced. Egypt (*n* 200) was represented from North Africa. Summary soil and plant Se concentration data for these countries are illustrated in Figs. 4 and 5. All data, including georeferenced locations, are reproduced in Supplementary Table 2.

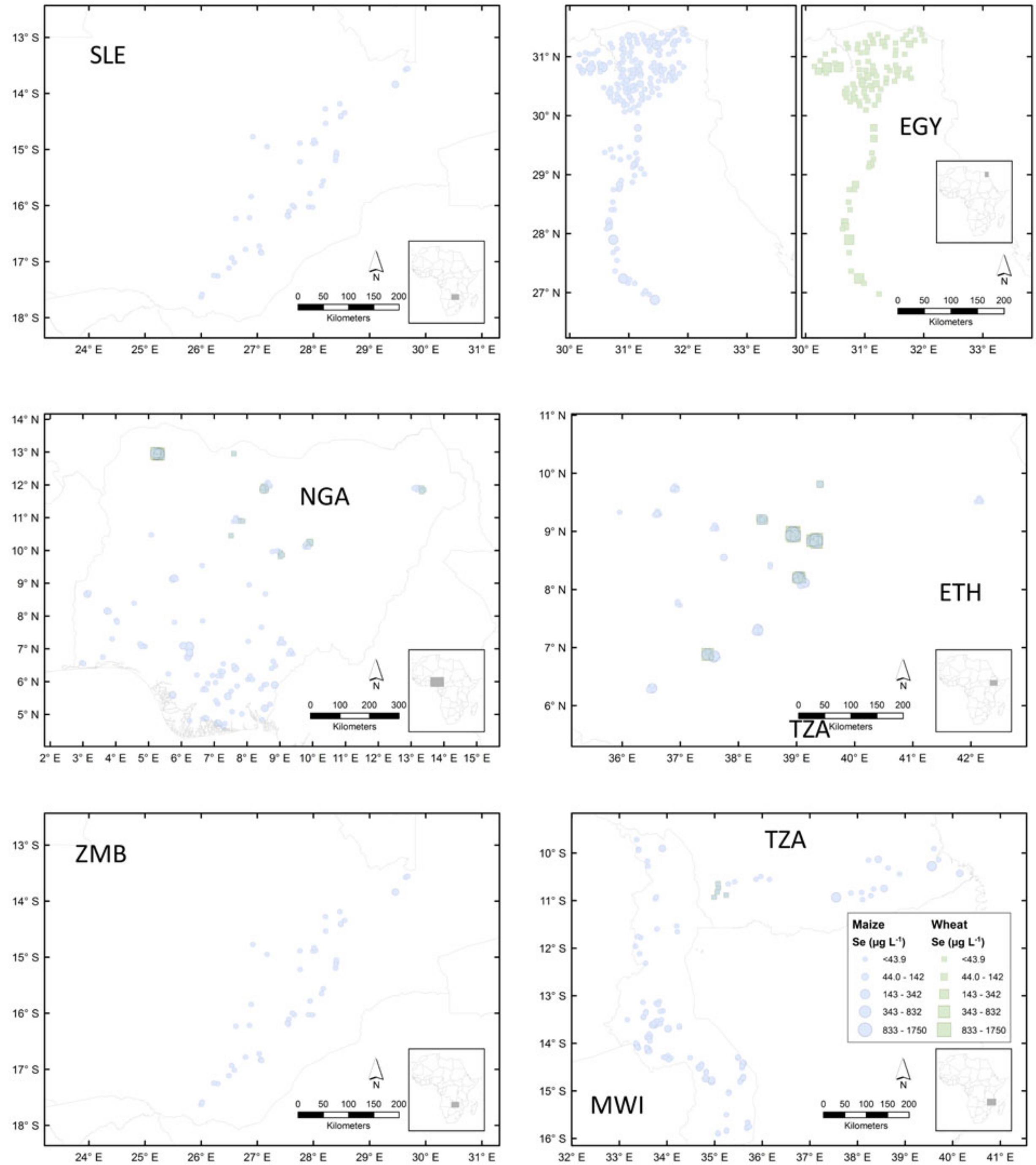

Fig. 5. Georeferenced selenium (Se) concentration data from Sillanpää and Jansson[57] for leaf maize (blue circles) and wheat (green squares): Egypt (EGY), Ethiopia (ETH), Malawi (MWI), Nigeria (NGA), Sierra Leone (SLE), Tanzania (TZA), Zambia (ZMB).

A GeoNutrition *perspective*

There is clear scope for increasing the quality of geospatially defined information on the Se status of soil, crop, livestock and human subjects in SSA. Soil maps from the Africa Soil Information Service include continental-scale elemental maps which are based on various data sources including spectral (e.g. X-ray fluorescence, mid infra-red) analysis techniques[62]. Unfortunately, it is not possible to quantify soil/crop Se concentration or human (or livestock) biomarkers of Se status, using spectral methods. Sensitive 'wet chemistry' preparation methods and instrumental analysis, e.g. using inductively coupled plasma-MS, together with good quality control procedures, is needed to measure Se accurately and rapidly.

The *GeoNutrition* project, funded by the Bill & Melinda Gates Foundation, began in 2018 with the explicit aim of mapping soil–crop–human micronutrient linkages and their uncertainties, including for Se. The primary locations for the project are cropland areas of Malawi and Ethiopia, in which co-located topsoils and mature cereal grains are being sampled and analysed. The project is also testing the effectiveness of increasing the Se concentration of cereal starch using Se fertilisers (agro-fortification)[63]. The study areas are in Malawi and Ethiopia, respectively, where previous studies have indicated that a high prevalence of Se deficiency is likely.

The protocol for the Addressing Hidden Hunger with Agronomy, Malawi trial (Registered March 2019; ISCRTN85899451) was published recently[64]. A double-blind, randomised controlled trial is being conducted in rural villages in Kasungu District, Central Region, Malawi. In this two-arm trial, 180 women (aged 20–45 years) and 180 children (aged 5–10 years) are randomised at the household level so that participants receive maize starch (330 g/capita/d) that is either enriched with Se through agro-fortification, or a control starch not enriched with Se. The primary trial outcome is serum Se concentration. The hypothesis is that the consumption of maize starch agro-fortified with Se will increase serum Se concentration in a Se-deficient population. A subsequent trial in Ethiopia will use a similar design with teff instead of maize[64]. The *GeoNutrition* project is also exploring wider socio-economic and ethical dimensions of agro-fortification and alternative interventions to address micronutrient deficiencies.

Anticipated outcomes of the *GeoNutrition* project include the stimulation of discussions on how best to use geospatial information to support policies to alleviate Se and other micronutrient deficiencies. Thus, new baseline maps and evidence (and uncertainties therein) will help to integrate evidence across the agriculture–nutrition–health domains to support policy decisions that are cost-effective and most expedient. For example, national micronutrient surveys, which currently focus solely on biomarkers and proxy outcomes of micronutrient status, could be integrated with geospatially-resolved food composition/consumption surveys. Such data could then be viewed in the context of current and future agricultural production and trade which, in turn, will be affected by demographic, socio-economic and environmental change at multiple scales[65].

Supplementary material

The supplementary material for this article can be found at https://doi.org/10.1017/S0029665120006904

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Conflict of Interest

None.

Authorship

The paper was conceived and written by I. S. L., F. P. P. and M. R. B.. D. K. B. georeferenced the primary data from Sillanpää and Jansson[57]. E. J. M. J. contributed to the literature survey of blood selenium concentration data from continental Africa. E. L. A. contributed to the production of new and revised figures. All authors contributed to the final version of the paper.

References

1. Fairweather-Tait SJ, Bao YP, Broadley MR *et al.* (2011) Selenium in human health and disease. *Antioxid Redox Signal* **14**, 1337–1383.
2. Rayman MP (2000) The importance of selenium to human health. *Lancet* **356**, 233–241.
3. Rayman MP (2008) Food-chain selenium and human health: emphasis on intake. *Br J Nutr* **100**, 254–268.
4. Rayman MP (2012) Selenium and human health. *Lancet* **379**, 1256–1268.
5. Thomson CD (2004) Selenium and iodine intakes and status in New Zealand and Australia. *Br J Nutr* **91**, 661–672.
6. Hurst R, Armah CN, Dainty JR *et al.* (2010) Establishing optimal selenium status: results of a randomized, double-blind, placebo-controlled trial. *Am J Clin Nutr* **91**, 923–931.
7. IOM, Institute of Medicine of the National Academies (2002) *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids*. Washington, DC: National Academies Press.
8. Phiri FP, Ander EL, Lark RM *et al.* (2020) Urine selenium concentration is a useful biomarker for assessing population level selenium status. *Environ Int* **134**, 105218.
9. Hays SM, Macey K, Nong A *et al.* (2014) Biomonitoring equivalents for selenium. *Regul Toxicol Pharmacol* **70**, 333–339.
10. Combs GF (2015) Biomarkers of selenium status. *Nutrients* **7**, 2209–2236.
11. Longnecker MP, Stram DO, Taylor PR *et al.* (1996) Use of selenium concentration in whole blood, serum, toenails, or urine as a surrogate measure of selenium intake. *Epidemiology* **7**, 384–390.
12. Combs GF (2001) Selenium in global food systems. *Br J Nutr* **85**, 517–547.
13. Goyens P, Golstein J, Nsombola B *et al.* (1987) Selenium deficiency as a possible factor in the pathogenesis of

myxoedematous endemic cretinism. *Acta Endocrinol* (*Copenh*) **114**, 497–502.
14. Vanderpas JB, Contempré B, Duale NL *et al.* (1990) Iodine and selenium deficiency associated with cretinism in northern Zaire. *Am J Clin Nutr* **52**, 1087–1093.
15. Contempre B, Dumont JE, Ngo B *et al.* (1991) Effect of selenium supplementation in hypothyroid subjects of an iodine and selenium deficient area: the possible danger of indiscriminate supplementation of iodine-deficient subjects with selenium. *J Clin Endocrinol Metab* **73**, 213–215.
16. Contempré B, Duale NL, Dumont JE *et al.* (1991) Effect of selenium supplementation on thyroid hormone metabolism in an iodine and selenium deficient population. *Clin Endocrinol* **36**, 579–583.
17. Thilly C-H, Swennen B, Bourdoux P *et al.* (1993) The epidemiology of iodine-deficiency disorders in relation to goitrogenic factors and thyroid-stimulating hormone regulation. *Am J Clin Nutr* **57**, 267S–270S.
18. Ngo DB, Dikassa L, Okitolonda W *et al.* (1997) Selenium status in pregnant women of a rural population (Zaire) in relationship to iodine deficiency. *Trop Med Int Health* **2**, 572–581.
19. Tuakuila J, Kabamba M, Mata H *et al.* (2014) Toxic and essential elements in children's blood (<6 years) from Kinshasa, DRC (the Democratic Republic of Congo). *J Trace Elem Med Biol* **28**, 45–49.
20. Bumoko GM-M, Sadiki NH, Rwatambuga A *et al.* (2015) Lower serum levels of selenium, copper, and zinc are related to neuromotor impairments in children with konzo. *J Neurol Sci* **349**, 149–153.
21. Gashu D, Stoecker BJ, Adish A *et al.* (2016a) Association of serum selenium with thyroxin in severely iodine-deficient young children from the Amhara region of Ethiopia. *Eur J Clin Nutr* **70**, 929–934.
22. Gashu D, Stoecker BJ, Adish A *et al.* (2016b) Ethiopian pre-school children consuming a predominantly unrefined plant-based diet have low prevalence of iron-deficiency anaemia. *Public Health Nutr* **19**, 1834–1841.
23. Gashu D, Marquis GS, Bougma K *et al.* (2018) Selenium inadequacy hampers thyroid response of young children after iodine repletion. *J Trace Elem Med Biol* **50**, 291–295.
24. Gashu D, Marquis GS, Bougma K *et al.* (2019) Spatial variation of human selenium in Ethiopia. *Biol Trace Elem Res* **189**, 354–360.
25. Arnaud J, Malvy D, Richard MJ *et al.* (2001) Selenium status in a deficient population of the west Ivory Coast. *J Physiol Anthropol* **20**, 81–84.
26. Tiahou G, Maire B, Dupuy A *et al.* (2004) Lack of oxidative stress in a selenium deficient area in Ivory Coast. Potential nutritional antioxidant role of crude palm oil. *Eur J Nutr* **43**, 367–374.
27. van Lettow M, Harries AD, Kumwenda JJ *et al.* (2004) Micronutrient malnutrition and wasting in adults with pulmonary tuberculosis with and without HIV co-infection in Malawi. *BMC Infect Dis* **4**, 61.
28. van Lettow M, West CE, van der Meer JWM *et al.* (2005) Low plasma selenium concentrations, high plasma human immunodeficiency virus load and high interleukin-6 concentrations are risk factors associated with anemia in adults presenting with pulmonary tuberculosis in Zomba district, Malawi. *Eur J Clin Nutr* **59**, 526–532.
29. Donovan UM, Gibson RS, Ferguson EL *et al.* (1992) Selenium intakes of children from Malawi and Papua New Guinea consuming plant-based diets. *J Trace Elem Electrolytes Health Dis* **6**, 39–43.
30. Chilimba ADC, Young SD, Black CR *et al.* (2011) Maize grain and soil surveys reveal suboptimal dietary selenium intake is widespread in Malawi. *Sci Rep* **1**, 72.
31. Hurst R, Siyame EWP, Young SD *et al.* (2013) Soil-type influences human selenium status and underlies widespread selenium deficiency risks in Malawi. *Sci Rep* **3**, 1425.
32. Stefanowicz FA, Talwar D, O'Reilly DSJ *et al.* (2013). Erythrocyte selenium concentration as a marker of selenium status. *Clin Nutr* **32**, 837–842.
33. Phiri FP, Ander EL, Bailey EH *et al.* (2019) The risk of selenium deficiency in Malawi is large and varies over multiple spatial scales. *Sci Rep* **9**, 6566.
34. Fordyce F (2005) Selenium deficiency and toxicity in the environment. In *Essentials of Medical Geology*, pp. 373–415 [O Selinus, B Alloway, J Centeno, R Finkelman, R Fuge, U Lindh and P Smedley, editors]. London, UK: Elsevier.
35. Broadley MR, White PJ, Bryson RJ *et al.* (2006) Biofortification of U.K. food crops with selenium (Se). *Proc Nutr Soc* **65**, 169–181.
36. Johnson CC, Fordyce FM & Rayman MP (2010) Factors controlling the distribution of selenium in the environment and their impact on health and nutrition. *Proc Nutr Soc* **69**, 119–132.
37. Joy EJM, Ander EL, Young SD *et al.* (2014) Dietary mineral supplies in Africa. *Physiol Plant* **151**, 208–229.
38. Joy EJM, Broadley MR, Young SD *et al.* (2015a) Soil type influences crop mineral composition in Malawi. *Sci Total Environ* **505**, 587–595.
39. Joy EJM, Kumssa DB, Broadley MR *et al.* (2015b) Dietary mineral supplies in Malawi: spatial and socioeconomic assessment. *BMC Nutr* **1**, 42.
40. Carriquiry AL (1999) Assessing the prevalence of nutrient inadequacy. *Public Health Nutr* **2**, 23–34.
41. Benemariya H, Robberecht H & Deelstra H (1993) Daily dietary intake of copper, zinc, and selenium by different population groups in Burundi, Africa. *Sci Total Environ* **136**, 49–76.
42. Eick F, Maleta K, Govasmark E *et al.* (2009) Food intake of selenium and sulphur amino acids in tuberculosis patients and healthy adults in Malawi. *Int J Tuberc Lung Dis* **13**, 1313–1315.
43. Ligowe IS, Young SD, Ander EL *et al.* (2020) Agronomic biofortification of leafy vegetables grown in an Oxisol, Alfisol and Vertisol with isotopically labelled selenium (^{77}Se). *Geoderma* **361** [Epublication ahead of print version].
44. Chilimba ADC (2001) Vertisols management in Malawi. In *The Sustainable Management of Vertisols*, pp. 73–84 [JK Syers, FP de Vries and P Nyamudeza, editors]. Oxfordshire, UK: CAB International.
45. Courtman C, van Ryssen JBJ & Oelofse A (2012) Selenium concentration of maize grain in South Africa and possible factors influencing the concentration. *S Afr J Anim Sci* **42** Suppl. 1, 454–458.
46. Ngigi PB, Lachat C, Masinde PW *et al.* (2019) Agronomic biofortification of maize and beans in Kenya through selenium fertilization. *Environ Geochem Health* **41**, 2577–2591.
47. Kumssa DB, Joy EJM, Young SD *et al.* (2017) Variation in the mineral element concentration of *Moringa oleifera* Lam. and *M. stenopetala* (Bak. f.) Cuf.: role in human nutrition. *PLoS ONE* **12**, e0175503.
48. Watts MJ, Middleton DRS, Marriott AL *et al.* (2019) Source apportionment of micronutrients in the diets of Kilimanjaro, Tanzania and Counties of Western Kenya. *Sci Rep* **9**, 14447.
49. Watkinson JH (1981) Changes of blood selenium in New Zealand adults with time and importation of Australian wheat. *Am J Clin Nutr* **34**, 936–942.

50. Thomson CD & Robinson MF (1996) The changing selenium status of New Zealand residents. *Eur J Clin Nutr* **50**, 107–114.
51. Fan M-S, Zhao F-J, Poulton PR *et al*. (2008) Historical changes in the concentrations of selenium in soil and wheat grain from the Broadbalk experiment over the last 160 years. *Sci Total Environ* **389**, 532–538.
52. Williams PN, Lombi E, Sun GX *et al*. (2009) Selenium characterization in the global rice supply chain. *Environ Sci Technol* **43**, 6024–6030.
53. Beladel B, Nedjimi B, Mansouri A *et al*. (2013) Seleniun content in wheat and estimation of the selenium daily intake in different regions of Algeria. *App Radiat Isot* **71**, 7–10.
54. Alfthan G, Eurola M, Ekholm P *et al*. (2015) Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: from deficiency to optimal selenium status of the population. *J Trace Elem Med Biol* **31**, 142–147.
55. Jones GD, Droz B, Greve P *et al*. (2017) Selenium deficiency risk predicted to increase under future climate change. *Proc Natl Acad Sci USA* **114**, 2848–2853.
56. Maskall JE & Thornton I (1989) The mineral status of Lake Nakuru National Park, Kenya – a reconnaissance survey. *Afr J Ecol* **27**, 191–200.
57. Sillanpää M & Jansson H (1992) *Status of Cadmium, Lead, Cobalt and Selenium in Soils and Plants of Thirty Countries*. FAO Soils Bulletin 65, 195 pp. Rome, Italy: Food and Agriculture Organization of the United Nations.
58. Sillanpää M (1982) *Micronutrients and the Nutrient Status of Soils: A Global Study*. FAO Soils Bulletin 48, 444 pp. Rome, Italy: Food and Agriculture Organization of the United Nations.
59. Sillanpää M (1990) *Micronutrient Assessment at the Country Level: An International Study*. FAO Soils Bulletin 63, 208 pp. Rome, Italy: Food and Agriculture Organization of the United Nations.
60. Sippola J (1994) Acid ammonium acetate – EDTA universal extractant in soil testing and environmental monitoring. *Commun Soil Sci Plant Anal* **25**, 1755–1761.
61. White PJ (2015) Selenium accumulation by plants. *Ann Bot* **117**, 217–235.
62. Hengl T, Heuvelink GBM, Kempen B *et al*. (2015) Mapping soil properties of Africa at 250 m resolution: random forests significantly improve current predictions. *PLoS ONE* **10**, e0125814.
63. Chilimba ADC, Young SD, Black CR *et al*. (2012) Agronomic biofortification of maize with selenium (Se) in Malawi. *Field Crops Res* **125**, 118–128.
64. Joy EJM, Kalimbira AA, Gashu D *et al*. (2019) Can selenium deficiency in Malawi be alleviated through consumption of agro-biofortified maize flour? Study protocol for a randomised, double-blind, controlled trial. *Trials* [Epublication 30 December 2019].
65. Nelson G, Bogard J, Lividini K *et al*. (2018) Income growth and climate change effects on global nutrition security to mid-century. *Nat Sustain* **1**, 773–781.