Global magnesium supply in the food chain


A School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough, LE12 5RD, UK.
B Centre for Environmental Geochemistry, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.
C Crops For the Future, The University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia.
D Center for Magnesium Education & Research, LLC, 13-1255 Malama St., Pahoa, HI 96778, USA.
E The James Hutton Institute, Invergowrie, Dundee, DD2 5DA, UK; Distinguished Scientist Fellowship Program, King Saud University, Riyadh, Saudi Arabia.
F Corresponding author. Email: martin.broadley@nottingham.ac.uk

Abstract. Magnesium (Mg) is an essential mineral micronutrient in humans. Risks of dietary Mg deficiency are affected by the quantity of Mg ingested and its bioavailability, which is influenced by the consumption of other nutrients and ‘anti-nutrients’. Here, we assess global dietary Mg supplies and risks of dietary deficiency, including the influence of other nutrients. Food supply and food composition data were used to derive the amount of Mg available per capita at national levels. Supplies of Mg were compared with estimated national per capita average requirement ‘cut points’. In 2011, global weighted mean Mg supply was 613 ± 69 mg person−1 day−1 compared with a weighted estimated average requirement for Mg of 173 mg person−1 day−1. This indicates a low risk of dietary Mg deficiency of 0.26% based on supply. This contrasts with published data from national individual-level dietary surveys, which indicate greater Mg deficiency risks. However, individuals in high-income countries are likely to under-report food consumption, which could lead to overestimation of deficiency risks. Furthermore, estimates of deficiency risk based on supply do not account for potential inhibitors of Mg absorption, including calcium, phytic acid and oxalate, and do not consider household food wastage.

Additional keywords: bioavailability, calcium, cereal, phytic acid, EAR.

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Introduction

Magnesium (Mg) is an essential mineral micronutrient in humans, required for a variety of physiological functions. The recommended nutrient intake for men 19–65 years old is 260 mg day−1 (WHO and FAO 2004). A healthy adult contains ~24 g Mg, mainly in bone, muscle and soft tissues (Ebel and Güntner 1980; Elin 1987; Vormann 2003; WHO and FAO 2004). Magnesium is a cofactor in >350 enzymatic reactions, with roles including protection from oxidative stress, and metabolism of calcium (Ca), vitamin D and potassium (Ebel and Güntner 1980; Elin 1987; WHO and FAO 2004; Atkinson et al. 2009; Broadley et al. 2012; Deng et al. 2013; Das 2014; Dibaba et al. 2014; Rodríguez-Moran and Guerrero-Romero 2014). Deficiency in Mg can manifest as metabolic syndrome (Gartside and Glueck 1995; Hata et al. 2013; Rosanoff and Plesset 2013; Cosaro et al. 2014; Ju et al. 2014; Panhwar et al. 2014), lower bone-mineral density (Orchard et al. 2014), premenstrual syndrome (Elin 1987), and attention deficit hyperactivity disorder (Blaszczyk and Duda-Chodak 2013).

Magnesium is obtained primarily from food sources, although drinking and cooking water can make important contributions depending on its hardness and the volume of water consumed (Ong et al. 2009). Median dissolved Mg concentrations of North American spring, mineral, and groundwater from various regions ranged from 0 to 130 mg L−1 (Azoulay et al. 2001). Magnesium contents of some commercially available bottled waters in Europe were, for example, 36, 110, and 128 mg L−1 for Abbey Well from the UK, Vichy Nouvelle from Finland, and Robacher Well from the UK, respectively (Azoulay et al. 2001). However, unrefined cereals, legumes and green leafy vegetables are the primary dietary sources of Mg (Broadley and White 2010; Blaszczyk and Duda-Chodak 2013). The bioavailability and absorption of ingested Mg is affected by other nutrients and ‘anti-nutrients’. For example, high concentrations of phytate in cereal and legume seeds, and oxalate in some leafy vegetables, can reduce Mg absorption through chelation in the gut (Brink and Beynen 1991; Bohn et al. 2004a). Addition of 1.5 mmol of phytic acid (PA, in dodecasodium salt hydrate form) to white bread reduced Mg absorption from 33% to 13% in human feeding studies (Bohn et al. 2004b). Similarly, Bohn et al. (2004a) reported that Mg absorption from a meal containing oxalate-rich spinach (Spinacia oleracea L.) was 27%, compared
with 37% from a meal containing kale (Brassica oleracea L.), which has a lower oxalate concentration. Fractional Mg absorption of 44% (Sabatier et al. 2003) and 35% (Marshall et al. 1976) has been reported in typical Western diets. A study on rats showed that increased Ca intake led to reduced intestinal absorption and renal re-absorption of Mg (Bertinato et al. 2014), although Palacios et al. (2013) reported no effects of Ca intake on urinary Mg excretion in females aged 11–15 years. Nonetheless, absorption of Mg is under homeostatic control and can increase when there is deficiency of Mg in the human body (Hansen et al. 2014).

Dietary Mg intake and the prevalence of deficiency risks can be estimated from tissue biomarkers, food recall or food balance sheets (FBSs) (Ford and Mokdad 2003; Broadley et al. 2012; Joy et al. 2013, 2014; Ju et al. 2014; Rodriguez-Moran and Guerrero-Romero 2014; Kumssa et al. 2015). However, the accuracy of estimates of the prevalence of Mg deficiency risks, using tissue biomarkers, suffers from the lack of a reliable index (Reinhart 1988; Hansen et al. 2014; Ong et al. 2014). Estimates based on dietary intakes are preferred, particularly for wide-scale assessment. Dietary recall studies suggest high risks of Mg deficiency. For example, ~60% of the USA population were reported to consume Mg below an estimated average requirement (EAR) of 330 mg person \(^{-1}\) day \(^{-1}\) for men aged 19–30 based on the National Health and Nutrition Examination Survey (NHANES) 24-h dietary recall in 1999 and 2000 (Ford and Mokdad 2003). The EAR is the daily nutrient intake estimated to meet the requirements of half of the healthy individuals in a given age- and sex-specific population (IOM 2000). During the 2001–02 NHANES, 64% and 67% of men and women ≥19 years of age, respectively, had Mg intake less than the EAR (Moshegh et al. 2005, cited in Rosanoff 2010). Similarly, in the UK, the National Diet and Nutrition Survey (NDNS) from 2008–09 to 2011–12 reported that 53% of females aged 11–18 years, 14% of adults aged 19–64 years and 19% of males ≥65 years had dietary Mg intakes below their lower reference nutrient intake (LRNI), as measured using a 4-day diary dietary record (Bates et al. 2014). The LRNI is an intake level sufficient for <2.5% of the age- and sex-specific population group and is 190 mg person \(^{-1}\) day \(^{-1}\) for all people aged 15–18 years and adult males. However, dietary-recall or diary methods are known to be affected by misreporting, especially under-reporting in developed countries, and behavioural change (Bingham et al. 1994; IOM 2000; Rennie et al. 2004, 2005, 2007; Mirmiran et al. 2006; Liberato et al. 2009; Archer et al. 2013; Bates et al. 2014; Winkler 2014). In addition, dietary survey data are lacking in many developing countries (Gibson 2005), as well as site-specific and relevant food composition data to determine the Mg concentrations of foods consumed (Joy et al. 2014, 2015; Kumssa et al. 2015).

Global-scale estimates of Mg supply and deficiency risks have not been reported. However, estimates of mean global Ca supply in 2011 of 684 ± 211 mg person \(^{-1}\) day \(^{-1}\) by Kumssa et al. (2015) based on FBSs were similar to those of Imamura et al. (2015), who estimated median Ca intake of 611 mg person \(^{-1}\) day \(^{-1}\) (third quintile range 553–658) from a large meta-analysis of milk consumption as a proxy for Ca intake, based primarily on dietary recall data. The global risk of zinc (Zn) deficiency has been estimated, based on FBS supply, to be 16% in 2011 by Kumssa et al. (2015) and 17% in 2003–07 by Wessells and Brown (2012). In Africa, a mean continental Mg supply of 678 mg person \(^{-1}\) day \(^{-1}\) was estimated from FBSs and African food composition data, with a 0.7% prevalence of deficiency risk (Joy et al. 2014). The aims of the present study were (i) to estimate the global risk of dietary Mg deficiency based on food supply, composition and demographics; and (ii) to assess the potential impact of the supply of other components of human diet that might affect the bioavailability of Mg.

Materials and methods

Methods are identical to those described previously for estimating the risks of dietary Ca and Zn deficiencies (Kumssa et al. 2015). Briefly, secondary data for food supply, food composition, demography and EAR for Mg were integrated for 145 countries with populations ≥1 million by using food-supply and demographic data from 1992 to 2011. The EAR ‘cut-point’ (EAR-CP) method was used to assess the prevalence of Mg deficiency risks.

Data sources

The four types of datasets required for this study were food supply, food composition, the EAR for Mg, and national demographic data. Per capita food supply data for 94 food items were obtained from the Food and Agriculture Organisation of the United Nations (FAO) Statistics Division (FAOSTAT) website for the years 1992–2011 (FAO 2014). Food composition data were obtained from the United States Department of Agriculture (USDA) National Nutrient Database for Standard Reference 26 (USDA SR26), which was released in 2013 (USDA 2013). The EARs for Mg were obtained from the World Health Organisation (WHO) and FAO vitamin and mineral requirements (WHO and FAO 2004). Demographic data were obtained from the United Nations Department of Economic and Social Affairs Population Division, Population Estimates and Projection (United Nations 2013). Spatial aggregation of countries was made based on FAO regional and continental classification (http://faostat.fao.org/site/371/default.aspx). Income level aggregation was obtained from the World Data Bank, World Development Indicators in February 2015, and countries are kept within the same group from 1992–2011 (http://databank.worldbank.org/data/reports.aspx?source=World-Development-Indicators).

Magnesium supply

The 94 food items from the FAOSTAT food supply (g person \(^{-1}\) day \(^{-1}\)) data (see Supplementary Materials table S1, available on the Journal’s website) were matched (sensu Stadlmayr et al. 2011) with the Mg composition of fresh and/or uncooked food commodities in the nutrient composition data. The nutrient composition of food items was assumed not to change with time or location. Per capita Mg supply from each food item in each country was calculated by multiplying the per capita food supply by its nutrient concentration. Magnesium supply from each food commodity was summed within country to obtain the per capita nutrient supply at a national level. Magnesium supplies from fortification and supplements, and drinking and cooking water were not accounted for in this study.
Magnesium intakes and requirements
Magnesium intakes were estimated as the mean per capita Mg supply at a national level, with an inter-individual coefficient of variation of 25% (Wessells and Brown 2012; Joy et al. 2013). The EAR for Mg is available according to age (~5-year groupings) and gender classes (WHO and FAO 2004). As a result, a national weighted EAR was calculated (WtdEAR) (Eqn 1), using the population size in each age and gender group for each country and year. For a given age or gender group, the EAR was assumed to remain unchanged whereas the WtdEAR varied with the population structure, which in turn varied between countries and years. The WtdEAR for Mg is hence assumed to approximate the per capita intake that fulfils the Mg requirements of half of the healthy individuals in a population of a given country in a specific year:

\[
WtdEAR = \frac{\sum (EAR_{\text{group}} \times \text{GroupPop})}{\text{TotalPop}} \quad (1)
\]

where \(EAR_{\text{group}}\) is the EAR for Mg of a given age or gender group, \(\text{GroupPop}\) is the population size of a given age or gender group, and \(\text{TotalPop}\) is the total population in a given year for a given country.

Estimated average requirement ‘cut-point’
The prevalence of Mg-deficiency risk was assessed using the EAR-CP as described and used by Carriquiry (1999), Wuehler et al. (2005), Joy et al. (2014) and Kumssa et al. (2015). The EAR-CP method yields an estimate of the number of people in a given country and year with intakes of Mg below the WtdEAR, which is termed hereafter as the ‘deficiency risk’. The EAR-CP method has been applied with the following underlying assumptions: (i) little correlation between requirement and intake; (ii) the distribution of requirement is symmetrical around the EAR; and (iii) variability in intake is greater than the variability in requirement (IOM 2000).

Nutritional ratio
Dietary Ca and phytate, which represents the mixed salts of PA, or myo-inositol hexakisphosphate, were calculated in a similar manner to Mg. The PA and Ca data are those presented previously (Kumssa et al. 2015). The Ca : Mg ratio was calculated on a gravimetric basis (Rosanoff 2010), whereas the Mg : PA ratio was derived from the molar weights (Mg = 24.3 g mol\(^{-1}\), PA = 660 g mol\(^{-1}\)) (Cheryan et al. 1983).

Aggregating information
Spatial aggregation (i.e. regional, continental, global) and income level aggregations (i.e. low income, lower middle income, upper middle income, high income) of the mean and standard deviation (s.d.) of Mg supply, WtdEAR, and deficiency risk, and Ca : Mg and Mg : PA ratios, were weighted by the national population size. (See example in Eqns 2 and 3 below.) Aggregated information is presented as mean ± s.d. unless specified.

Data analyses and visualisation
Datasets were compiled using Microsoft Excel 2013 and exported to Microsoft Access 2013 (Microsoft Corp., Redmond, WA, USA) to make a relational database. The database was queried to extract the per capita Mg supply, and the WtdEAR for Mg. The risk of Mg deficiency during the 20-year period was then calculated in Microsoft Excel. Visualisations and calculations of descriptive statistics were carried out in Tableau Software for desktop version 8.3 (Tableau Software, Seattle, WA, USA), GraphPad Prism 6 (GraphPad Software, San Diego, CA, USA) and ArcGIS 10.2.1 (Esri, Redlands, CA, USA). Country boundaries for thematic mapping were obtained from the GADM Global Administrative Areas database (http://gadm.org/; Version 2; accessed January 2014). Aggregation of (i) per capita mean (Eqn 2) and (ii) standard deviation (Eqn 3) of supply (mg person\(^{-1}\) day\(^{-1}\)), WtdEAR (mg person\(^{-1}\) day\(^{-1}\)), and deficiency risk (%) of Mg at regional level are presented as an example:

\[
WtdMeanMgSup_i = \frac{\sum (\text{MgSup}_j \times \text{PCountry}_j)}{\sum \text{Population}} \quad (2a)
\]

where \(WtdMeanMgSup_i\) is the weighted mean Mg supply in region \(i\), \(\text{MgSup}_j\) is the Mg supply in country \(j\), and \(\text{PCountry}_j\) is the population in country \(j\).

\[
WtdMgWtdMeanEAR_i = \frac{\sum (\text{WtdEAR}_j \times \text{PCountry}_j)}{\sum \text{Population}} \quad (2b)
\]

where \(WtdMgWtdMeanEAR_i\) is the weighted mean Mg WtdEAR in region \(i\) and \(\text{WtdEAR}_j\) is the per capita Mg WtdEAR in country \(j\).

\[
WtdMgMeanDefRisk_i = \frac{\sum (\text{MgDefRisk}_j \times \text{PCountry}_j)}{\sum \text{Population}} \quad (2c)
\]

where \(WtdMgMeanDefRisk_i\) is the weighted Mg deficiency risk (%) in region \(i\), and \(\text{MgDefRisk}_j\) is the Mg deficiency risk (%) in country \(j\).

\[
SD_{\text{MgPerFood}} = \sqrt{\frac{\sum_j (\text{MgPerFood}_j - WtdMeanMgPerFood_i)^2 \times \text{PCountry}_j}{\sum \text{Population}}} \quad (3a)
\]

where \(SD_{\text{MgPerFood}}\) is the standard deviation of Mg supply per food item in region \(i\), \(\text{MgPerFood}_j\) is the Mg composition of a food item in country \(j\) in region \(i\), \(WtdMeanMgPerFood_i\) is the weighted mean of Mg composition of a food item in region \(i\), \(\text{PCountry}_j\) is the population of country \(j\) in region \(i\), and \(\sum \text{Population}\) is the sum of population in region \(i\).

\[
SD_{\text{MgSup}} = \sqrt{\frac{\sum_j (\text{MgSup}_j - WtdMeanMgSup_i)^2 \times \text{PCountry}_j}{\sum \text{Population}}} \quad (3b)
\]

where \(SD_{\text{MgSup}}\) is the standard deviation of Mg supply in region \(i\).
Results

Magnesium supply and deficiency risk

Globally, the weighted mean Mg supplies were 558 ± 61 mg person\(^{-1}\) day\(^{-1}\) in 1992 and 613 ± 69 mg person\(^{-1}\) day\(^{-1}\) in 2011, and the respective weighted mean WtdEARs were 166 ± 3 and 173 ± 3 mg person\(^{-1}\) day\(^{-1}\). Consequently, 0.37% and 0.26% of the population were likely at risk of dietary Mg deficiency in 1992 and 2011, respectively. Globally in 2011, the number of people likely to be at risk of Mg deficiency was ~14 million based on supply data (Fig. 1 and Supplementary table S2).

At a continental level in 2011, the supplies of Mg in Africa, the Americas, Asia, Europe and Oceania, respectively, were 653 ± 95, 556 ± 45, 615 ± 69, 627 ± 54 and 552 ± 4 mg person\(^{-1}\) day\(^{-1}\); the WtdEARs for Mg were 159 ± 3, 174 ± 3, 174 ± 3, 180 ± 1 and 178 ± 1 mg person\(^{-1}\) day\(^{-1}\); and the risks of Mg deficiency were 0.19%, 0.33%, 0.26%, 0.24% and 0.33% (Supplementary table S3). In Africa, the Americas, Asia, Europe and Oceania, respectively, the number of people at risk of Mg deficiency in 2011 was 1.2, 2.8, 8.6, 1.6 and 0.1 million (Supplementary table S3). Regionally in 2011, Mg supplies ranged from 492 ± 34 person\(^{-1}\) day\(^{-1}\) for Southeast Asia to 848 ± 114 mg person\(^{-1}\) day\(^{-1}\) for Northern Africa. The risk of Mg deficiency in 2011 ranged from 0.08% in Northern Africa to 0.64% in Caribbean (Fig. 2 and Supplementary table S4). At a country level, the supply of Mg in 2011 ranged from 340 to 944 mg person\(^{-1}\) day\(^{-1}\) (Fig. 3 and Supplementary table S5). In 1992, the supplies of Mg ranged from 460 ± 93 mg person\(^{-1}\) day\(^{-1}\) in low-income countries to 594 ± 57 mg person\(^{-1}\) day\(^{-1}\) in high-income countries, with respective deficiency risks of 0.75% and 0.27%. In 2011, the supplies of Mg ranged from 549 ± 103 mg person\(^{-1}\) day\(^{-1}\) in low-income countries to 679 ± 107 mg person\(^{-1}\) day\(^{-1}\) in upper middle-income countries, with respective Mg deficiency risks of 0.35% and 0.21% (Fig. 4 and Supplementary table S6).

Sources of dietary magnesium

Typically, 40–80% of dietary Mg in all regions and years originated from cereals (Fig. 5). For example, in 2011, 79% of dietary Mg in Afghanistan originated from wheat, 64% in

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**Fig. 1.** Global weighted mean magnesium (Mg) supply, weighted estimated average requirement (WtdEAR) and deficiency risk between 1992 and 2011. Capped lines are ± standard deviation.
Fig. 2. Regional population-weighted mean magnesium (Mg) supply and deficiency risk between 1992 and 2011. Horizontal broken lines represent the population-weighted mean weighted estimated average requirement.

Fig. 3. National magnesium (Mg) supplies in (a) 1992 and (c) 2011, and Mg deficiency risks in (b) 1992 and (d) 2011.
Bangladesh from rice, and 63% in Zambia from maize (Supplementary table S7). In high-income countries, wheat provided 43% of dietary Mg, while aquatic plants, nuts, potatoes and vegetables contributed 6% each to dietary Mg

**Nutritional ratios**

Globally, the Ca : Mg supply ratios were 0.96 ± 0.49 in 1992 and 1.11 ± 0.38 in 2011 (Supplementary table S2). In 2011 at a continental level, the Ca : Mg ratios were 0.72 ± 0.24 in Africa, 1.55 ± 0.41 in the Americas, 1.01 ± 0.23 in Asia, 1.57 ± 0.21 in Europe and 1.69 ± 0.08 in Oceania (Supplementary table S3). In 2011, regionally, the Ca : Mg ratios ranged from 0.61 ± 0.1 in Western Africa to 2.00 ± 0.08 in Northern America (Supplementary table S4), and at a country level from 0.36 to 2.15 (Fig. 7 and Supplementary table S5). For low and high income countries, respectively, Ca : Mg ratios ranged from 0.64 ± 0.20 to 1.72 ± 0.55 in 1992 and from 0.71 ± 0.23 to 1.64 ± 0.32 in 2011 (Fig. 4 and Supplementary table S6).

Global Mg : PA ratios were 8.00 ± 1.53 in 1992 and 7.99 ± 1.48 in 2011 (Supplementary table S2). At a continental level, the Mg : PA ratios in 2011 were 6.81 ± 1.26 in Africa, 7.97 ± 1.59 in the Americas, 8.00 ± 1.33 in Asia, 9.49 ± 0.94 in Europe and 8.91 ± 0.68 in Oceania (Supplementary table S3). Regionally, the Mg : PA ratios in 2011 ranged from 5.65 ± 0.49 in Central America to 11.18 ± 0.65 in Central Asia (Supplementary table S4). At a country level, the Mg : PA ratios ranged from 4.67 to 13.49 in 2011 (Fig. 7 and Supplementary table S5). For low and high income countries, respectively, the Mg : PA ratios ranged from 6.02 ± 0.8 to 9.49 ± 1.03 in 1992 and from 6.11 ± 0.96 to 9.21 ± 0.87 in 2011 (Fig. 4 and Supplementary table S6).

**Discussion**

The global prevalence of dietary Mg-deficiency risk, based on food supply data, was <1% during 1992–2011 and decreased over this period. In 2011, 14 million people globally were likely at risk of dietary Mg deficiency, based on these data. The decreasing trend in the risk of dietary Mg deficiency is likely due to the overall increase in global food production, especially cereals, which are the major sources of dietary Mg (Welch and Graham 1999; Pingali 2012; FAO, IFAD, WFP 2014). This is in agreement with published estimates of dietary Mg-deficiency risks for Africa (Broadley et al. 2012; Joy et al. 2013, 2014). The risk of dietary Mg deficiency is greater in low-income countries.

Estimates of the risk of dietary Mg deficiency based on dietary recalls are much greater than the above estimates (14–53%, UK NDNS data, Bates et al. 2014; 64–67%, NHANES data, Moshfegh et al. 2005, cited in Rosanoff 2010). Those reports contrast markedly with the results presented here, which suggest that the risks of dietary Mg deficiency for USA and UK in 2011 were 0.32% and 0.25%, respectively. This discrepancy might be attributed in part to misreporting of dietary intakes by respondents participating in dietary-recall surveys (Bingham et al. 1994; IOM 2000; Rennie et al. 2004, 2005, 2007; Mirmiran et al. 2006; Liberato et al. 2009; Archer et al. 2013; Bates et al. 2014; Winkler 2014). For example, energy intake was under-reported from 24-h dietary recall by 15% in Brazil (Avelino et al. 2014), >25% in the UK (Rennie et al. 2007), and 67% for men and 59% for women in the USA (Archer et al. 2013). Galan et al. (2002) reported dietary Mg intake in France for adult female (35–60 years) and male (45–60 years) tapwater drinkers of 284 and 377 mg day⁻¹, respectively, using 24-h recall surveys. Charlton et al. (2005) reported dietary Mg intakes in Cape Town, South Africa, of 228,
Fig. 5. Regional temporal trends in the percentage contribution of food groups to magnesium (Mg) supplies between 1992 and 2011. Data are shown for (a) Africa, (b) the Americas, (c) Asia, (d) Europe and Oceania.
261, and 285 mg person$^{-1}$ day$^{-1}$ for mixed ancestry, black and white ethnic groups, respectively, using 24-h recall surveys of men and women aged 20–65 years. These reported Mg intakes are less than half of our estimates of 600 and 637 mg person$^{-1}$ day$^{-1}$ of Mg supply in 2011 for France and South Africa, respectively. By contrast, Ca supply calculated from FBS (Kumssa et al. 2015) was only 15% greater than that estimated from dietary-recall data using milk as a proxy (Imamura et al. 2015).

Other caveats in this study include the lack of spatial and temporal resolution in food composition data. Thus, Mg concentration data for foods were sourced from the USDA-SR26 food composition database, which is centred on foods grown in North America (USDA 2013). Thus, the impact of different crop varieties, soil types and agronomy (White and Broadley 2009) between and within countries and over time cannot be accounted for in the present study (White and Broadley 2005; Davis 2009). Therefore, the estimated risks of dietary Mg deficiency will be compromised by the absence of relevant, reliable and up-to-date food composition data, which require more detailed local study. For example, in a recent analysis of dietary duplicates in Malawi from a single day (Hurst et al. 2013), mean and median Mg intakes were 418 and 353 mg person$^{-1}$ day$^{-1}$ ($n = 114$). This is in broad agreement with the low estimated risk of Mg deficiency based on FBS supply data, but is still lower than the Mg supply estimate of 530 mg person$^{-1}$ day$^{-1}$ in the present study. However, large differences were observed in Mg intake from those living in Zombwe Extension Planning Area (predominantly non-calcareous soil; $n = 56$) and Mikalango Extension Planning Area (predominantly calcareous soil; $n = 58$). Median Mg intake in Zombwe was 267 mg person$^{-1}$ day$^{-1}$, compared with 538 mg person$^{-1}$ day$^{-1}$ in Mikalango (unpublished data collected during the study of Hurst et al. 2013). These differences were due primarily to differences in cereal Mg concentrations between soil types (Broadley et al. 2012; Joy et al. 2015) and to dietary choices.

Other methodological weaknesses in determining Mg deficiency risks from food-supply data include effects of food processing and food waste at the household level. In terms of food processing, the USDA food composition table (USDA 2013) shows that enriched white bread-wheat flour (25 mg 100 g$^{-1}$) contains much less Mg than whole-grain wheat flour (137 mg 100 g$^{-1}$). Thus, if food processing is not captured accurately by FBS data, then further discrepancies in estimates of Mg deficiency risks could arise from supply-based methods v. dietary recall. Food balance sheets also do not capture waste at the household level and will therefore overestimate consumption (FAO 2001). In developed countries, household food wastage occurs from unplanned purchases, behaviour and ‘best-before-dates’ (Parfitt et al. 2009).
Gustavsson et al. (2011) estimated food waste in Europe and North America was 95–115 kg person\(^{-1}\) year\(^{-1}\), compared with 6–11 kg person\(^{-1}\) year\(^{-1}\) in sub-Saharan Africa, and South and Southeast Asia. For cereals, 2–25% of the initial production is wasted at household level (Gustavsson et al. 2011). Given that cereals are the major source of dietary Mg (Fig. 6), quantifying deficiency based on FBSs is likely to systematically underestimate Mg deficiency risk. Drinking and cooking water can also have an important contribution to Mg nutrition, where water Mg concentrations are sufficiently elevated (Marier 1982; Rosanoff 2013; Kanadha et al. 2014), but this was not assessed in this study.

The risk of Mg deficiency is determined not only by Mg intake but also by the proportion of other nutrients and anti-nutrients (e.g. Ca, PA, oxalate, fibre, saturated fat, etc.) in the gut that affect its bioavailability (Vitale et al. 1957; Seeling 1964; Reinhold et al. 1976; Cheryan et al. 1983; Pallauf et al. 1998; Coudray et al. 2003; Bohn et al. 2004). The dietary Ca : Mg ratios based on dietary recall were 2.9 in France (Galan et al. 2002) and 1.9 in South Africa (Charlton et al. 2005), compared with our estimates of 1.69 and 0.65, respectively, in 2011. Dai et al. (2007) reported that a Ca : Mg ratio >2.8 may affect Mg absorption. In our study, the Ca : Mg ratio from food supply was generally <2; however, processing of cereals is likely to result in larger reductions in intake of Mg than of Ca, thereby increasing Ca : Mg ratios at the intake level. For example, the concentration of Mg in whole grain wheat was reduced by 82%, whereas Ca was reduced by 56% when processed into un-enriched bread flour (USDA 2013). Thus, in countries where Ca : Mg supply ratio approaches or exceeds ~2, the impact of Ca and other nutrients on Mg bioavailability needs to be investigated further. Interestingly, Seeling (2006) has argued that the rise in recommended Ca intake could affect Mg absorption if there is not a concurrent increase in Mg. High concentrations of PA in cereals and legumes, and oxalates in some green leafy vegetables, can also reduce Mg absorption in the gut because of chelation (Brink and Beynen 1991; Bohn et al. 2004a). In high-income countries, aquatic plants provided 6% of the total dietary Mg (Fig. 6), indicating the important potential role of underutilised crops in human dietary Mg nutrition. The estimated Mg : PA molar ratio in all countries was 4.6–6.5, which is in the range observed to affect the absorption of Mg (Cheryan et al. 1983). At a global scale, our results indicate that while Mg supply from agricultural production is likely to be sufficient to meet the requirements of the population, the prevalence of high Mg : PA ratios in diets around the world requires further study to determine the extent to which Mg absorption might be impaired.

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