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REGULAR ARTICLE

Risk of dietary magnesium deficiency is low in most African countries based on food supply data

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Abstract

Background Dietary mineral deficiencies are widespread in Africa. Our previous studies in Malawi revealed population-level shortfalls in dietary calcium and selenium supply but adequate dietary magnesium (Mg) supply. Here we examine dietary Mg supply throughout Africa.

Methods Food supply data from 1961 to 2007 were compiled using Food and Agriculture Organization (FAO) Food Balance Sheets (FBSs). Magnesium supply was estimated for each country using regional food Mg composition tables.

Results Mean Mg supply in 2007 was 649 mg *capita*$^{-1}$ d^{-1}, ranging from 188 mg d^{-1} in Eritrea to 1,828 mg d^{-1} in Burkina Faso. Magnesium supply was greater in West Africa than in other regions, was dominated by sorghum, maize and wheat and was correlated with calorie supply. The World Health Organization (WHO) Estimated Average Requirement (EAR) for Mg (217 mg *capita*$^{-1}$ d^{-1} for adult males) was exceeded in most countries. Using the EAR cut-point method, the risk of dietary Mg deficiency in Africa is <4 % and unlikely to be a major problem, assuming access to sufficient food and that phytic acid does not compromise Mg absorption.

Conclusions Estimating Mg supply is highly sensitive to concentration data available for the primary staple crops. Given that soil factors profoundly affect crop Mg concentration, there is a need to increase the spatial resolution of food composition tables for the staple crops.

Keywords Biofortification · Calcium · Fertilisers · Food balance sheets · GIS · Magnesium · Maize · Micronutrients · Soil

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Introduction

Magnesium (Mg) is an essential mineral for human health and is abundant in the human body (reviewed in Department of Health 1991; Institute of Medicine 1997). A typical human contains *c.* 25 g of Mg, of which 60 % is in bones, where it plays a major role in skeletal development. Magnesium has a major physiological role in maintaining electrical potentials, especially in nerve and muscle membranes. Dietary Mg deficiency is linked to numerous physiological disorders, including effects on energy metabolism, electrolyte balance, cardiovascular and neuromuscular disorders. For example, Mg deficiency has been shown to increase risks of coronary heart disease and metabolic disorders, with hypomagnesemia a common feature in type-2 diabetes (Abbott et al. 2003; He et al. 2006). Despite its vital biological importance, Mg has been less widely studied in agricultural and food systems from a human health perspective than elements such as iron (Fe), zinc (Zn), iodine (I) and selenium (Se). Dietary deficiencies of Fe, Zn, I and Se linked to public health issues such as stunting, cognitive development and immune functioning have led to the introduction of food fortification programmes and, more recently, efforts to biofortify crops for human consumption through breeding and fertiliser usage (Nestel et al. 2006; Cakmak 2008; White and Broadley 2009).

The incidence of dietary Mg deficiency among many groups is uncertain because levels of circulating Mg are under tight homeostatic regulation and thus biomarkers of Mg status in blood serum are not considered to be informative (Sanders et al. 1999). Furthermore, it is thought that Mg deficiency is avoided through reduced urinary excretion if Mg intake is insufficient or absorption is inhibited by phytic acid (Hurrell 2003; Bohn et al. 2004). Finally, estimating risks of dietary Mg deficiency at a population level is complicated by uncertainties in defining what constitutes an adequate dietary Mg intake. However, potential dietary Mg deficiencies can be inferred at an individual or household level using dietary recall questionnaires combined with food composition tables (e.g. Bates et al. 2011) or by measuring composite diets directly (e.g. Moser et al. 1988). In wider populations, dietary Mg deficiencies can be identified using food balance sheets (FBSs), which represent supply data at a retail level, produced by the United Nations Food and Agriculture Organization (FAO), and food composition tables. Survey-based (individual/household level) and supply-based (retail level) approaches have their own inherent assumptions and must be interpreted with caution (de Haen et al. 2011; Food and Agriculture Organization 2001). The use of retail-level supply-based approaches is generally considered to be less accurate than dietary surveys, which can also incorporate food supply data with socioeconomic and demographic indicators (de Haen et al. 2011).

The World Health Organization (WHO) Estimated Average Requirement (EAR) for Mg, defined as the average daily intake level that meets the needs of 50 % of the "healthy" individuals in a population, is 217 mg *capita*$^{-1}$ d^{-1} for adult males. The US Recommended Daily Amount (RDA) is 320 and 420 mg *capita*$^{-1}$ d^{-1} for adult females and males, respectively (Institute of Medicine 1997). Approximately 9 % of UK and US adults may be consuming Mg in quantities below the UK Lower Reference Nutrient Intake (LRNI; an intake which meets the needs of 2.5 % of a healthy population), based on individual dietary recall surveys in 2000/01 and national food composition tables (Broadley and White 2010), although more recent UK data suggest this figure could be higher (Bates et al. 2011). In Malawi, an average Mg supply of 789 mg *capita*$^{-1}$ d^{-1} was estimated from FBSs for 2007 and national food composition tables (Broadley et al. 2012). This compares to an average intake of 237 and 298 mg d^{-1} for females and males (aged 19–64), respectively, in the UK in 2008–10 (Bates et al. 2011). The risk of Mg deficiency among the population may therefore be lower in Malawi than in the UK or US, although intakes of phytic acid are potentially much higher. At a retail level, *c.* 70 % of dietary Mg supply in Malawi was estimated to be from maize, which had a consistently high Mg grain concentration in national surveys (Chilimba et al. 2011; Broadley et al. 2012). Estimates of Mg supply in Malawi from FBSs were within 2 % of estimates of Mg supply at the household level from the Second Malawi Integrated Household Survey (IHS-2; National Statistics Office 2004; Ecker and Qaim 2011); maize supply predicted from the FBSs (354 g *capita*$^{-1}$ d^{-1}) was close to that reported in the IHS-2 (381 g *capita*$^{-1}$ d^{-1}).

This study tested whether there is evidence of shortfalls in Mg supply in Africa using FBSs and regional food Mg composition tables. A survey-based approach was not possible as representative household survey data are available only for a minority of African countries. Although FBSs and food composition tables have been applied at a global scale to estimate the supply of dietary Zn at a national population level (Wuelher et al. 2005), this approach has not previously been attempted for Mg to our knowledge.

Materials and methods

Per capita supply of Mg was estimated for all countries in Africa as the product of food supply data and food Mg concentration, an approach previously used by Wuelher et al. (2005) to estimate the global prevalence of Zn deficiency. A similar approach was employed for Malawi by Chilimba et al. (2011) for Se, and by Broadley et al. (2012) for Ca and Mg.

Food supply data

All available Food Balance Sheet (FBS) data were sourced from Food and Agriculture Organization (FAO) member countries in Africa (FAO 2011). FBS datasets provide estimates of the annual food supply at a retail level for up to 92 separate food items, e.g. "Maize", "Tomatoes", "Freshwater Fish", "Bovine Meat" etc. Quantities are based on national production statistics adjusted for imports/exports, losses during transport, storage and processing, non-food uses such as industrial products and livestock feed, and food stock balances (FAO 2001). Data are presented on a *per capita* basis in terms of quantity, energy, carbohydrate, fat, and protein composition. All African countries were studied except small island states (Cape Verde, Comoros, Mauritius, Sao Tome and Principe and Seychelles) because of their likely high dependence on imports and exports, or countries with no FBS data (Equatorial Guinea, Somalia, Western Sahara Mayotte, Réunion, and Saint Helena). FBS data were analysed for 44 countries between 1961 and 2007 inclusive, for Ethiopia and Eritrea between 1993 and 2007, and the People's Democratic Republic of Ethiopia (Ethiopia PDR; pre-Eritrean secession) between 1961 and 1992.

Food magnesium concentration

Data were sourced from published food composition tables. The initial aim was to create five food Mg concentration databases, covering all foods in the FBSs, which mapped onto the five United Nations (UN) African sub-regions: 'Northern' (N), 'Eastern' (E), 'Southern' (S), 'Middle' (M) and 'Western' (W) Africa. Because large-scale comparative datasets were not identified for N and M Africa, three food Mg concentration databases were generated: E, S (also used for N Africa) and W (also used for M Africa) (Supplementary Table 1). The geographical focus and the extent of records were used to prioritise sources, with those containing more food items used as the preferred sources. Data for E Africa were sourced primarily from Tanzanian food composition tables (Lukmanji et al. 2008), complemented by data from Malawi (Ferguson et al. 1989) and Mozambique (Korkalo et al. 2011). The W Africa data were sourced primarily from Stadlmayr et al. (2010), complemented by data from Gambia (Prynne and Paul 2011). The S Africa data were sourced primarily from Wolmarans et al. (2010). Food composition tables were searched to find a "best-fit" match with FBS items. A single data point was selected for each regional food Mg composition table, with no averaging of data from different sources. Where suitable food Mg concentration data could not be identified, data from the other regions were used. Remaining data gaps were filled using US food composition tables (US Department of Agriculture, Agricultural Research Service, USDA-ARS 2011). All Mg concentration data are expressed as mg 100 g^{-1} fresh weight (FW) edible portion. Food Mg concentration data, literature sources and best-fit FBS categories are shown in Supplementary Table 1.

Data integration

The FBS and food Mg concentration data were integrated using standard database queries (Microsoft Access 2010, Microsoft Corporation, Redmond, WA, US). First, a *per capita* supply of Mg was estimated for each country in Africa for the years 1961–2007, based on the product of food supply and Mg composition. Second, the likely prevalence of deficiency was estimated using the EAR cut-point method, whereby population risk of inadequate intake is assumed to equal the proportion of the population with intakes below the EAR (Carriquiry 1999). EAR values can be calculated from a Reference Nutrient Intake (RNI) level, using an appropriate conversion factor. The RNI is the intake level of a mineral which meets the nutrient requirements of almost all (97.5 %) apparently healthy individuals in a population group and are age- and sex-specific. Because FBS food supply data are not age- or sex-specific, a single value of 260 mg for the Mg RNI was used, based on adult males (FAO/WHO 2004), and a standard conversion of RNI=1.2*EAR (Allen et al. 2006) to provide an EAR for Mg of 217 mg. Given that adult males have the highest RNI for Mg of all population subgroups, this approach will overestimate the risks of Mg deficiency among the whole population. Daily intake by populations was assumed to follow a normal distribution, centred on mean dietary supply and with a coefficient of variation (CV) of 25 %, as used by Wuelher et al. (2005) for zinc intake. Prevalence of Mg deficiency was estimated using 2011 population figures (CIA World Factbook 2011). Data were mapped using ArcGIS (Version 9.3, ESRI, Redlands, CA, US).

Results

Mean magnesium supply for 46 African countries in 2007 (Fig. 1a) was 649 mg *capita*$^{-1}$d^{-1}, and ranged from 188 mg *capita*$^{-1}$d^{-1} in Eritrea to 1,828 mg *capita*$^{-1}$d^{-1} in Burkina Faso (Supplementary Table 2). With the exceptions of Eritrea and Djibouti (189 mg *capita*$^{-1}$d^{-1}), Mg supply in all countries exceeded the WHO EAR for adult males of 217 mg *capita*$^{-1}$d^{-1}. Mean regional supply of Mg was 1,019 mg *capita*$^{-1}$ d^{-1} in W Africa, 605 mg *capita*$^{-1}$d^{-1} in S Africa, 561 mg *capita*$^{-1}$d^{-1} in N Africa, 524 mg *capita*$^{-1}$d^{-1} in M Africa and 417 mg *capita*$^{-1}$d^{-1} in E Africa.

Across all countries in Africa, the estimated risk of dietary Mg deficiency in 2007 was 3.8 % based on the EAR cut-point method (Fig. 1b; Supplementary Table 2), representing *c.* 40 million individuals; 22 million of these were within the E Africa region. At a regional scale, the risk of Mg deficiency was greater in E Africa (6.9 %) and M Africa (7.0 %) than in N Africa (2.7 %), S Africa (0.6 %) or W Africa (0.5 %). Countries with the greatest risk of deficiency were Eritrea (73 %), Djibouti (72 %) and Madagascar (25 %) (Fig. 1b). Countries with the greatest prevalence of Mg deficiency were the Democratic Republic of the Congo (8.0 m), Ethiopia (7.8 m) and Madagascar (5.4 m).

Cereals provided >50 % of the mean Mg supply in 2007 in all five regions, ranging from 53 % in M Africa to 76 % in S Africa (Fig. 2). Maize was the major source of dietary Mg in S and E Africa (56 % and 45 %, respectively), whereas sorghum was the major source of Mg in W and M Africa (50 % and 25 %, respectively). However, this estimate is highly dependent on the very high value for Mg concentration in sorghum in the W Africa food composition table (559 mg 100 g^{-1} FW), 16-fold greater than the corresponding value in E Africa, combined with the greater consumption of sorghum in W and M Africa. Cassava was an important secondary source of Mg (23 %) in M Africa, while wheat was the major source of Mg in N Africa (43 %) and was important in S Africa (18 %). Animal products represented a small proportion of Mg supply overall (6 %), although there were marked regional differences between N Africa (10 %), S Africa (9 %), E Africa (8 %), M Africa (4 %) and W Africa (3 %). Most of the Mg supply from animal products in N Africa was from the FBS category ‘Milk—Excluding Butter’ (58 %). There was a correlation

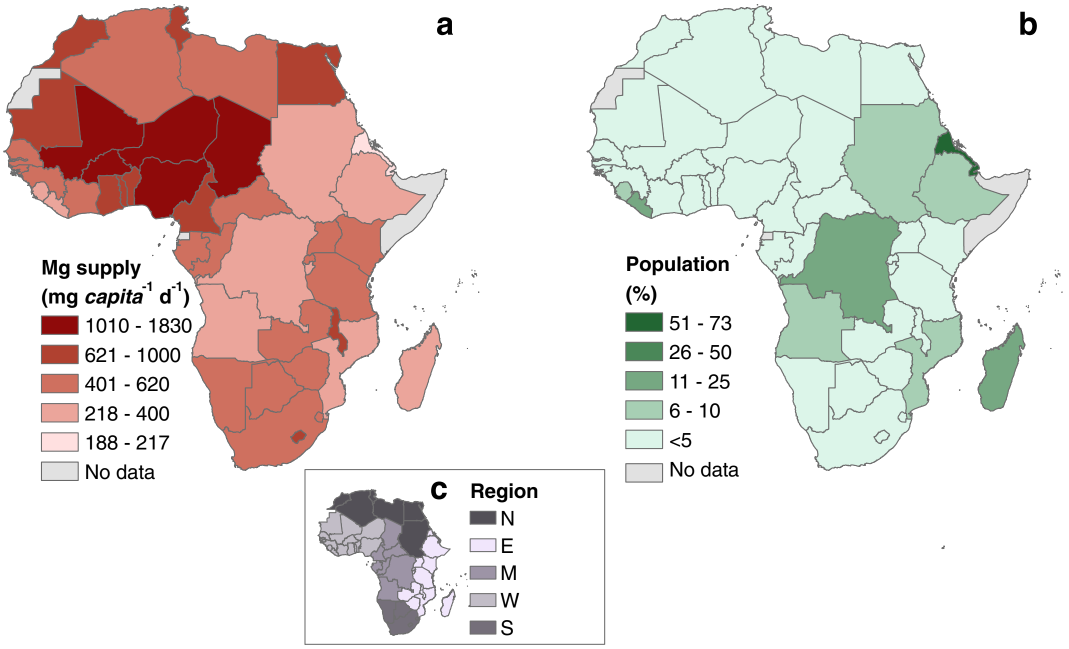

Fig. 1 **a** Mean daily Mg supply *per capita*, and **b** estimated population risk of inadequate Mg supply, based on an Estimated Average Requirement (EAR) of 217 mg Mg *capita*$^{-1}$d^{-1}. Data were derived from national-level food balance sheets for 46 African countries in 2007 and three regional food composition tables for E, S and W Africa. The S Africa food composition table was used for N Africa and the W Africa food composition table was used for M Africa. Regions are based on United Nations (UN) subregions (http://unstats.un.org/unsd/methods/m49/m49regin.htm) as shown in the inset (**c**)

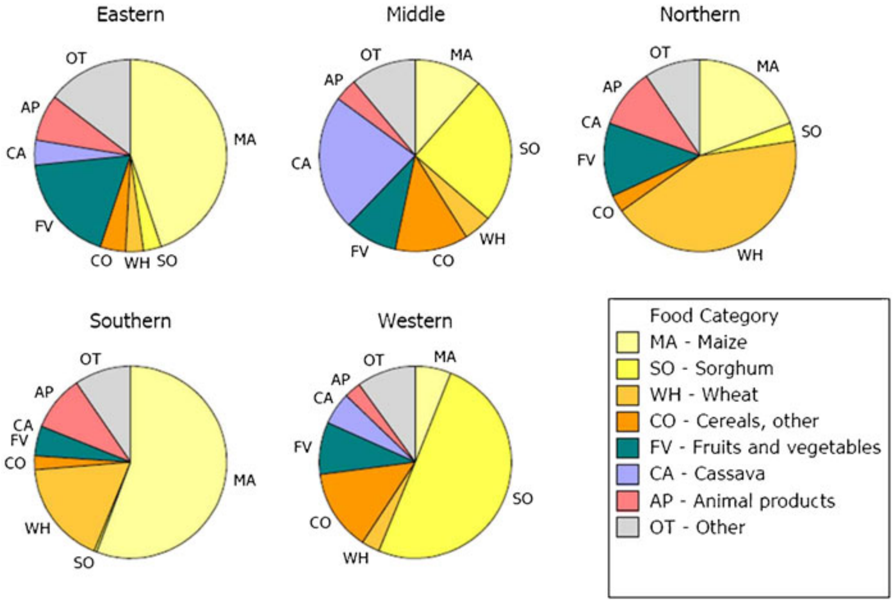

Fig. 2 Proportion of total Mg supply by food category in each African region. National data (2007) were combined to give regional averages for each food category after being weighted using population data for 2011 (Central Intelligence Agency 2011). Cereals are coloured in yellow-to-orange scale. Regions are based on United Nations (UN) sub-regions

between energy and Mg supply (r=0.33; *P*=0.025; Fig. 3). Within this correlation, countries were clustered according to region, with E African countries typically having both the lowest energy and Mg supply.

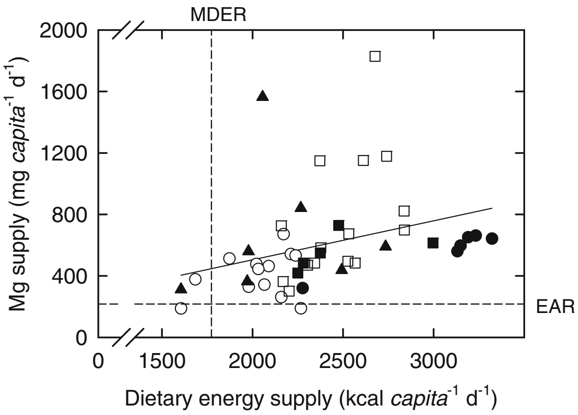

Fig. 3 Dietary Mg supply as a function of dietary energy supply. Data derived from national-level food balance sheets for 46 African countries in 2007 and regional food composition tables. Black circles, Northern Africa; white circles, Eastern Africa; black squares, Southern Africa; white squares, Western Africa; black triangles, Middle Africa. Regions are based on United Nations (UN) sub-regions. Equation for the fitted linear regression: y=0.254×–2.95; r=0.33, *P*=0.025. Dashed lines show the Estimated Average Requirement (EAR) for Mg of 217 mg *capita*$^{-1}$d^{-1} and the Minimum Dietary Energy Requirement (MDER) of 1773 kcal *capita*$^{-1}$d^{-1}. MDER is the average of MDER values for all 46 countries (http://www.fao.org/fileadmin/templates/ess/documents/food_security_statistics/MinimumDietaryEnergyRequirement_en.xls)

Historical FBSs could be sourced from FAO for the period between 1961 and 2007 for most countries. Whilst temporal variation in Mg supply occurred in some countries, there is no evidence that the risk of dietary Mg deficiency increased significantly during this period (Fig. 4). In N Africa, Mg supply increased over time; for example, Mg supply in Algeria, Egypt, Morocco and Tunisia increased by an average of 278 mg *capita*$^{-1}$d^{-1} between 1961 and 2007, with wheat and animal products (mostly milk) accounting for much of this increase. The sharp decrease in Mg supply in Libya between 1983 and 1984 (1,046 to 658 mg *capita*$^{-1}$d^{-1}) was due to the decline in Mg supply from wheat, from 809 to 426 mg *capita*$^{-1}$d^{-1}. The apparent decrease in wheat supply in 1984 appears to have been due to a net transfer of wheat into stocks (50,000 t moved into stocks), which contrasts markedly with a depletion of stocks (521,000 t moved out of stocks) in 1983. The sharp increase in Mg supply in Togo between 1977 and 1978 was due to sorghum production, supply of which was apparently zero until 1977, but at least 45 g *capita*$^{-1}$d^{-1} thereafter. Temporal variation in Mg supply was greater in W Africa than in N Africa, although there were no systematic temporal changes. However, estimates of dietary Mg supply in W Africa are very sensitive to changes in sorghum supply in the FBSs, due to the high concentration of Mg in sorghum in the W Africa food composition table. For example, in Chad, Mg supply in 1993, 1994 and 1995 was 1,008, 1,416 and 1,200 mg *capita*$^{-1}$d^{-1},

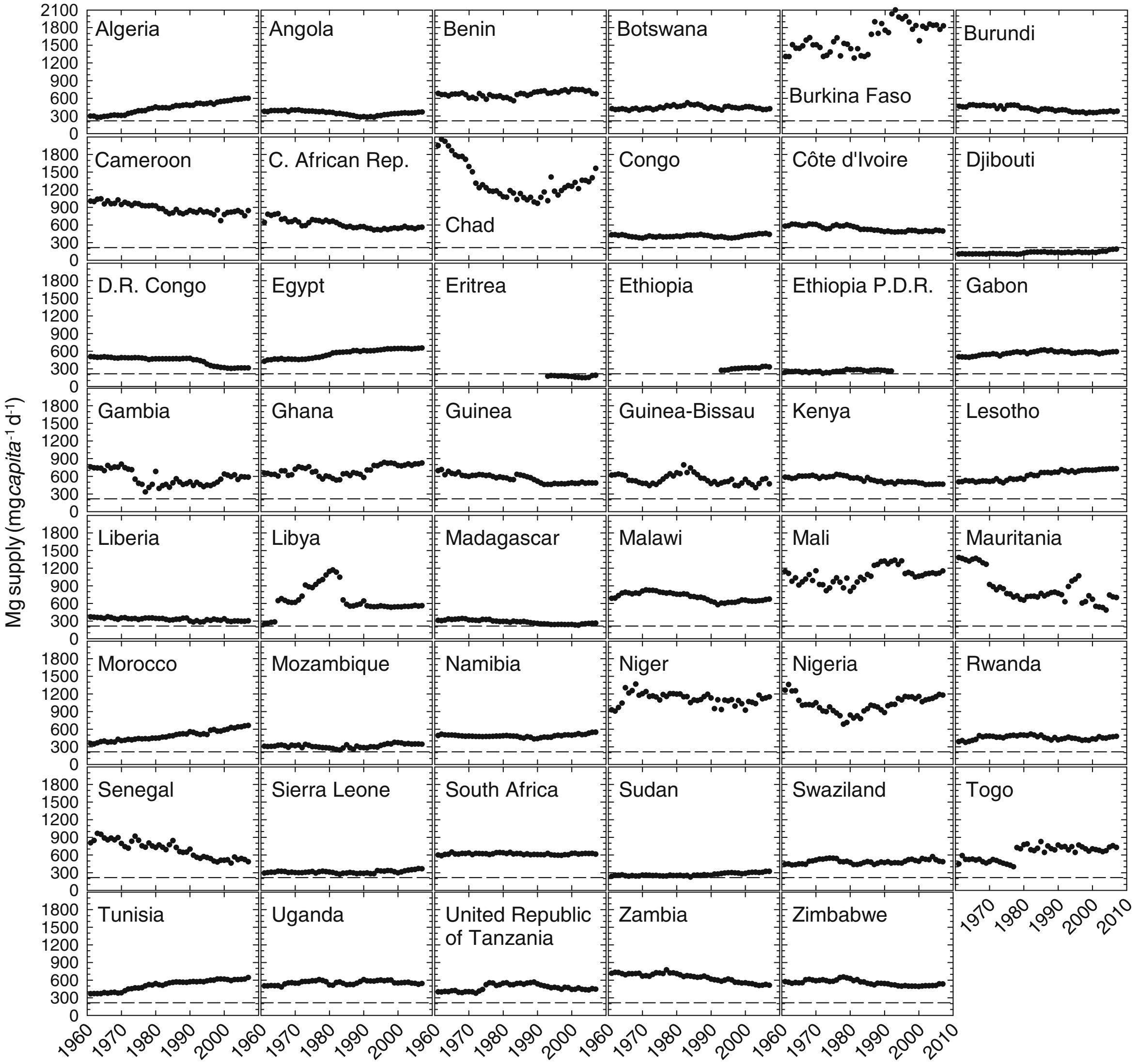

Fig. 4 Trends in daily Mg supply from 1961 to 2007 for 47 African countries. Data are based on national-level food balance sheets and three regional food composition tables (see Supplementary Table 1). Horizontal dashed lines show the Estimated Average Requirement (EAR) for Mg of 217 mg *capita*$^{-1}$ d^{-1}

respectively. Magnesium supply from sorghum alone was 580, 897 and 730 mg *capita*$^{-1}$ d^{-1} for the same period. Mean Mg supply in Chad for 1961–2007 from sorghum was 881 with a standard deviation of 313 mg *capita*$^{-1}$ d^{-1}. East, S and M African countries experienced relatively stable Mg supplies over this period.

Discussion

The risk of dietary Mg deficiency based on food supply appears to be low for most African countries, being <4 % across the entire continental population, i.e. affecting *c.* 40 m people. This observation contrasts with estimates of greater dietary Mg deficiency risks in the UK and US, albeit based on different methodologies. Thus, the UK National Diet and Nutrition Survey (NDNS) in 2000/01 (Henderson et al. 2003) reported that 13 % and 9 % of UK adult females and males, respectively, were consuming Mg at below the LRNI, i.e. <150 (females) and <190 (males) mg *capita*$^{-1}$ d^{-1}. A more recent survey between 2008 and 2010 reported that 9 % and 15 % of UK adult females and males, respectively, were consuming Mg at levels below the

LRNI (Bates et al. 2011). In the US, 12 % and 5 % of US adult females and males were consuming Mg at levels below the UK LRNI with many more at risk of suboptimal Mg nutrition (Broadley and White 2010; Rosanoff 2010). In France, *c*. 20 % of adults were found to consume Mg at less than two-thirds of the RDA when assessed by dietary recall (Galan et al. 1997). However, the UK and US Mg intake data were derived from dietary surveys rather than food supply data. According to FBS data (FAO 2011), food supply in the UK was 3,416 kcal $capita^{-1}\,d^{-1}$ in 2001 compared to 2,455 kcal $capita^{-1}\,d^{-1}$ in Africa in 2007, whereas energy intakes in the 2000/01 UK NDNS were reported as 1,642 and 2,323 kcal $capita^{-1}\,d^{-1}$ for adult females and males, respectively (Hoare et al. 2004). It must therefore be emphasised that supply data do not necessarily represent consumption data, as discussed below. For example, the UK survey data may be confounded by under-reporting of energy intake by up to 25 % (Broadley and White 2010). However, given the use of a threshold of 217 mg $capita^{-1}\,d^{-1}$ for the African assessment, we tentatively conclude that the overall risk of dietary Mg deficiency is lower in most African countries than in the UK. Individuals and groups with low calorie intake are still at high risk of Mg deficiency. Furthermore, the influence of other dietary components on Mg absorption requires further investigation. For example, cereals and some vegetables are high in phytic acid, which can inhibit Mg absorption through the formation of stable chelate complexes (Hurrell 2003; Bohn et al. 2004). Conversly, fermentable fibres in vegetable products can increase the solubility and uptake of Mg in the large intestine (Coudray and Rayssiguier 2001). Preparation methods, including germination, fermentation and cooking, can also help to reduce phytic acid concentration (Bishnoi et al. 1994); information on these practices would further improve data on Mg absorption and deficiency risks. However, the risk of dietary Mg deficiency in Africa appears to be lower than for many other elements, including Fe (Stoltzfus 2003), Zn (Wuelher et al. 2005), I (de Benoist et al. 2008), Se (Chilimba et al. 2011) and Ca (Broadley et al. 2012).

The risk of dietary Mg deficiency exceeded 10 % in a limited number of African countries, i.e. Eritrea, Djibouti, Madagascar, Liberia and the Democratic Republic of Congo. These countries warrant further investigation, initially with regard to the limitations in accuracy of the FBSs, which are compiled from a variety of FAO and national sources (FAO 2001). For example, consumption can be underestimated due to omission of subsistence production from FBS data. Other systemic problems inherent in using FBS data to estimate consumption include the lack of consideration of food waste at the retail level.

West African countries show a high temporal variation in dietary Mg supply estimates due to the impact of sorghum. Libya also shows substantial temporal variation between consecutive years, for example, 1983 and 1984 (Fig. 4), due to variation in wheat supply described previously. Finally, it is critical to note that food supply is only a proxy for consumption, and multiple factors affect the relationship between food supply and consumption, including household purchasing power and intra-household inequalities (Sen 1981). Extrapolations from mean population mineral intakes based on FBS data must always be done with these inherent caveats in mind. However, it is noteworthy that in a previous study, estimates of dietary Mg intake based on the household-level IHS-2 (807 mg $capita^{-1}\,d^{-1}$) in Malawi were within 2 % of those based on population supply data derived from the 2007 FBS (792 mg $capita^{-1}\,d^{-1}$; Broadley et al. 2012) .

Estimated risks of Mg deficiency in the present study are based on the assumption of a normal distribution of Mg intake among populations and a coefficient of variance (CV) of 25 %. As the CV is used to determine the proportion of the population lying below the EAR using the cut-point method, any supply-based method is highly sensitive to the choice of CV value. In the UK, the 2000/01 NDNS reported a mean Mg intake in adult males (aged 19–64) of 308 mg d^{-1} (standard deviation=99 mg d^{-1}) from food sources, giving a CV of 32 % (Henderson et al. 2003; Hoare et al. 2004). In France, the SU.VI.MAX cohort survey of Mg intake found male and female dietary intakes of 369±106 and 280±84 mg $capita^{-1}\,d^{-1}$ respectively, giving CVs of 29 % and 30 % (Galan et al. 1997). However, estimates of CV from dietary surveys are inflated as they include intra-individual intake variation. Whilst nationally-representative individual intake survey data from African countries would substantiate estimates of deficiency prevalence, in the absence of such robust information, this paper has assumed an inter-individual CV for Mg intake of 25 %, as used by Wuelher et al. (2005) for global analyses of Zn deficiency risks. A CV of 25 % results in an estimate of a 3.8 % risk of dietary Mg deficiency for Africa. A CV of 20 % reduces the estimate of dietary Mg deficiency risk to 2.3 %, whereas a CV of 30 % increases the estimate of dietary Mg deficiency risk to 5.7 %.

The Mg concentration in the yield component of crops is highly dependent on soil type, agronomy and crop genotype (White and Broadley 2009; Broadley and White 2010). In the present study, the Mg concentration of staple crops shows large variation between the E, S and W food composition tables. For example, sorghum grain contained 34 mg 100 g^{-1} FW in the S and E Africa tables, but 559 mg 100 g^{-1} FW in the W Africa table. Magnesium uptake by plants can be impaired by soil salinity, low soil pH and aluminium toxicity (Tan et al. 1993; Netondo et al. 2002), and is affected by vesicular-arbuscular mycorrhizal (VAM) inoculation and P fertiliser (Bagayoko et al. 2000). Furthermore, Al-tolerant genotypes give a higher influx of Mg into roots (Baligar et al. 1993). The W Africa data for the Mg concentration of sorghum come from the study of Stadlmayr et al. (2010), in which a mean value was derived from two data points (430 and 687 mg 100 g^{-1} FW), so providing some validation that the high Mg concentration is not a result of reporting or experimental error. Additional data are nevertheless needed to explain the variation in sorghum Mg concentration between different studies. Estimates of population risk of dietary Mg deficiency are highly sensitive to such data for staple crops. For example, the estimated risk of Mg deficiency in E Africa would double if maize Mg concentration were set at 85 mg 100 g^{-1} FW (as found in the data for W Africa) rather than 127 mg 100 g^{-1} FW (as found in E Africa). As a nationwide survey of Mg concentrations in maize grain in Malawi provided values ranging from 55 to 139 mg 100 g^{-1} FW (Broadley et al. 2012), there is significant uncertainty which needs to be addressed and it is clear that estimates of risks of Mg deficiency could be improved considerably through the use of spatially-resolved Mg concentration data for the staple food crops. Such information could be used to inform where best to target food fortification and dietary education programmes, or crop biofortification programmes with Mg through breeding and fertiliser use (White and Broadley 2009), if required.

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