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Review

Edible plant tissue and soil calcium:magnesium ratios: data too sparse to assess implications for human health

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Abstract. Unlike yield, the plant calcium (Ca) : magnesium (Mg) ratio increases at higher soil Ca : Mg and decreases at lower soil Ca : Mg. Edible plant tissue Ca : Mg at various soil ratios has not been robustly studied. Such studies are appropriate because high Ca : Mg dietary ratios may be associated with increased risk of chronic diseases such as cardiovascular disease and diabetes, and human dietary Ca : Mg ratio is rising as populations integrate more processed foods into traditional diets. This review explores whether increasing the soil Ca : Mg ratio is likely to increase edible plant tissue Ca : Mg ratio, a result that could, if substantial, affect human health.

A literature search gathered published articles reporting Ca and Mg values for plants grown in soils or nutrient solutions with various Ca : Mg ratios. For each study, soil or solution ratio was plotted against plant ratio, and Pearson's *r* and 2-tailed *P* values were calculated. Findings reveal that reporting Ca and Mg content of edible plant tissues is rare in studies assessing the impact of soil Ca : Mg on crop yields, nutrient uptake or crop quality; Ca : Mg of whole plants and most shoots increases as soil Ca : Mg rises; leaf Ca : Mg of some but not all crops increases as soil Ca : Mg rises; Ca : Mg ratios of edible grain, fruit and root tissues are smaller than those of leaves or shoots of the same crop; and Ca : Mg of grain, bean and fruit tissue may not respond to changes in soil Ca : Mg as much as Ca : Mg of plants, shoots and leaves. However, the data are too sparse for conclusions or even speculation. Further measurements of Ca and Mg in edible tissues destined for human consumption are necessary to asses any impact of soil Ca : Mg on the rising dietary Ca : Mg of humans and its health consequences.

Additional keywords: calcium, Ca to Mg ratio, cardiovascular diseases, diseases of global concern, magnesium.

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Introduction

Human intakes of calcium (Ca) in the USA have risen significantly more than intakes of magnesium (Mg) and energy over the past 30 years (Rosanoff 2010), resulting in a rising Ca : Mg dietary intake ratio in this population. A survey of human Ca and Mg intakes from nutrition studies indicates a trend towards rising Ca : Mg as populations move from traditional to modern processed-food diets (Table 1). Possible negative health consequences of consuming a diet with Ca : Mg >2.8 have been reported (Dai *et al*. 2007; Rosanoff *et al*. 2012).

Cardiovascular disease (CVD), diabetes and their risk factors are among the fastest growing and most pressing problems of global human health (Lozano *et al*. 2012). CVD is heart and blood vessel disease that can progress to disability or death. It includes numerous problems, many of which are related to an unhealthy build-up of plaque, which narrows and stiffens arteries, making it harder for blood to flow through the cardiovascular system, potentially leading to heart attack or stroke. Diabetes diseases involve impaired regulation or control of blood glucose levels and can progress in severe cases to disability and/or death. Cellular, epidemiological and clinical studies suggest an impact of dietary Ca : Mg (wt/wt) ratio in these diseases (Resnick 1993; Rosanoff 2010; Rosanoff *et al*. 2012).

Recent investigation has shown that the Ca : Mg of the global supply rose between 1992 and 2011 (Kumssa *et al.* 2015). Therefore, it is timely to consider whether a high soil Ca : Mg affects the Ca : Mg of plant tissues, especially those that are edible human food, to see whether the growing conditions that alter soil Ca : Mg might be partially responsible for this rise in Ca : Mg in the global supply and global human diet. Soil Ca : Mg has often

Table 1. Studies providing measures of human dietary Ca : Mg intakes from foods

Population and year	Ca : Mg intake ratio	Reference
	Traditional	
Rural India, underprivileged, 1998	0.5	Kapil *et al.* 1998
Rural China, mid-old, 2009[A]	0.8	Li *et al.* 2009
Bedouin traditional, 2009	0.9	Abu-Saad *et al.* 2009
	Transitional	
China, upper class young, 1941	1.1	Chu *et al.* 1941
Ceylon medical students, 1950	1.3	Cullumbine *et al.* 1950
Bedouin, transitional, 2009[B]	1.5	Abu-Saad *et al.* 2009
	Modern developed	
Japan, 1971	1.5	Sei *et al.* 1993
Japan, 1985	1.7	Sei *et al.* 1993
Japan, 1995–98	1.6–1.9	Ma *et al.* 2010
China, 1997	1.7	Cai *et al.* 2004
Canada, adults, 2004	2.6	Health Canada 2004
Europe, adults, 2009	2.7	Welch *et al.* 2009
Turkey, teens, 2008	2.9	Garipagaoglu *et al.* 2008
Sweden, women, 1987–90	2.9–3.1	Larsson *et al.* 2005
UK, adults, 2000–01	3.3–3.4	Bates *et al.* 2010
UK, adults, 2008–09[C]	3.1	Bates *et al.* 2010
USA, adults, 1977	2.6	Rosanoff 2010
USA, adults, 2009–10	3.3	From NHANES (USDA-ARS 2012)

[A]Value given is for healthy group ($n = 142$); hypertension ($n = 150$), impaired fasting glucose ($n = 11$) and diabetes groups ($n = 21$) had dietary Ca : Mg ≥0.9.
[B]Mean of all adults, both male and female; transitional Bedouins have added store-bought, white bread to diets. Note: Bedouins eating a more transitional diet, i.e. more white bread than traditional whole wheat bread, also showed an increase in high cholesterol, from 6.5% to 24.3%; hypertension, from 16% to 30% (double); diabetes, from 6.5 to 19.7%; chronic heart disease from none to 6.5%. These rises in chronic diseases occur even though the transitional Bedouins are smoking less (28.2% in traditional, 17.8% in transitional), more transitional are dieting (2.5% *v.* 9.8%), and their sedentary lifestyle is about the same (87.9% *v.* 85.6%).
[C]UK dietary Ca : Mg may be decreasing; flour was enriched with Ca beginning in WWII.

shown no real yield effect at a wide range of ratios (Liebhardt 1981; Fox and Piekielek 1984; Reid 1996; Stevens *et al.* 2005). Plant tissue Ca : Mg at various soil ratios has not been as robustly studied. This review will explore how soil or substrate Ca : Mg affects plant tissue Ca : Mg, to begin research into whether soil Ca : Mg might affect human health.

Human dietary Ca : Mg intake is rising

Human dietary Ca : Mg intake ratios

Because both Mg and Ca are essential nutrients for humans and animals, both are necessary in adequate amounts for optimal health, but is there a healthy Ca : Mg dietary intake ratio? Traditional recommendations that human dietary Ca : Mg intake ratios remain close to 2.0 (wt/wt) for humans (Durlach 1989) were not evidence-based until Dai *et al.* (2007) found that Ca : Mg dietary intake ratios >2.8 (wt/wt) were associated with enhanced expression of a colorectal cancer allele in humans. Thus, a value approaching or exceeding 2.8 can be deemed appropriate for assessing the effect of the Ca : Mg ratio in edible plant tissue and diets on human health.

Rising dietary Ca : Mg ratio in human populations

Much of the global human population is in dietary transition with increased modern processed foods in their diet, resulting in increased dietary Ca : Mg intake ratios (Table 1). To compile this information, human studies measuring both Ca and Mg intakes were collected, and dietary Ca : Mg for each study was calculated on a wt/wt basis by using mean Ca and Mg intakes. Table 1 is thus preliminary, giving only approximate values for Ca : Mg intake ratios; in addition, no variance is available because Ca : Mg was not calculated on an individual-subject basis in any of the studies. Populations consuming traditional diets comprising largely seeds, nuts, whole grains and traditional vegetables have dietary Ca : Mg ratios <1.0 (Table 1). These populations have a high dietary Mg intake, >400 and up to 600 mg Mg day^{-1} (Rosanoff 2013). Cardiovascular disease, type 2 diabetes and their risk factors are usually low or not present in these populations. Populations in 'transition' from their traditional diets to the modern processed-food diet have dietary intake Ca : Mg ratios that increase from ~1 to 1.5 as their mean dietary Mg intakes fall to <350 mg day^{-1}. These 'transition' populations have rising levels of cardiovascular disease (Reddy and Yusuf 1998; Tamir *et al.* 2007) and type 2 diabetes (King *et al.* 1998). Populations consuming modern processed-food diets have Ca : Mg dietary intake ratios >1.5 and some >2.8, a value above which has been determined to be a risk for disease (Dai *et al.* 2007, 2011, 2012; Dai and Baron 2008). In populations with these high ratios caused by a marginal to deficient Mg intake plus a rising Ca intake (Rosanoff 2010, 2013), there is a substantial presence of chronic, non-communicable diseases such as cardiovascular disease, type 2 diabetes and some cancers. Although a rising Ca : Mg may have little effect when diet is adequate in both Mg and Ca, a high Ca intake is of special concern when Mg intakes are deficient (especially <250 mg day^{-1}) (Seelig 2006; Nielsen 2010). In addition, there is evidence that this rising trend is continuing in developed countries, because the dietary Ca : Mg ratio has risen 18–22% in the USA since 1977 (Rosanoff 2010) and may still be rising in Japan (Sei *et al*. 1993). The UK presents a special case, where flour has been enriched with Ca starting in World War II, and the Ca : Mg intake ratio calculated from reported intakes in the National Diet and Nutrition Survey was >3.1 for adults in both the 2000–01 and 2008–09 surveys (Bates *et al*. 2010, 2012). The Ca : Mg ratios for both men and women were slightly less in the 2008–09 survey than the 2000–01 survey, so the ratio may be stabilising or even decreasing in the UK; however, this is still being determined.

Possible sources of rising dietary Ca : Mg

The rise in dietary Ca : Mg in the USA is due to a rising Ca intake (Rosanoff 2010). In other populations, this rising Ca : Mg can be due to a decrease in Mg intake (Rosanoff 2013). Bedouins in transition apparently have raised their Ca : Mg intake ratio from 0.9 to 1.5, just by incorporating store-bought bread into their traditional diet (Abu-Saad *et al*. 2009; see also Table 1), which has led to a significant decrease in mean Mg intake from 490 to 262 mg day^{-1}. With this seemingly small change in the Ca : Mg ratio but large decrease in Mg intake has come more self-reported high cholesterol, hypertension, diabetes and heart disease, even with no change in body mass index and lower levels of smoking.

Ca : Mg and human health, chronic diseases

Population studies have shown that high Ca : Mg dietary intake ratios correlate with cardiovascular disease (Karppanen *et al*. 1978; Seelig 2006). An underlying cellular imbalance between Ca and Mg is a root cause of the cellular phenotypes that manifest as risk factors and disease states of both cardiovascular disease and type 2 diabetes (see Fig. 1). As intracellular Mg goes down, Ca influx into cells rises, raising the intracellular Ca : Mg (Zhang *et al*. 1992, 1996; Delpiano and Altura 1996; Altura *et al*. 1997, 2001).

Ca : Mg and risk of cardiovascular disease

Concomitant with high cellular Ca : Mg, blood platelet cells become sticky and tend to clot when Mg is low (Penglis and Michal 1969; Provincial, Regional and National Summary Data Tables, Vol. 1, p. 197 in Herrmann *et al.* 1970; Gawaz 1996). This can lead to clots in the brain, which cause stroke, and clots in the heart, which can cause heart attack. Smooth muscle cells (cells that line blood vessels) with a high intra-cellular Ca : Mg show hyper-contractility (Resnick 1992*a*; Yang *et al*. 2000), an aspect of heart disease. In addition, hearts with high Ca : Mg ratio have a large left ventricular mass index (Resnick *et al*. 1990*c*), which is more predictive of adverse heart events and mortality than is high blood pressure, a CVD risk factor that also is proportional to cellular Ca : Mg (Resnick 1990, 1992*a*, 1993, 1999; Resnick *et al*. 1990*b*). Studies with *in vitro* animal models show that a low-Mg environment also makes vascular smooth muscle cells prone to constriction and stiffness (Turlapaty and Altura 1980), which are aspects of high blood pressure or hypertension, the most common risk factor for heart disease worldwide (Lozano *et al*. 2012).

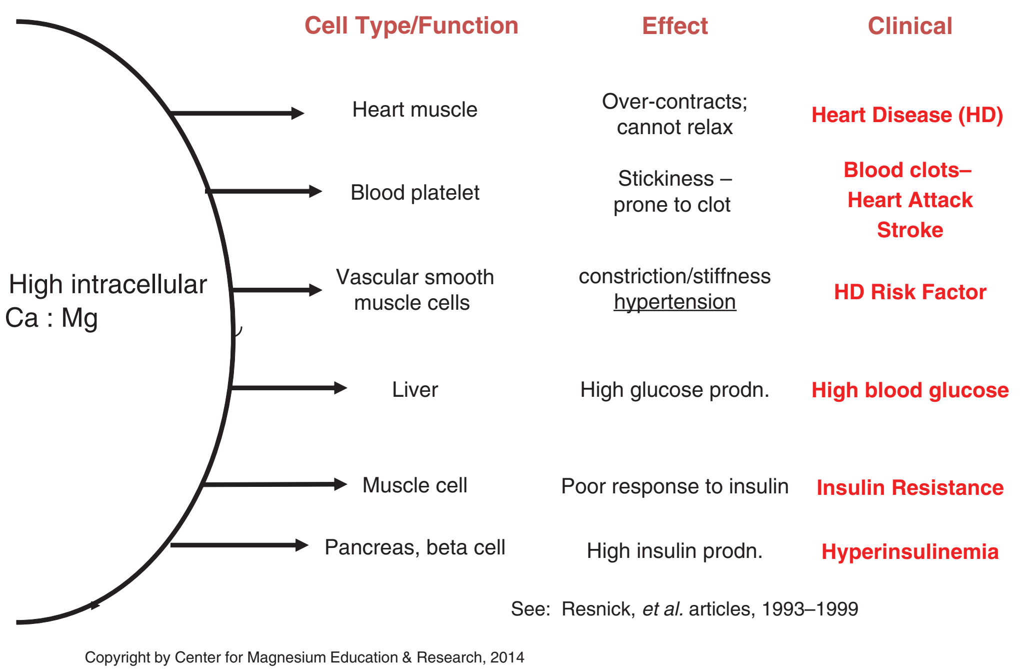

Fig. 1. Cellular effects in humans of high Ca : Mg ratio.

Ca : Mg and risk of type 2 diabetes

In addition to cardiovascular disease, several crucial aspects of type 2 diabetes are linked by high Ca : Mg in various cells (Resnick *et al.* 1988, 1990*b*, 1993*a*, 1993*b*; Resnick 1992*b*, 1993; Seelig and Rosanoff 2003*a*) that can result in high blood glucose levels, a poor response to insulin and an overproduction of insulin. When these three characteristics of type 2 diabetes are combined with the heart-disease risk factors of high cholesterol and high blood pressure, the condition is termed 'metabolic syndrome' or pre-diabetes—itself a heart-disease risk factor.

All of the cellular phenotypes in Fig. 1 are associated with an abnormally high Ca : Mg cellular ratio (Resnick *et al.* 1993*b*). Which conditions manifest, be they risk factors or disease states, depends on individual genetics, medical history and environmental history of the individual (Seelig and Rosanoff 2003*b*). Of course, diet is a huge part of the environmental history.

Adequacy of essential nutrients is as important as dietary intake ratio for long-term human health. Hypothetically, an individual with an inadequate intake of 450 mg Ca day^{-1} and an inadequate 225 mg Mg day^{-1} would have a healthy Ca : Mg of 2.0 but increased risk of chronic disease from suboptimal Ca and Mg intakes. However, a high intake of Ca with a low intake of Mg is especially important because high dietary Ca interferes with the transport of Mg across the cell membrane of non-excitable cells, such as those involved in intestinal transport. In addition, Ca can compete with Mg for the ubiquitously expressed ion channel TRPM 7, which plays a central role in Mg absorption and homeostasis. Dysregulation of TRPM 7 has been associated with molecular processes that promote vascular calcification, an aspect of cardiovascular disease (Schmitz *et al.* 2003; Dai *et al.* 2007; Touyz 2008).

Does high dietary Ca in low-Mg populations cause cardiovascular disease or diabetes?

One trial performed on insulin-dependent diabetic children compared with age- and sex-matched controls showed that 60 days of oral Mg (6 mg kg^{-1} day^{-1}) plus 3 days of a low-Ca diet brought many biomarkers of these patients into the range of the healthy control subjects (Saggese *et al.* 1991). Placebo-controlled, randomised clinical studies in menopausal women have shown rises in CVD with Ca supplementation (Bolland *et al.* 2008, 2010). However, a large clinical study of Ca-supplementation in women in the USA, the country with the highest dietary Ca : Mg intake ratio yet measured (see Table 1), has shown conflicting results upon sub-analysis (see note at end of *Discussion*). Unfortunately, Mg intakes were not reported from any of these studies, so we cannot calculate Ca : Mg to see whether it can explain some of the conflicting results. However, other USA studies have shown that increasing Mg intakes by 200–375 mg day^{-1} will significantly lower CVD rates in this high-Ca : Mg population (Chiuve *et al.* 2011; Zhang *et al.* 2012; Del Gobbo *et al.* 2013), whereas same levels of Mg supplementation were associated with higher rates of mortality in China, where the background dietary Ca : Mg is much lower, at ~1.7 (Dai *et al.* 2013). It must be remembered, though, that lower Mg intakes, even with a dietary Ca : Mg as low as 1.5, increased risk factors for Bedouins in transition (Abu-Saad *et al.* 2009).

Impact of soil Ca : Mg on plant tissue Ca : Mg

Given that a small dietary change such as adding commercially prepared bread can have a significant effect on the Ca : Mg ratio and chronic disease incidence (Table 1, including footnote), it is appropriate to ask whether current farming practices using Ca-rich soil amendments (e.g. calcitic limestone and gypsum) might be affecting human dietary Ca : Mg intake ratios.

Addition of Ca-based soil amendments to soils is widely used in modern farming to assure optimal chemical and/or physical conditions. Studies of this practice may provide extractable data to explore any effects of varying soil Ca : Mg on Ca : Mg in plant tissues, especially products destined for human consumption. Considering the apparent global human health impact of a rising dietary Ca : Mg ratio, this would be a worthy endeavour.

Increasing soil Ca : Mg does not significantly affect yield

Increasing soil pH to levels considered optimal for plant nutrient uptake, decreasing toxic forms of soluble aluminium (Al), and imparting Ca to soil for improved plant nutrition are major reasons for much of the amendment of soils with calcitic ($CaCO_3$) or dolomitic ($CaMg(CO_3)_2$) limestone. Because yield is of primary importance for soil treatments, many yield studies with varying soil Ca : Mg ratios have been reported. In one study, yield of finger millet (*Eleusine coracana* (L.) Gaertn) was reported to be affected by soil Ca : Mg, with an optimal soil Ca : Mg range between 3.1 : 1 and 3.4 : 1, in an extremely precise study measuring heights to 0.01 cm and yields to 0.01 g (Ansari *et al.* 2010). Two studies found that yield was stable at large ranges of soil or solution Ca : Mg, except when substrate Ca : Mg was <0.5, where yield dropped substantially for citrus plants (Martin and Page 1969) and for Russian Red kale shoot biomass (Kopsell *et al.* 2013). Generally, however, no change in yields for these and several other crops was reported when soil Ca : Mg ranged from 20 : 1 to 1 : 10 (Hunter 1949; Giddens and Toth 1951; Key *et al.* 1962; McLean and Carbonell 1972; Simson *et al.* 1979; Liebhardt 1981; Fox and Piekielek 1984; Schulte and Kelling 1993; Reid 1996; WANTFA 2005; Kopittke and Menzies 2007).

Increasing soil Ca : Mg affects whole plant, leaf, shoot and reproductive tissue Ca : Mg differently

We searched the agricultural literature for experiments that measured plant Ca and plant Mg and/or plant Ca : Mg in growth experiments at various Ca : Mg ratios in either soil or nutrient solution (see Fig. 2). We especially searched for impacts of varying soil or substrate Ca : Mg on edible plant tissues for human consumption—grains, nuts and seeds—which provide the majority of human Mg nutrition. We surveyed 1003 articles (994 from online database searches plus nine identified by manual searching) by title and abstract to identify studies that might include Mg and Ca contents in grains, bean, fruits or other edible plant tissue. Promising articles (41) were given full text review, resulting in 23 articles (54 studies) with proper extractable data that included Mg and Ca contents of plant tissues as well as data on soil exchangeable Ca and Mg. We calculated soil or solution

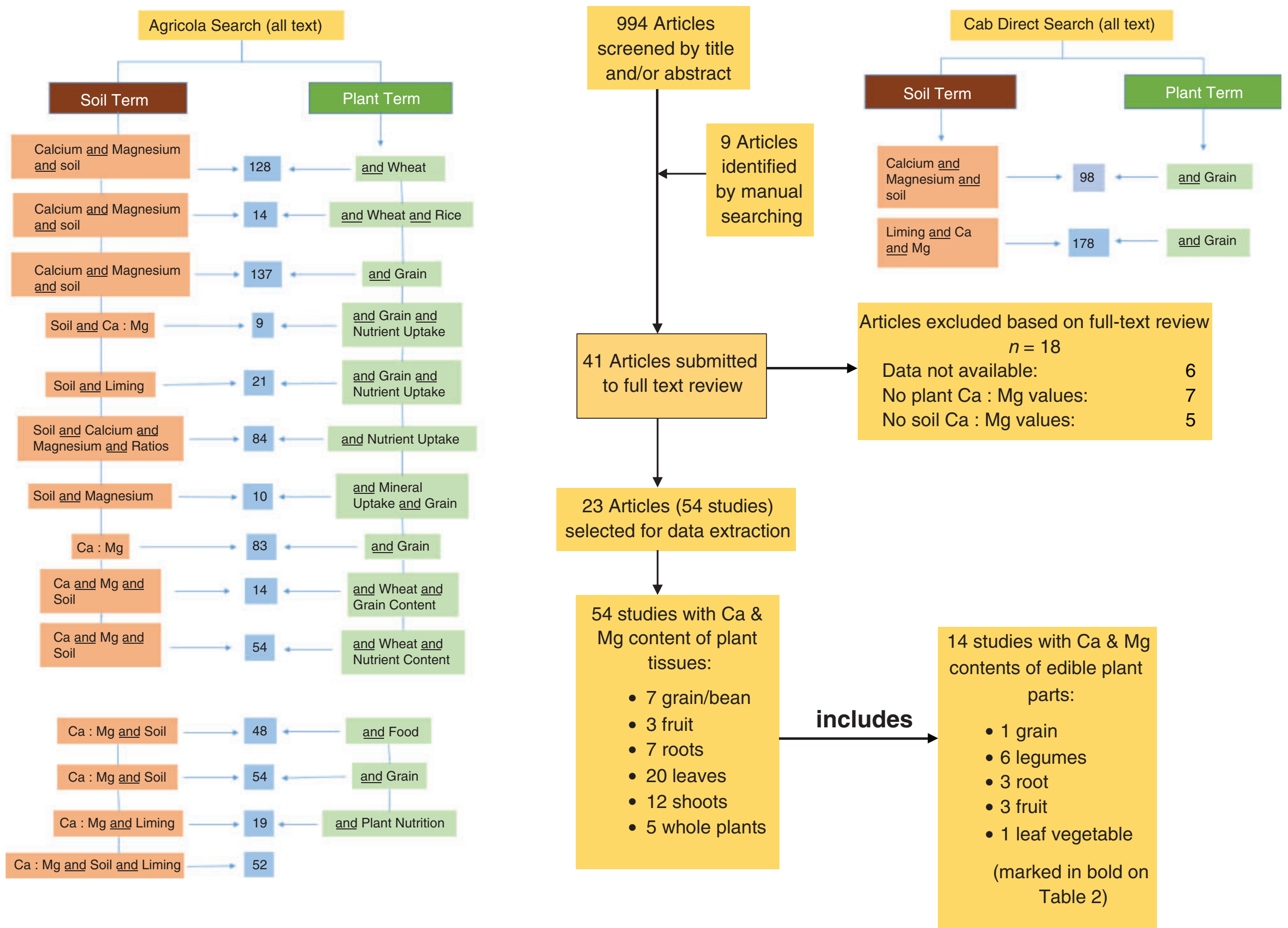

Fig. 2. Flow chart for literature search and selection process to find extractable data for both soil and edible plant tissue Ca : Mg.

Ca : Mg on a wt/wt basis and plant tissue Ca : Mg on a wt/wt basis from the data for each of the 54 studies. Using Excel, we calculated Pearson's correlation coefficient (*r*) for each study and determined 2-tailed *P*-value for each correlation coefficient using standard statistical tables (see Table 2).

Our search found several high-quality studies that measured plant tissue Ca and Mg uptake at various experimental levels of soil Ca : Mg. Most studies reported Ca and Mg contents for whole plants, roots, shoots and/or leaves. Very few reported Ca and Mg content of reproductive tissues such as grain, bean, seed or fruit. None reported nuts. These well-designed studies compare surface liming with incorporated liming and test increasing levels of calcite and/or dolomitic agricultural limestones, gypsum ($CaSO_4.2H_2O$), Epsom salts ($MgSO_4.7H_2O$) or other chemical sources of Ca and Mg by using plot surface application, chemical saturation of soil in pots, and soil-free nutrient solutions. Results are tabulated in Table 2, and Fig. 3 shows *x*–*y* scatter plots, on the same scale, for the studies where $n \geq 3$, of shoot, leaf and edible plant tissue Ca : Mg for these various crops grown in a range of soil or substrate Ca : Mg ratios. Leaf data of Martin and Page (1969) were not added to Fig. 3 because the scale was too wide.

Whole plant, leaf and shoot tissue Ca : Mg increases with soil Ca : Mg

All five whole-plant studies showed a significant increase in plant tissue Ca : Mg with increasing soil Ca : Mg ($P < 0.05$ for all studies, Table 2). Nine of ten shoot studies in this collection showed a positive correlation between shoot Ca : Mg and soil Ca : Mg. Eight of these were significant ($P < 0.05$), in studies using a wide range of soil or substrate Ca : Mg (see Table 2, Fig. 3*c*). One shoot study on wheat straw showed an insignificant increase in plant tissue Ca : Mg with soil Ca : Mg (Sultana *et al.* 2009). The change in Ca : Mg of leaf tissue with increasing soil or substrate Ca : Mg was not as great or as consistent as for shoot and whole plant (Table 2, P <0.01–0.98; Fig. 3*b*); however, the ranges of soil Ca : Mg in these studies were not as wide as for whole plant and shoot studies.

As a whole, these experiments show that non-edible plant tissue Ca : Mg, especially whole plant, shoot and leaf Ca : Mg, can vary widely with soil or substrate Ca : Mg, whereas yield is generally not affected. This flexible plant tissue Ca : Mg can vary with soil type (Schulte and Kelling 1993), or with cultivar or species; for example, compare Vernal alfalfa

Table 2. Ranges of Ca : Mg in plant tissues and soils (wt/wt)

Bold values denote studies showing content of edible plant tissues. Pearson's correlation coefficient *r* with 2-tailed *P*-values calculated for all studies where $n > 4$

Reference	Species	Ca : Mg of plant tissues: Whole plant	Shoots	Roots	Leaves	Grain, bean	Fruit	Soil Ca : Mg range	Pearson's *r*	2-tailed *P* for *r*	Comments
Studies with edible plant tissue analysis											
Sultana *et al.* 2009	Wheat		3.8–5.7			**0.6–0.8**		3–5.4	Straw –0.57, grain 0.21	Straw 0.14, grain 0.6	Dolomitic lime 0–3.5 t ha^{-1}
Fageria *et al.* 2008	Beans		2.3			**1.4**		4.6	n <3		Soil Ca : Mg at harvest, after gypsum liming at 12 Mg ha^{-1}, one site, single soil Ca : Mg
Rashed and Awadallah 1998	Faba bean		2.8		3.6	**1.3–2.2**		4 (8 after planting)	n <3		No liming; one soil Ca : Mg; grain Ca : Mg is range of seed parts
Moodley *et al.* 2013	African fruit *Harpephyllum caffrum*						**2.8–7.5**	0.8–13.7	0.36	>0.3	No lime treatment, various soils
Warman 2005	Beans				3.0–4.6	**1.0–2.3**		9.7–11	n <3	No r; $n = 2$	NPK or compost, no liming
	Carrot			**2.2–2.3**	3.2–3.5			9.3–11	n <3	No r; $n = 2$	
	Onion			**1.2–2.3**	4.3–4.6			11.2–12.6	n <3	No r; $n = 2$	
	Pepper				3.0–3.3		**1**	11–11.8	n <3	No r; $n = 2$	
	Tomato				4.4–4.6		**1.1**	11.1–11.7	n <3	No r; $n = 2$	
Reddy *et al.* 2011	Amadumbe bulb			**0.6–2.2**				2.8–8.8	0.2	0.63	8 sites; no liming
	Amadumbe peel			2.6–3.7				2.8–8.8	0.91	0.0017	
Caires *et al.* 2008	Soybean				1.4–1.6	**0.6**		2.7–2.9	Grain, –0.11, leaf –0.02	Grain 0.89[A], leaf 0.98[A]	Dolomitic lime, 0–7.5 t ha^{-1}; leaf Ca 5× bean Ca, leaf Mg 2× bean Mg
Caires *et al.* 2006	Soybean 2002–03					**0.8–0.9**		2.7–3.5	0.19	0.8[A]	Soil Ca : Mg av. of 0–0.05 and
	Soybean 2003–04					**0.9–1.0**		As above	0.75	0.25[A]	0.05–0.10 m depths; 4 lime treatments: 0, 1.5 t ha^{-1} of surface lime for 3 years; 4.5 t ha^{-1} of surface or incorporated lime
Kopsell *et al.* 2013	Red Russian kale				**0.2–8.24**			0.1–9.0	0.97	<0.01	Leaf Ca rose and Mg fell as substrate Ca : Mg rose
Studies with leaf tissue analysis											
Joris *et al.* 2013	Corn				1.2–2.6			1.7–2.1	–0.42	0.58[A]	Dolomitic lime, 0–12 t ha^{-1}
	Soybean				1.3–1.6			1.7–2.2	–0.02	0.98[A]	
Michalovicz *et al.* 2014	Corn				0.9–1.5			3.6–7.5	0.96	0.0097[A]	Gypsum rate 0–6 t ha^{-1}
	Barley				3.2–4.3			3.6–7.5	0.71	0.176[A]	
Fageria and Breseghello 2004	Rice				0.9–2.0			1.9–6.4	0.48	<0.01	No lime treatment, 43 sites
Webster 1985;	Apple				1.92–4.22			1.4–11.4	0.97	<0.01	Gypsum and Epsom salt
Caires *et al.* 2004	Maize, limestone				1.3–1.8			3.1–3.8	–0.2	0.8[A]	Av. Ca : Mg at 0–0.1 m depth

	Maize, gypsum				0.95–2.0	2.4–4.7	0.97	0.03[A]	
Tissi *et al.* 2004	Corn				1.1–1.2	2.2–2.4	–0.69	0.31[A]	Limestone 0–3 t ha^{-1}
Martin and Page 1969	Sweet orange				2.6–33.6	0.4–7.3	0.93	0	Yolo loam
					0.8–60	0.1–32	0.84	<0.01	Merriam sandy loam
					0.6–45	0.2–24	0.77	<0.01	Hanford sandy loam
Studies with shoot tissue analysis									
Favaretto *et al.* 2008	Corn		0.3–1.6			0.5–8.0	0.97	0.007[A]	Calcite, $CaCl_2$ and $MgCl_2$ to get target soil Ca : Mg ratios
Fageria and Baligar 1999	Bean		3.2–7.7			2.7–9.8	0.97	0.006[A]	Low Mg lime, 0–150 g pot^{-1}
	Rice		0.9–1.7			2.7–9.9	0.93	0.022[A]	
	Wheat		1.7–3.7			2.7–9.10	0.98	0.003[A]	
	Corn		1.7–4.4			2.7–9.11	0.99	0.0016[A]	
	Soybean		2.8–4.8			2.7–9.12	0.61	0.27[A]	
Grant and Racz 1987	Barley cv. Bonanza		0.67–4.4	0.8–8.4		0.4–6.6	Shoot 0.99, root 0.96	<0.01	Nutrient soln Expt 1
	Barley cv. Johnson		0.33–9.25	0.42–10.3		0.2–13.0	Shoot 0.99, root 0.64	≤0.025	Nutrient soln Expt 2
	Barley cv. Bonanza		0.26–9.4	0.48–8.8		0.2–13.1	Shoot 0.99, root 0.75	≤0.005	
Studies with whole plant analysis									
Schulte and Kelling 1993	Alfalfa	2.15–4.14				2.3–13.9	0.84	0.002	Soil with gypsum and Epsom salts
Simson *et al.* 1979	Alfalfa	1.3–3.0				2.6–7.8	0.86	0.001	Ca 0–1800 kg ha^{-1}, Mg 0–1700 kg ha^{-1} added
	Corn	0.73–1.75				1.8–5.3	0.77	0.009	Ca 0–1160 kg ha^{-1}, Mg 0–710 kg ha^{-1} added. Soil with gypsum and/or Epsom salt
Ansari *et al.* 2010	Finger millet	1.1–1.7				3.4–4.3	0.68	0.04	Ca 0–1585 kg ha^{-1}, Mg 0–475 kg ha^{-1} added. $CaCl_2$ and $MgCl_2$ added to soil
Hunter 1949	Alfalfa	0.91–13.0				0.25–32	>0.8	<0.05	Summary data of 2 harvests at 2 P levels

[A]Small sample size (n <6) requires a very high r-value to be significant, i.e. $P < 0.05$.

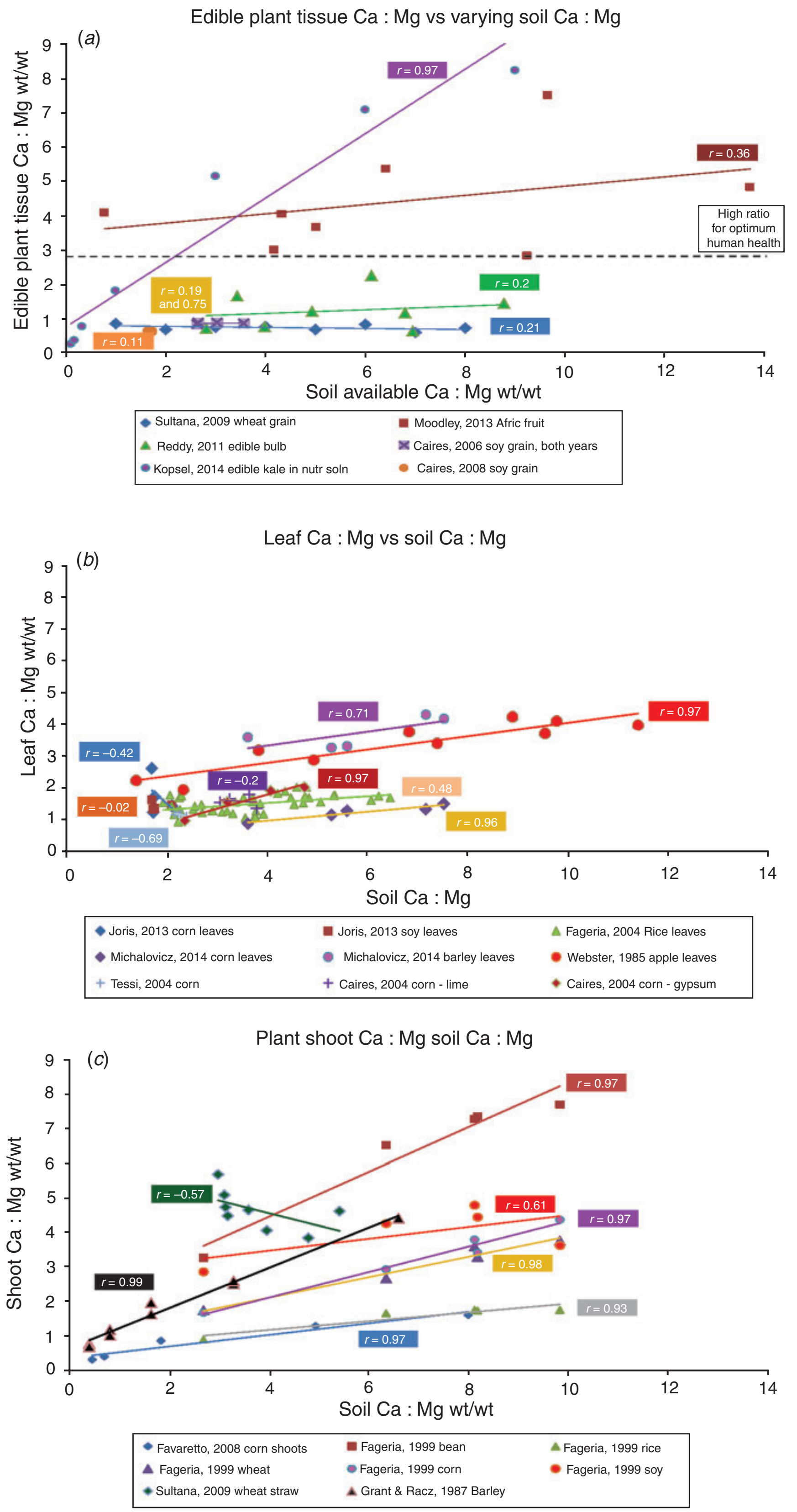

Fig. 3. Relation between soil Ca : Mg and (*a*) edible plant tissue Ca : Mg, (*b*) leaf Ca : Mg and (*c*) plant shoot Ca : Mg.

(Simson *et al*. 1979; Schulte and Kelling 1993) with Grimm alfalfa (Hunter 1949); also compare barley and maize leaves (Michalovicz *et al*. 2014). Flexible plant tissue Ca : Mg can also vary with environmental factors such as soil phosphorus level (Hunter 1949) and harvest season (Hunter 1949; Webster 1985), which can bring variations in meteorological conditions affecting insolation, daylength, precipitation, temperature and/or other factors.

Most of these experiments have not included analysis of Ca and Mg for the edible portions of these crops. Their purpose has been to quantify plant uptake of Ca, Mg and other plant nutrients. Grain and fruit uptakes of mineral nutrients appear to be a small portion of total plant uptake, and so their measurement was possibly deemed not worth the effort in the crop-uptake quantification goals.

Edible fruit, grain and bean Ca : Mg may not vary with soil Ca : Mg—data insufficient for conclusion

Of the 54 studies found appropriate for data extraction, only 14 (26%) provided Mg and Ca contents of edible plant tissues (these are noted in bold in Table 2). The edible plant tissues with measured Ca and Mg contents over a range of soil Ca : Mg consisted of one grain study (wheat, Sultana *et al.* 2009) and two legume studies (soybean, Caires *et al.* 2006). None of these three studies showed a change in grain or bean Ca : Mg with change in soil Ca : Mg (see Table 2, Fig. 2*a*), but each study had a narrower range of soil Ca : Mg than most of the leaf, shoot and whole-plant studies (soil Ca : Mg range for wheat 3–5.4, for soybean 2.7–3.5). Three other studies showed edible tissue Ca and Mg contents over a wide range of soil or substrate Ca : Mg; these included a rare African fruit (Moodley *et al*. 2013), an African edible bulb (Reddy *et al*. 2011) and Russian Red kale leaves (Kopsell *et al*. 2013). Of all three, only the Russian Red kale leaves showed a significant increase in leaf Ca : Mg with rising substrate Ca : Mg; however, it was grown in nutrient solution and so there were no attenuating influences of soil in this experiment.

The one fruit for which we have data from a wide soil Ca : Mg range (0.8–13.7), the rare African fruit, showed a non-significant rise in Ca : Mg, but this study was done on eight different soil sites with no experimental design to vary soil Ca : Mg. This fruit showed very high Ca (2300–8500 mg/kg DW) and Mg (830–1900 mg/kg DW) contents as well as a high Ca : Mg (i.e. >2.8, see discussion above) in its unique fruit tissue. It is inappropriate to generalise these results to other fruit tissues or to say whether fruit tissues in general may respond differently from grains or beans to rising soil Ca : Mg from this analysis or whether fruit tissue in general will exceed a Ca : Mg of 2.8 if soil Ca : Mg is high enough.

The study by Warman (2005) tested NPK fertiliser *v.* organic compost on several edible plants, and so provides data of edible tissue Ca : Mg for a two-point range of soil Ca : Mg for each crop, confounded by type of fertiliser. However, all edible plant tissue in this study (i.e. roots, bean and fruits) showed lower Ca : Mg than leaves from the same study plants (see Table 2). All other studies reporting edible plant tissue Ca and Mg provide only one soil Ca : Mg ratio value (Rashed and Awadallah 1998; Fageria *et al*. 2008) or a very narrow range of soil Ca : Mg (Caires *et al.* 2008). As with the crops of Warman (2005), all of these studies had edible tissue Ca : Mg that was lower than shoot or leaf Ca : Mg reported in the same study (see Table 2). In general, all collection studies of edible tissue, except for the African fruit and kale grown in substrate solution, showed Ca : Mg <2.8, the level deemed safe for human health.

Discussion

Rising plant Ca : Mg ratios may be the result of rising plant Ca or lower plant Mg

The Ca : Mg ratio in soil can affect not only the Ca : Mg ratio in the resulting plant tissue, but also the adequacy and availability of these two essential nutrients to the growing plant. High Ca content in the soil decreases Mg bioavailability to plants (Wilkinson *et al*. 1990; Gransee and Fuhrs 2013), and soils limed to near neutrality with calcitic limestone show consistent reductions in crop Mg uptake (Sumner *et al*. 1978). High availability of soil Ca and potassium (K) can lead to strong decreases in Mg uptake (Marschner 2012) and displacement of exchangeable Mg into soil solution by Ca-based soil amendments and K fertilisers that increase leaching losses of Mg (Gransee and Fuhrs 2013). Therefore, K fertilisation as well as application of Ca-based soil amendments as plant nutrients may inadvertently be contributing to reduced plant Mg concentrations. However, if liming materials simultaneously increase pH-dependent cation exchange capacity, some of this Mg leaching risk may be averted (Tamimi *et al*. 1974). However, in some instances, liming to a pH near neutrality or higher can reduce Mg availability by inducing the formation of insoluble, mixed Al–Mg hydroxides (termed Mg fixation), thereby contributing to reduced Mg uptake (Sumner *et al*. 1978; Riggs *et al*. 1995; Thibaud 2012; Gransee and Fuhrs 2013).

Additionally, it should be noted that the integrity of root-cell plasma membranes can show disruption as a consequence of toxic effects to roots of H^+ and Al^{3+} ions when Ca availability is very low, leading to ion leakage and impaired Mg uptake. Therefore, increasing Ca in low-Ca soils improves Mg uptake up to a point, but further increases in soil Ca can convert this positive synergy to a detrimental antagonism that limits Mg^{2+} uptake (Fageria 1973, 2009; Marschner 2012). Lastly, soil depletion of Mg can be a frequent problem caused by poor attention to offtake in harvest and unbalanced fertilisation practices whereby Mg fertiliser applications based on soil test recommendations are not considered (Gransee and Fuhrs 2013).

From a nutritional point of view, it is important to increase Mg concentration in edible parts of plants, as well as to decrease Ca : Mg ratio. This is especially important because diets increasingly include processed food. Liming with dolomite rather than calcite limestone can alter soil Ca : Mg. In a study on five soil types (Riggs *et al*. 1995), soil treatment with calcite increased the Ca : Mg ratios in all soils, whereas each soil limed with dolomite had a lower soil Ca : Mg than untreated soils (3.6 *v.* 7.4). These highly varying changes in soil Ca : Mg with calcite and dolomite were accomplished by a rise in soil pH from a mean of 4.0 to 6.1 with calcite liming and 4.0 to 5.9 with dolomite liming. In addition, all soils limed with dolomite had a pH >5.5, the pH that has been suggested as necessary to alleviate phytotoxicity from soil aluminium (Thibaud 2012), although some plants are sensitive even at this pH (Sanchez 1976).

In addition to liming as a tool to target soil Ca : Mg, there are ways to increase Mg concentration in plants (different types of fertilisers, including organic fertilisers, foliar sprays with different composition, use of physiologically active compounds, plant breeding, etc.), regardless of Ca level and Ca : Mg ratio in soil. Interestingly, in comprehensive nutritional analysis of transgenic cv. Rainbow papaya to establish substantially similar status to its non-transgenic counterpart, Ca content in the transgenic ripe fruit was about half that in the non-transgenic ripe fruit, whereas Mg in both were similar (Tripathi *et al*. 2011).

Potential effect of soil or plant Ca : Mg on human or animal health—inconclusive

The results can generally be interpreted as follows:

- In studies designed to assess the impact of soil Ca : Mg on plants, measurement of Ca and Mg in edible plant tissues is rare.
- Plant tissue Ca : Mg ratios of whole plants, most shoots, plus some leaves increase when soil Ca : Mg increases.
- Edible grain, fruit and root Ca : Mg ratios are less than the Ca : Mg of leaves or shoots of the same crop.
- Grain, bean and fruit Ca : Mg ratios may not respond nearly as much to changes in soil Ca : Mg as do Ca : Mg ratios of whole plants, shoots and leaves, some of which are edible such as Russian Red kale.

Because plant leaves, shoots and stems are not major food sources of Ca and Mg for humans, it is not possible at this time to assess whether farm practices with Ca additives or Ca and Mg additives are affecting human Ca : Mg intake ratios. To make such an assessment, more Ca : Mg data for human food components of plants need to be collected or generated with varying soil Ca : Mg ratios. However, it is possible that rising soil Ca : Mg ratios are altering the Ca : Mg ratios in leafy vegetables consumed by humans and in forage consumed by animals.

Potentially helpful studies

Studies of further edible plant tissues from crops grown in soils with varying Ca : Mg ratios are needed in addition to comparisons of crop Ca : Mg, with use of calcitic limestone or gypsum *v.* dolomite and Mg sulfate salts such as kieserite and epsomite, alone as well as with varying levels of K fertilisation. Reporting quantities of Ca and Mg added with applications of these soil amendments might add to knowledge. Determining whether soil Ca : Mg ratios are actually increasing around the world through use of lime, gypsum and other Ca-rich soil amendments might provide insights, as might a comparison of soil Ca : Mg in USA and other countries where dietary Ca : Mg is >3. In addition, it might be worthwhile to explore any indications of increasing Ca : Mg in plant foods by comparing current with historical food tables.

Note

One sub-analysis surprisingly showed that Ca and vitamin D supplementation increased rates of both heart attacks and strokes in women who were not supplementing with Ca and vitamin D before the study (Bolland *et al*. 2011). By contrast, women who took the study supplements of Ca and vitamin D in addition to their personal supplements showed no rise in CVD compared with placebo. However, the personal-supplement subgroup had lower rates of stroke and myocardial infarction at start of study (Bolland *et al*. 2011), and it is known that supplementation in adults in the USA tends to increase both Mg intake and Ca : Mg (Burnett-Hartman *et al*. 2009). Another sub-analysis (Prentice *et al*. 2013) of the same study found no difference in CVD when non-users of personal supplements were compared with the overall study of all participants. That sub-analysis did not separately analyse participants using personal supplements of $\geq$500 mg day^{-1} of Ca and/or $\geq$400 IU day^{-1} of vitamin D, so we do not know whether this subgroup showed a similar result to that in the Bolland *et al*. (2011) study. It appears to be still in question whether older women in a low-Mg, high-Ca : Mg dietary category and using Ca supplements as a preventive of osteoporosis show increases in CVD.

References

Abu-Saad K, Shai I, Kaufman-Shriqui V, German L, Vardi H, Fraser D (2009) Bread type intake is associated with lifestyle and diet quality transition among Bedouin Arab adults. *British Journal of Nutrition* **102**, 1513–1522. doi:10.1017/S0007114509990675

Altura BT, Memon ZI, Zhang A, Cheng TP, Silverman R, Cracco RQ, Altura BM (1997) Low levels of serum ionized magnesium are found in patients early after stroke which result in rapid elevation in cytosolic free calcium and spasm in cerebral vascular muscle cells. *Neuroscience Letters* **230**, 37–40. doi:10.1016/S0304-3940(97)00471-0

Altura BM, Zhang A, Cheng TP, Altura BT (2001) Extracellular magnesium regulates nuclear and perinuclear free ionized calcium in cerebral vascular smooth muscle cells: possible relation to alcohol and central nervous system injury. *Alcohol* **23**, 83–90. doi:10.1016/S0741-8329(00)00131-2

Ansari MA, Kumar SA, Subbarayappa CT, Sudhir K (2010) Effect of calcium–magnesium ratios in an Alfisol on growth and yield of finger millet in a red sandy clay loam soil. *Mysore Journal of Agricultural Science* **44**, 735–741.

Bates B, Lennox A, Swan GE (2010) National Diet and Nutrition Survey. Food Standards Agency, London. Available at: www.food.gov.uk/science/dietarysurveys/ndnsdocuments/ndns0809year1 (accessed 25 March 2012).

Bates B, Lennox A, Prentice A, Bates C, Swan G (2012) National Diet and Nutrition Survey: headline results from years 1, 2 and 3 (combined) of the Rolling Programme 2008/09–2010/11. Department of Health UK. Available at: http://transparency.dh.gov.uk/2012/07/25/ndns-3-years-report/ (accessed 25 March 2012).

Bolland MJ, Barber PA, Doughty RN, Mason B, Horne A, Ames R, Gamble GD, Grey A, Reid IR (2008) Vascular events in healthy older women receiving calcium supplementation: randomised controlled trial. *BMJ* **336**, 262–266. doi:10.1136/bmj.39440.525752.BE

Bolland MJ, Avenell A, Baron JA, Grey A, MacLennan GS, Gamble GD, Reid IR (2010) Effect of calcium supplements on risk of myocardial infarction and cardiovascular events: meta-analysis. *BMJ* **341**, c3691. doi:10.1136/bmj.c3691

Bolland MJ, Grey A, Avenell A, Gamble GD, Reid IR (2011) Calcium supplements with or without vitamin D and risk of cardiovascular events: reanalysis of the Women's Health Initiative limited access dataset and meta-analysis. *BMJ* **342**, d2040. doi:10.1136/bmj.d2040

Burnett-Hartman AN, Fitzpatrick AL, Gao K, Jackson SA, Schreiner PJ (2009) Supplement use contributes to meeting recommended dietary intakes for calcium, magnesium, and vitamin C in four ethnicities of middle-aged and older Americans: the Multi-Ethnic Study of Atherosclerosis. *Journal of the American Dietetic Association* **109**, 422–429. doi:10.1016/j.jada.2008.11.023

Cai H, Shu XO, Hebert JR, Jin F, Yang G, Liu DK, Gao YT, Zheng W (2004) Variation in nutrient intakes among women in Shanghai, China. *European Journal of Clinical Nutrition* **58**, 1604–1611. doi:10.1038/sj.ejcn.1602013

Caires EF, Kusman MT, Barth G, Garbuio FJ, Padilha JM (2004) Changes in soil chemical properties and corn response to lime and gypsum applications. *Revista Brasileira de Ciencia do Solo* **28**, 125–136. doi:10.1590/S0100-06832004000100013

Caires EF, Churka S, Garbuio FJ, Ferrari RA, Morgano MA (2006) Soybean yield and quality a function of lime and gypsum applications. *Scientia Agricola* **63**, 370–379. doi:10.1590/S0103-90162006000400008

Caires EF, Fernando JG, Barth G (2008) Surface application of lime and cover black oat and corn residues for no-till soybean production. *Communications in Soil Science and Plant Analysis* **39**, 2102–2118. doi:10.1080/00103620802135138

Chiuve SE, Korngold EC, Januzzi JL, Jr, Gantzer ML, Albert CM (2011) Plasma and dietary magnesium and risk of sudden cardiac death in women. *The American Journal of Clinical Nutrition* **93**, 253–260. doi:10.3945/ajcn.110.002253

Chu HI, Liu SH, Hsu HC, Choa HC, Cheu SH (1941) Calcium, phosphorus, nitrogen, and magnesium metabolism in normal young Chinese adults. *Chinese Medical Journal* **59**, 1.

Cullumbine H, Basnayake V, Lemottee J, Wickramanayake TW (1950) Mineral metabolism on rice diets. *British Journal of Nutrition* **4**, 101–111. doi:10.1079/BJN19500025

Dai Q, Baron J (2008) Magnesium, calcium, and colorectal adenoma recurrence: Results from a randomized trial. In 'Seventh Annual International Conference on Frontiers in Cancer Prevention Research'. Abstract A62. (American Association for Cancer Research: Philadelphia)

Dai Q, Shrubsole MJ, Ness RM, Schlundt D, Cai Q, Smalley WE, Li M, Shyr Y, Zheng W (2007) The relation of magnesium and calcium intakes and a genetic polymorphism in the magnesium transporter to colorectal neoplasia risk. *The American Journal of Clinical Nutrition* **86**, 743–751.

Dai Q, Motley SS, Smith JA, Jr, Concepcion R, Barocas D, Byerly S, Fowke JH (2011) Blood magnesium, and the interaction with calcium, on the risk of high-grade prostate cancer. *PLoS One* **6**, e18237. doi:10.1371/journal.pone.0018237

Dai Q, Sandler R, Barry E, Summers R, Grau M, Baron J (2012) Calcium, magnesium, and colorectal cancer. *Epidemiology* **23**, 504–505. doi:10.1097/EDE.0b013e31824deb09

Dai Q, Shu XO, Deng X, Xiang YB, Li H, Yang G, Shrubsole MJ, Ji B, Cai H, Chow WH, Gao YT, Zheng W (2013) Modifying effect of calcium/magnesium intake ratio and mortality: a population-based cohort study. *BMJ Open* **3**, e00211. doi:10.1136/bmjopen-2012-002111

Del Gobbo LC, Imamura F, Wu JH, de Oliveira Otto MC, Chiuve SE, Mozaffarian D (2013) Circulating and dietary magnesium and risk of cardiovascular disease: a systematic review and meta-analysis of prospective studies. *The American Journal of Clinical Nutrition* **98**, 160–173. doi:10.3945/ajcn.112.053132

Delpiano MA, Altura BM (1996) Modulatory effect of extracellular Mg^{2+} ions on K^{+} and Ca^{2+} currents of capillary endothelial cells from rat brain. *FEBS Letters* **394**, 335–339. doi:10.1016/0014-5793(96)00980-5

Durlach J (1989) Recommended dietary amounts of magnesium: Mg RDA. *Magnesium Research* **2**, 195–203.

Fageria NK (1973) 'Uptake of nutrients by rice plants from dilute solutions.' (Catholic University of Louvain: Louvain, Belgium)

Fageria NK (2009) 'The use of nutrients in crop plants.' (CRC Press, Taylor and Francis Group: London)

Fageria NK, Baligar VC (1999) Growth and nutrient concentrations of common bean, lowland rice, corn, soybean, and wheat at different soil pH on an Inceptisol. *Journal of Plant Nutrition* **22**, 1495–1507. doi:10.1080/01904169909365730

Fageria NK, Breseghello F (2004) Nutritional diagnostic in upland rice production in some municipalities of State of Mato Grosso, Brazil. *Journal of Plant Nutrition* **27**, 15–28. doi:10.1081/PLN-120027544

Fageria NK, Stone LF, Moreira A (2008) Liming and manganese influence on common bean yield, nutrient uptake, and changes in soil chemical properties of an Oxisol under no-tillage system. *Journal of Plant Nutrition* **31**, 1723–1735. doi:10.1080/01904160802324720

Favaretto N, Norton LD, Brouder SM, Joern BC (2008) Gypsum amendment and exchangeable calcium and magnesium effects on plant nutrition under conditions of intensive nutrient extraction. *Soil Science* **173**, 108–118. doi:10.1097/SS.0b013e31815edf72

Fox RH, Piekielek WP (1984) Soil magnesium level, corn (*Zea mays*) yield, and magnesium uptake. *Communications in Soil Science and Plant Analysis* **15**, 109–123. doi:10.1080/00103628409367459

Garipagaoglu M, Oner N, Vatansever U, Inan M, Kucukugurluoglu Y, Turan C (2008) Dietary intakes of adolescents living in Edirne, Turkey. *Journal of the American College of Nutrition* **27**, 394–400. doi:10.1080/07315724.2008.10719716

Gawaz M (1996) Antithrombocytic effectiveness of magnesium. *Fortschritte der Medizin* **114**, 329–332. [in German]

Giddens J, Toth SJ (1951) Growth and nutrient uptake of Ladino clover on red and yellow grey-brown podzolic soils containing varying ratios of cations. *Agronomy Journal* **43**, 209–214. doi:10.2134/agronj1951.00021962004300050001x

Gransee A, Fuhrs H (2013) Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant and Soil* **368**, 5–21. doi:10.1007/s11104-012-1567-y

Grant CA, Racz GJ (1987) The effect of Ca and Mg concentrations in nutrient solution on the dry matter yield and Ca, Mg and K content of barley (*Hordeum vulgare* L.). *Canadian Journal of Soil Science* **67**, 857–865. doi:10.4141/cjss87-082

Health Canada (2004) 'Nutrient intakes from food.' (Health Canada: Ottawa, ON, Canada)

Herrmann RG, Lacefield WB, Crowe VG (1970) Effect of ionic calcium and magnesium on human platelet aggregation. *Proceedings of the Society of Experimental Biology and Medicine* **135**, 100–103.

Hunter AS (1949) Yield and composition of alfalfa as affected by variations in the calcium–magnesium ratio in the soil. *Soil Science* **67**, 53–62. doi:10.1097/00010694-194901000-00007

Joris HAW, Caires EF, Bini AR, Scharr DA, Haliski A (2013) Effects of soil acidity and water stress on corn and soybean performance under a no-till system. *Plant and Soil* **365**, 409–424. doi:10.1007/s11104-012-1413-2

Kapil U, Verma D, Goel M, Saxena N, Gnanasekaran H, Goindi G, Nayar D (1998) Dietary intake of trace elements and minerals among adults in underprivileged communities of rural Rajasthan, India. *Asia Pacific Journal of Clinical Nutrition* **7**, 29–32.

Karppanen H, Pennanen R, Passinen L (1978) Minerals, coronary heart disease and sudden coronary death. *Advances in Cardiology* **25**, 9–24. doi:10.1159/000402000

Kelling KA, Schulte EE, Peters JB (1996) One hundred years of Ca:Mg ratio research. New Horizons in Soil Science, Dept. of Soil Science, University of Wisconsin, Vol. 8, 10p.

Key JL, Kurtz LT, Tucker BB (1962) Influence of ratio of exchangeable calcium–magnesium on yield and composition of soybeans and corn. *Soil Science* **93**, 265–270. doi:10.1097/00010694-196204000-00007

King H, Aubert RE, Herman WH (1998) Global burden of diabetes, 1995–2025: prevalence, numerical estimates, and projections. *Diabetes Care* **21**, 1414–1431. doi:10.2337/diacare.21.9.1414

Kopittke PM, Menzies NW (2007) A review of the use of the basic cation saturation ratio and the "ideal" soil. *Soil Science Society of America Journal* **71**, 259–265. doi:10.2136/sssaj2006.0186

Kopsell DE, Kopsell DA, Sams CE, Barickman TC (2013) Ratio of calcium to magnesium influences biomass, elemental accumulations, and pigment concentrations in kale. *Journal of Plant Nutrition* **36**, 2154–2165. doi:10.1080/01904167.2013.789108

Kumssa DB, Joy EJM, Ander EL, Watts MJ, Young SD, Rosanoff A, White PJ, Walker S, Broadley MR (2015) Global magnesium supply in the food chain. *Crop & Pasture Science* **66**, 1278–1289.

Larsson SC, Bergkvist L, Wolk A (2005) Magnesium intake in relation to risk of colorectal cancer in women. *Journal of the American Medical Association* **293**, 86–89. doi:10.1001/jama.293.1.86

Li Y, Ma A, Sun Y, Liang H, Wang Q, Yi X, Han X (2009) Magnesium status and dietary intake of mid-old people in a rural area of China. *Magnesium Research* **22**, 66–71.

Liebhardt WC (1981) The basic cation saturation ratio concept and lime and potassium recommendations on Delaware's Coastal Plain soils. *Soil Science Society of America Journal* **45**, 544–549. doi:10.2136/sssaj1981.03615995004500030022x

Lozano R, Naghavi M, Foreman K, Lim S, Shibuya K, Aboyans V, Abraham J, Adair T, Aggarwal R, Ahn SY *et al*. (2012) Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **380**, 2095–2128. doi:10.1016/S0140-6736(12)61728-0

Ma E, Sasazuki S, Inoue M, Iwasaki M, Sawada N, Takachi R, Tsugane S (2010) High dietary intake of magnesium may decrease risk of colorectal cancer in Japanese men. *The Journal of Nutrition* **140**, 779–785. doi:10.3945/jn.109.117747

Marschner H (2012) 'Mineral nutrition of higher plants.' (Academic, Elsevier: Amsterdam)

Martin JP, Page AL (1969) Influence of exchangeable Ca and Mg and of percentage base saturation growth of citrus plants. *Soil Science* **107**, 39–46.

McLean EO, Carbonell MD (1972) Calcium, magnesium, and potassium saturation ratios in two soils and their effects upon yields and nutrient contents of German millet and alfalfa. *Soil Science Society of America Journal* **36**, 927–930. doi:10.2136/sssaj1972.03615995003600060027x

Michalovicz L, Muller MML, Foloni JSS, Kawakami J, do Nascimento R, Kramer LRM (2014) Soil fertility, nutrition and yield of maize and barley with gypsum application on soil surface in no-till. *Revista Brasileira de Ciência do Solo* **38**, 1496–1505. doi:10.1590/S0100-06832014000500015

Moodley R, Koorbanally N, Jonnalagadda SB (2013) Elemental composition and nutritional value of the edible fruits of *Harpephyllum caffrum* and impact of soil quality on their chemical characteristics. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **48**, 539–547. doi:10.1080/03601234.2013.774230

Nielsen FH (2010) Magnesium, inflammation, and obesity in chronic disease. *Nutrition Reviews* **68**, 333–340. doi:10.1111/j.1753-4887.2010.00293.x

Penglis F, Michal F (1969) The induction of blood platelet aggregation by divalent cations. *Experientia* **25**, 745–746. doi:10.1007/BF01897601

Prentice RL, Pettinger MB, Jackson RD, Wactawski-Wende J, Lacroix AZ, Anderson GL, Chlebowski RT, Manson JE, Van Horn L, Vitolins MZ, Datta M, LeBlanc ES, Cauley JA, Rossouw JE (2013) Health risks and benefits from calcium and vitamin D supplementation: Women's Health Initiative clinical trial and cohort study. *Osteoporosis International* **24**, 567–580. doi:10.1007/s00198-012-2224-2

Rashed MN, Awadallah RM (1998) Trace elements in faba bean (*Vica faba* L) plant and soil as determined by atomic absorption spectroscopy and ion selective electrode. *Journal of the Science of Food and Agriculture* **77**, 18–24. doi:10.1002/(SICI)1097-0010(199805)77:1<18::AID-JSFA978>3.0.CO;2-G

Reddy KS, Yusuf S (1998) Emerging epidemic of cardiovascular disease in developing countries. *Circulation* **97**, 596–601. doi:10.1161/01.CIR.97.6.596

Reddy MR, Moodley A, Kindness SBJ, Jonnalagadda SB (2011) Impact of soil quality on elemental uptake by, and distribution in, *Colocasia esculenta* (*Amadumbe*), and edible root. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* **46**, 247–256. doi:10.1080/03601234.2011.540533

Reid WS (1996) Influence of lime and calcium: magnesium ratio on alfalfa and birdsfoot trefoil yields. *Communications in Soil Science and Plant Analysis* **27**, 1885–1900. doi:10.1080/00103629609369676

Resnick LM (1990) Calciotropic hormones in human and experimental hypertension. *American Journal of Hypertension* **3**, 171S–178S. doi:10.1093/ajh/3.8.171

Resnick LM (1992*a*) Cellular calcium and magnesium metabolism in the pathophysiology and treatment of hypertension and related metabolic disorders. *The American Journal of Medicine* **93**, S11–S20. doi:10.1016/0002-9343(92)90290-R

Resnick LM (1992*b*) Cellular ions in hypertension, insulin resistance, obesity, and diabetes: a unifying theme. *Journal of the American Society of Nephrology* **3**, S78–S85.

Resnick LM (1993) Ionic basis of hypertension, insulin resistance, vascular disease, and related disorders. The mechanism of "syndrome X". *American Journal of Hypertension* **6**, 123S–134S.

Resnick L (1999) The cellular ionic basis of hypertension and allied clinical conditions. *Progress in Cardiovascular Diseases* **42**, 1–22. doi:10.1016/S0033-0620(99)70006-X

Resnick LM, Gupta RK, Gruenspan H, Laragh JH (1988) Intracellular free magnesium in hypertension: relation to peripheral insulin resistance. *Journal of Hypertension. Supplement* **6**, S199–S201. doi:10.1097/00004872-198812040-00059

Resnick LM, Gupta RK, Gruenspan H, Alderman MH, Laragh JH (1990*b*) Hypertension and peripheral insulin resistance. Possible mediating role of intracellular free magnesium. *American Journal of Hypertension* **3**, 373–379. doi:10.1093/ajh/3.5.373

Resnick LM, Roman MJ, Gupta RK, Devereus RB, Laragh JH (1990*c*) Intracellular cation determinants of left ventricular mass. *American Journal of Hypertension* **3**, 15A.

Resnick LM, Barbagallo M, Gupta RK, Laragh JH (1993*a*) Ionic basis of hypertension in diabetes mellitus. Role of hyperglycemia. *American Journal of Hypertension* **6**, 413–417.

Resnick LM, Altura BT, Gupta RK, Laragh JH, Alderman MH, Altura BM (1993*b*) Intracellular and extracellular magnesium depletion in type 2 (non-insulin-dependent) diabetes mellitus. *Diabetologia* **36**, 767–770. doi:10.1007/BF00401149

Riggs KS, Rimmer DL, Syers JK (1995) Effect of liming on the chemical composition of soils. *Journal of the Science of Food and Agriculture* **69**, 159–167. doi:10.1002/jsfa.2740690205

Rosanoff A (2010) Rising Ca:Mg intake ratio from food in USA adults: a concern? *Magnesium Research* **23**, S181–S193.

Rosanoff A (2013) Changing crop magnesium concentrations: impact on human health. *Plant and Soil* **368**, 139–153. doi:10.1007/s11104-012-1471-5

Rosanoff A, Weaver CM, Rude RK (2012) Suboptimal magnesium status in the United States: are the health consequences underestimated? *Nutrition Reviews* **70**, 153–164. doi:10.1111/j.1753-4887.2011.00465.x

Saggese G, Federico G, Bertelloni S, Baroncelli GI, Calisti L (1991) Hypomagnesemia and the parathyroid hormone-vitamin D endocrine system in children with insulin-dependent diabetes mellitus: effects of magnesium administration. *The Journal of Pediatrics* **118**, 220–225. doi:10.1016/S0022-3476(05)80486-X

Sanchez PA (1976) 'Properties and management of soils in the tropics.' (John Wiley & Sons: New York)

Schmitz C, Perraud AL, Johnson CO, Inabe K, Smith MK, Penner R, Kurosaki T, Fleig A, Scharenberg AM (2003) Regulation of vertebrate cellular Mg^{2+} homeostasis by TRPM7. *Cell* **114**, 191–200. doi:10.1016/S0092-8674(03)00556-7

Schulte EE, Kelling KA (1993) Soil calcium to magnesium ratios—Should you be concerned? A2986. University of Wisconsin-Extension, Madison, WI, USA. Available at: www.soils.wisc.edu/extension/pubs/A2986.pdf.

Seelig M (2006) Value of raising magnesium to calcium intake ratio for health. In 'New data in magnesium research'. pp. 69–84. (John Libbey Eurotext: Paris)

Seelig M, Rosanoff A (2003*a*) Metabolic syndrome X, diabetes, and magnesium. In 'The magnesium factor'. pp. 34–49. (Avery, Penguin: New York)

Seelig M, Rosanoff A (2003*b*) Magnesium and genetics: family history and sex differences. In 'The magnesium factor.' pp. 196–7; 355. (Avery, Penguin: New York)

Sei M, Nakamura H, Miyoshi T (1993) Nutritional epidemiological study on mineral intake and mortality from cardiovascular disease. *The Tokushima Journal of Experimental Medicine* **40**, 199–207.

Simson CR, Corey RB, Sumner ME (1979) Effect of varying Ca:Mg ratios on yield and composition of corn (*Zea mays*) and alfalfa (*Medicago sativa*). In 'Communications in soil science and plant analysis.' (Ed. MU Jakobsen) pp. 153–162. (Marcel Dekker, Inc.: New York)

Stevens G, Gladbach T, Motavalli P, Dunn D (2005) Soil calcium:magnesium ratios and lime recommendations for cotton. *Journal of Cotton Science* **9**, 65–71.

Sultana BS, Mian MMH, Islam MR, Rahman MM, Sarker BC, Zoha MS (2009) Effect of liming on soil properties, yield and nutrient uptake by wheat. *Current World Environment* **4**, 39–47.

Sumner ME, Farina PM, Hurst VJ (1978) Magnesium fixation—a possible cause of negative yield responses to lime applications. *Communications in Soil Science and Plant Analysis* **9**, 995–1007. doi:10.1080/00103627809366871

Tamimi YN, Uchida RS, Matsuyama DT (1974) The importance of the pH dependency of charge in tropical soils on crop fertilizer management. In 'Proceedings of the Fertilizer I.N.P.U.T.S. (Increasing productivity under tight supplies) Project, Planning and Organization Meeting'. 21–25 October 1974, Honolulu. (Ed. S Ahmed) pp. 81–90. (East-West Food Institute: Honolulu)

Tamir O, Peleg R, Dreiher J, Abu-Hammad T, Rabia YA, Rashid MA, Eisenberg A, Sibersky D, Kazanovich A, Khalil E, Vardy D, Shvartzman P (2007) Cardiovascular risk factors in the Bedouin population: management and compliance. *The Israel Medical Association Journal* **9**, 652–655.

Thibaud GR (2012) Liming and the relevance of soil calcium and magnesium ratios. In 'Proceeding of the Fertilizer Association of Southern Africa Technical Symposium'. 22 August 2012, Pretoria. pp. 69–84. (Fertilizer Association of Southern Africa: Pretoria)

Tissi JA, Caires EF, Pauletti V (2004) Effect of lime application on no-tillage corn. *Bragantia* **63**, 405–413.

Touyz RM (2008) Transient receptor potential melastatin 6 and 7 channels, magnesium transport, and vascular biology: implications in hypertension. *American Journal of Physiology. Heart and Circulatory Physiology* **294**, H1103–H1118. doi:10.1152/ajpheart.00903.2007

Tripathi S, Suzuki JY, Carr JB, McQuate GT, Ferreira SA, Manshardt RM, Pitz KY, Wall MM, Gonsalves D (2011) Nutritional composition of Rainbow papaya, the first commercialized transgenic fruit crop. *Journal of Food Composition and Analysis* **24**, 140–147. doi:10.1016/j.jfca.2010.07.003

Turlapaty PD, Altura BM (1980) Magnesium deficiency produces spasms of coronary arteries: relationship to etiology of sudden death ischemic heart disease. *Science* **208**, 198–200. doi:10.1126/science.7361117

USDA-ARS (2012) What We Eat in America, NHANES 2009–2010, Individuals 2 years and over (excluding pregnant and/or lactating females and breast-fed children), day 1 food and supplement intake data, weighted. United States Department of Agriculture Agricultural Research Service. Available at: www.ars.usda.gov/ba/bhnrc/fsrg (accessed15 October 2014)

WANTFA (2005) 'WANTFA Meckering R&D Site Trial Results 2004.' (Western Australian No-Tillage Farmers Association: Perth, W. Aust.)

Warman PR (2005) Soil fertility, yield and nutrient contents of vegetable crops after 12 years of compost or fertilizer amendments. *Biological Agriculture and Horticulture* **23**, 85–96. doi:10.1080/01448765.2005.9755310

Webster DH (1985) Effect of varied soil Ca/Mg ratios on Ca and Mg concentrations in leaf samples of two apple cultivars. *Canadian Journal of Plant Science* **65**, 959–968.

Welch AA, Fransen H, Jenab M, Boutron-Ruault MC, Tumino R, Agnoli C, Ericson U, Johansson I, Ferrari P, Engeset D, Lund E, Lentjes M, Key T, Touvier M, Niravong M, Larranaga N, Rodriguez L, Ocke MC, Peeters PH, Tjonneland A, Bjerregaard L, Vasilopoulou E, Dilis V, Linseisen J, Nothlings U, Riboli E, Slimani N, Bingham S (2009) Variation in intakes of calcium, phosphorus, magnesium, iron and potassium in 10 countries in the European Prospective Investigation into Cancer and Nutrition study. *European Journal of Clinical Nutrition* **63**(Suppl. 4), S101–S121. doi:10.1038/ejcn.2009.77

Wilkinson SR, Welch RM, Mayland HF, Grunes DL (1990) Magnesium in plants: uptake, distribution, function, and utilization by man and animals. In 'Metal ions in biological systems. Compendium on magnesium and its role in biology, nutrition, and physiology'. Vol. 26. (Eds H Sigel, A Sigel) pp. 33–56. (Marcel Dekker: New York)

Yang ZW, Wang J, Zheng T, Altura BT, Altura BM (2000) Low $[Mg^{2+}]_o$ induces contraction and $[Ca^{2+}]_i$ rises in cerebral arteries: roles of Ca^{2+}, PKC, and PI3. *American Journal of Physiology. Heart and Circulatory Physiology* **279**, H2898–H2907.

Zhang A, Cheng TP, Altura BM (1992) Magnesium regulates intracellular free ionized calcium concentration and cell geometry in vascular smooth muscle cells. *Biochimica et Biophysica Acta* **1134**, 25–29. doi:10.1016/0167-4889(92)90024-6

Zhang A, Fan SH, Cheng TP, Altura BT, Wong RK, Altura BM (1996) Extracellular Mg^{2+} modulates intracellular Ca^{2+} in acutely isolated hippocampal CA1 pyramidal cells of the guinea-pig. *Brain Research* **728**, 204–208.

Zhang W, Iso H, Ohira T, Date C, Tamakoshi A, Group JS (2012) Associations of dietary magnesium intake with mortality from cardiovascular disease: the JACC study. *Atherosclerosis* **221**, 587–595. doi:10.1016/j.atherosclerosis.2012.01.034