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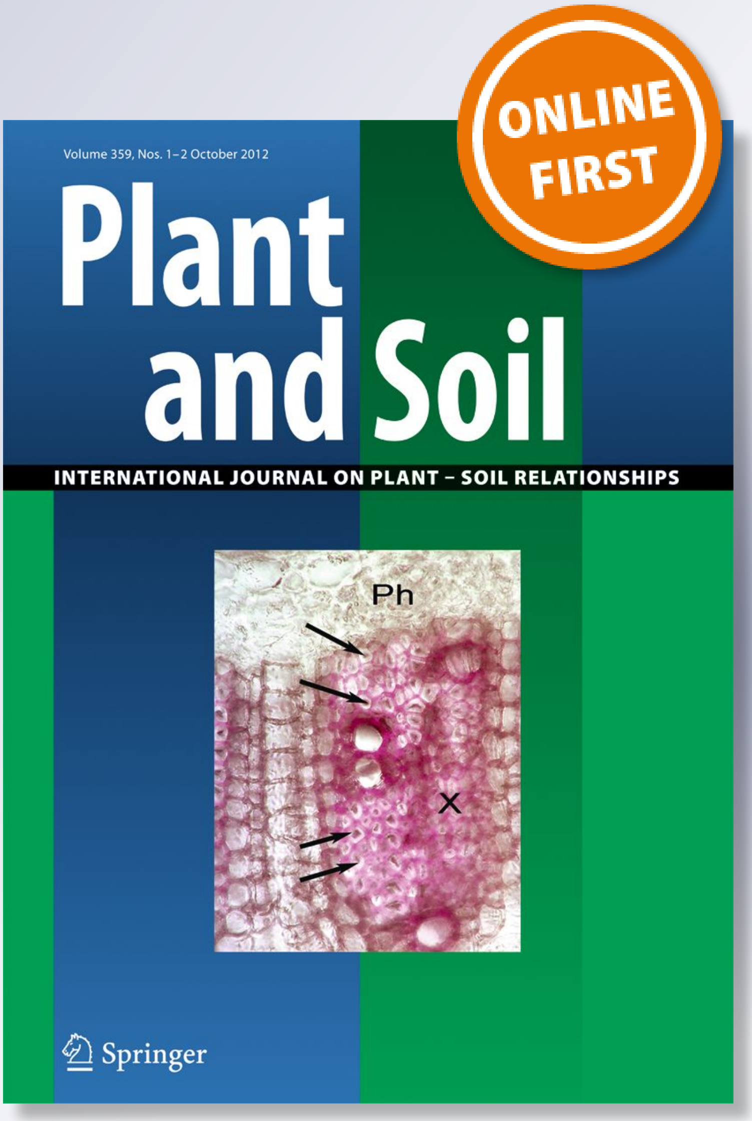

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REGULAR ARTICLE

Changing crop magnesium concentrations: impact on human health

Andrea Rosanoff

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Abstract
Aims Decreasing mineral concentrations in high-yield grains of the Green Revolution have coincided in time with rising global cardiovascular disease (CVD) mortality rates. Given the Magnesium (Mg) Hypothesis of CVD, it's important to assess any changes in food crop Mg concentrations over the past 50+ years.
Methods Using current and historical published sources, Mg concentrations in "old" and "new" wheats, fruits and vegetables were listed/calculated (dry weight basis) and applied to reports of USA's historic Mg supply, 1900–2006. Resulting trend in USA Mg supply was compared with USA trend in CVD mortality. Human Mg intake studies, old and new, were compared with the range of reported human Mg requirements.
Results Acknowledging assessment difficulties, since the 1850s, wheats have declined in Mg concentration 7–29 %; USA and English vegetables' Mg declined 15–23 %, 1930s to 1980s. The nadir of USA food Mg supply in 1968 coincides with the USA peak in CVD mortality. As humans transition from "traditional" to modern processed food diets, Mg intake declines.
Conclusions Rising global CVD mortality may be linked to lower Mg intakes as world populations transition from traditional high Mg foods to those low in Mg due to declining crop Mg and processing losses.

Keywords Magnesium · Human nutrition · Global nutrition · Mineral nutrition · Nutrient deficiencies · Non-communicable diseases · Metabolic syndrome · Cardiovascular diseases · The magnesium hypothesis of cardiovascular disease · Decreasing food crop magnesium concentrations

Introduction

In 1960, the world appeared to face a coming epidemic of hunger and starvation as the human population went into steep logarithmic growth. Globally, between 1960 and 1990, the Green Revolution negated this dire vision with increased yield of cereal grains providing food energy beyond the needs of the growing family of Man (FAO 1996; Tilman et al. 2002; Welch 2002). Since 1960, both the number and percentage of humans caught in chronic hunger have decreased (FAO 2012a), and surprisingly, obesity and overweight, the diseases of energy-over-nutrition, have become the scourge of humanity's future (WHO 2011a).

Obesity related non-communicable diseases (NCDs) now cause over half of the world's annual deaths. The World Health Organization predicts these NCDs (heart

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disease, stroke, cancer, osteoporosis, COPD and diabetes) will cause 75 % of all human deaths by 2030 (WHO 2008a, 2011b). As this major shift in "cause of death" patterns spreads to low- and middle-income countries, the expense to individuals, families and societies appears disastrous. Might changes in agriculture, again, negate a dire vision, this time of a "new" energy-overnutrition epidemic?

While increasing grain yields have provided a 35 % rise in per capita calories (joules) per day for the world human population (Welch 2002), increasing wheat yields of the past 40 years have come with decreasing concentrations of magnesium (Mg) (Murphy et al. 2008; Fan et al. 2008; Ficco et al. 2009). Low nutritional Mg status has been associated with the NCDs targeted by the World Health Organization (Rosanoff 2012; Seelig 1980). Magnesium is also related to the NCD risk factors so closely watched by medicine and public health organizations, e.g. cholesterol, high blood pressure, fasting blood sugar levels, and measures of abdominal obesity among others (Rosanoff 2012; Seelig and Rosanoff 2003). Assessment of food crop changes in Mg concentration over the past half-century with an analysis of possible impact on global human health is thus appropriate.

The role of nutritional Mg in human health

While world population has grown to 7 billion in 2012 from less than 3 billion in 1960—the start of the Green Revolution—the number and percentage of energy-undernourished persons in the world has been diminishing, from 26 % or 878 million in 1969–71 to only 13 % or 850 million in 2006–8 (FAO 2012a) Simultaneous with this beneficial, albeit unfinished trend, obesity and overweight have risen substantially in the world (Finucane et al. 2011). With grain-yield calories and work-saving technologies ample, the human family, on the whole, now has plenty of calories and less physical work to do than 50 years ago. Distribution of this "wealth" is still uneven, and pockets of hunger, starvation and hard labor remain, but since 1980, world-wide obesity rates have more than doubled (WHO 2011a), negating dire 1975 predictions of coming mass starvation (Davidson 1975). Associated with this rising body-weight-for-height or Body Mass Index (BMI) is a rising world-wide diabetes prevalence (School of Public and Health 2011) as well as rising global death rates from all NCDs, mostly cardiovascular disease (WHO 2011b). How much of this rise in NCDs might be due to declines in crop Mg concentrations?

Cardiovascular disease risk factors correlate, imperfectly, with disease

With no pathogen, cardiovascular disease (CVD) has long been diagnosed, assessed, predicted and treated using risk factors (Anonymous 1987; Greenland et al. 2003; NHLBI 2011a). No one risk factor or set of risk factors is totally predictive of heart disease, but persons diagnosed with diabetes, high blood pressure, abnormal cholesterol, obesity and/or any of the other many risk factors experience higher rates of CVD and mortality than do persons with fewer or zero risk factors (Berenson et al. 1998; Canto et al. 2011). Does everyone with diabetes, high blood pressure, obesity or high cholesterol get heart disease? No. Does everyone with heart disease have at least one of these risk factors? No. Making sense of a growing list of "risk factors" for CVD is a work in progress (Parikh and Mohan 2012).

The "metabolic syndrome" hypothesis of cardiovascular disease—the current paradigm

In 1988, Reaven proposed Insulin Resistance as the root cause at the center of this cluster of cardiovascular risk factors, naming it Syndrome X, or metabolic syndrome X (Reaven 1988). Rising global rates of obesity, diabetes prevalence and cardiovascular mortality have encouraged attempts to define "metabolic syndrome" with a highly predictive set of risk factors that can be easily and reliably measured. The progression of these attempts is seen in Table 1. Insulin Resistance fell away from definitions after 1999 as elevated plasma insulin became to be seen as "not mandatory" for the development of "metabolic syndrome" which became differentiated from "insulin resistance syndrome" (Einhorn et al. 2003). For later definitions of metabolic syndrome, obesity (i.e. BMI> 30) has given way to abdominal or central obesity, which became a required parameter until 2009 when a joint international task force deemed central obesity as no longer *required* to define metabolic syndrome, but rather one of five parameters (high blood pressure, low high-density lipoprotein (HDL) cholesterol, high

Table 1 Common cardiovascular disease risk factors and the evolving global definition of metabolic syndrome (MS), compared with Mg Hypothesis of cardiovascular disease

Cardiovascular disease risk factor	WHO-1999	EGIR-1999	NCEP-2002	AACE-2003	IDF-2006	Joint-2009	Risk factor associated with Mg status
Obesity	X			X			Yes
Central obesity	X	X	X		X̲	X	Yes
High triglyceride	X	X	X	X	X or treatment	X or treatment	Yes
Low HDL cholesterol	X	X	X+	X	X or treatment	X or treatment	Yes
High blood pressure	X	X	X+	X	X++ or treatment	X++ or treatment	Yes
High glucose		X	X		X+ or previous DM	X+ or previous DM	Yes
Impaired glucose tolerance	X̲	X		X			Yes
Insulin resistance	X̲	X̲					Yes
Diabetes—type 2	X̲				X	X	Yes
Other	Micro-Albuminuria			Many			Yes
Reference	WHO 1999	Balkau and Charles 1999	NCEP 2002	Einhorn et al. 2003	IDF 2006	Alberti et al. 2009	Rosanoff 2012

X̲ = risk factor required for MS diagnosis. X = risk factor part of MS diagnosis. X+ or X++ = risk factor set at more stringent standard. *DM* = diabetes mellitus

triglycerides, high fasting plasma glucose, and race/gender specific central obesity), any three of which is diagnostic of metabolic syndrome (Alberti et al. 2009; Ford et al. 2007; Parikh and Mohan 2012). This definition forms the current paradigm and focus on global prevention of CVD heart disease and diabetes: weight loss to reduce your waistline, reduction of other risk factors via medications or lifestyle changes including physical exercise, less tobacco use, higher consumption of fruits and vegetables, and reductions of salt, sugar and saturated fat in the diet (NHLBI 2011b; WHO 2008b). Can this approach succeed with lower than required intakes of nutritional magnesium and other essential nutrients which are low in the high-yield grains?

The low magnesium hypotheses of cardiovascular disease

Before Reaven proposed insulin resistance as the central aspect of metabolic syndrome and resulting cardiovascular disease, Dr. Mildred Seelig laid out a rigorously referenced alternative paradigm as the root cause of cardiovascular disease and all of its risk factors: nutritional magnesium deficit (Seelig 1980). Her hypothesis was bolstered by the work of Resnick and colleagues who found that all aspects of metabolic syndrome, including insulin resistance, manifest in tissues where cells are low in intra-cellular magnesium (Resnick 1992a, b, 1993). In such tissues, low intracellular Mg coincides with a concomitant rise in cellular calcium, resulting in a chronic high Ca: Mg intracellular ratio that appears to be the root cause of these various tissues' phenotypic transition into metabolic syndrome (Rosanoff et al. 2012). Evidence for Dr. Seelig's magnesium hypothesis has grown since 1980, and was updated in 2003 (Seelig and Rosanoff 2003). However, it's accurate predictions of rising rates of type 2 diabetes with ramifications for cardiovascular disease have remained pretty much "under the radar" of a scientific community that has shown 2 to 10 % annual reduction in CVD deaths (NIH 2012) with expensive (Kaiser 2011) regular use of pharmaceutical medications to treat common risk factors and medical procedures that prolong life in the face of the actual disease (Ford et al. 2007; NIH 2012; Farzadfar et al. 2011; Danaei et al. 2011).

Treatment of CVD diseases has become a wealth-intensive endeavor with pharmaceuticals used to lower high blood pressure (Egan et al. 2010; Ikeda et al. 2008; Khan et al. 2004; Ramsay et al. 1999), high cholesterol (Angeli et al. 2012; Martin et al. 2012; Minder et al. 2012; Reinhart and Woods 2012) and high blood sugar (Bennett et al. 2012; Qaseem et al.

2012), conditions that are all associated with low Mg status (Rosanoff 2012). The preventive effort relies on altering high risk factor life-style habits such as tobacco use, reducing dietary salt, sugar and saturated fat, increasing consumption of vegetables and fruits and reducing obesity (NHLBI 2011b; WHO 2008b). According to the Mg Hypothesis of CVD, all these life-style habits can be viewed as indirect attempts to lessen the impact of a marginal/low nutritional Mg status (Seelig and Rosanoff 2003; Rosanoff 2012).

If the Mg hypothesis of metabolic syndrome, diabetes and heart disease is even partly correct, world malnutrition is neither just hunger nor obesity, but a larger host of CVD conditions brought about, at least in part, by lower Mg concentrations of high-yield food crops and food processing which removes Mg. Is this low nutritional Mg the only cause of rising CVD rates? In 1975, Dr. Leslie M. Klevay introduced the zinc/copper hypothesis of coronary heart disease, linking high zinc/copper ratios, sometimes derived from low levels of dietary copper, as a factor in the etiology of coronary heart disease (Klevay 1975). As has Mg, both copper and zinc have declined in wheat grain since the 1960s (Fan et al. 2008).

Declining Mg concentration of food crops

Discerning real changes, if any, of food crop Mg concentrations over time is a difficult task. We can compare modern food crop Mg values with historic values, but differences in analytic methods, geographic source, soil and soil treatments, water, season and crop cultivar, at the very least, disallow direct comparisons. Additionally, comparisons of fleshy fruits and vegetables on afresh weight basis can be compromised by storage-dependent changes in water content. We have modern analyses of the continuous field trials of wheat grown at Rothamsted, England as well as field trials with historic and modern wheat cultivars. We also have Mg concentrations of several food crops both in food tables that go back to the first 40 years of the 20th century as well as the historical analytical papers and reports that support those food tables. With the resources available we here attempt to discern if there have been real changes in the Mg concentrations of crops important to human Mg nutrition.

Wheat Mg concentrations declined with modern high-yield cultivars

The Green Revolution increased yields for wheat, corn, rice, sorghum and barley. Declining Mg concentration with these increased yields has been quantified for wheat in three historical experiments which are summarized in Table 2.

In the *Broadbalk Wheat Experiment* in Rothamsted England, Mg concentrations of archived wheat grains produced over time (1843 to 2005) on similar plots began decreasing in 1968 with introduction of the first high yield cultivars (Fan et al. 2008). Wheat Mg concentrations dropped an average of 19.6 %, from a mean range of 115–126 mg/100 g dry weight (DW) before 1968 to 91–101 mg/100 g DW after 1968. These results, shown in Fig. 1, suggest the Mg concentration of wheat is still in decline.

Lower Mg concentration in high-yield wheats was confirmed in Italian Durum wheat. Ten "Modern" (1974–2000) and 17 "Advanced" (2000+) cultivars had a 12.5 % lower Mg DW concentration when compared with 57 "old" (1910–1974) varieties (Ficco et al. 2009), Fig. 2. We found this change in Mg concentration from 134 mg/100 g DW in the "old" varieties to 117 mg/100 g DW in the modern and advanced varieties to be a statistically significant result when tested with a two-tailed, unpaired Student's *t*-test (results in Fig. 2).

Murphy et al. (2008), compared 56 historical (1842–1965) to 7 modern (2003) spring wheat cultivars grown in the Pacific Northwest region of the USA for minerals. This study found an overall 7 % drop in Mg concentration, from 140 mg/100 g DW in the historical to 130 mg/100 g DW in the modern wheats, representing a decrease in Mg concentration only in soft white wheat, not in hard red wheat.

Accuracy of historic analyses for Mg in food crops

The Fan et al. 2008 study used modern analytical methods (ICP-AES, atomic emission spectroscopy) to analyze modern and archived wheats grown at Rothamsted in the most reliable method available to ascertain any change in Mg concentration of wheat grain over time. We also have the historic results of Lawes and Gilbert (1884) who published "magnesia" in ash, reported in mg/kg dry grain for wheats grown at Rothamsted on the same unmanured plots, on

Table 2 Mg concentrations of "old" and "new" whole wheat (WW) grains and flours; used for re-calculating change in Mg available to USA food supply, 1900–2006 (see Fig. 4a)

Crop	Date of "old" Mg concentration value	"Old" Mg concentration, mg/100 g DW	Date of "new" Mg concentration value	"New" Mg concentration, mg/100 g DW	% change in Mg concentration	Reference
Whole wheat grains						
Continuous field trials						
English wheat at Rothamsted (see Fig. 1)	1845–1965	115–126	1968–2005	91–101	−19.6 % (−12 to −28 %)	Fan et al. 2008
Field trials comparing varieties with different release dates						
84 Italian Durum wheat cultivars (see Fig. 2)	1910–1974	133.7	1974–2000+	117	−12.5 %	Ficco et al. 2009
63 North American spring wheat cultivars	1842–1965	140.3	2004–5	130.8	−6.8 %	Murphy et al. 2008
Current & historic values from publications & food tables (see Fig. 3)						
English Wheat at Rothamsted	1849–1852	125[a] 116–135				Lawes and Gilbert 1884
"Old" Utah/"new" North American wheats	1929	184	1989	131[b]	−29 %	Greaves and Hirst 1929/USDA 2011 and Health-Canada 2012
"Old" Kentucky/"new" North American wheats	1937 (assumed)	170	1989	131[b]	−23 %	Beeson 1941/USDA 2011 and Health-Canada 2012
North American WW grains	1963	183[c]	1989	131[b]	−28 %	Watt et al. 1963/USDA 2011 and Health-Canada 2012
Whole wheat flours						
English WW flours	1943 Pre-1978[e]	125–166[d] 163[e]	1977–81	139.5[f]	+11.9 to −16 % −14 %	Medical Research Council 1946; Paul and Southgate 1978/Food Standards Agency 2002
English WW flours	1942	160[g]	1978–80	148[h]	−7.5 %	McCance et al. 1945/Wenlock 1982

[a] 16-year mean elemental Mg concentration calculated assuming Lawes and Gilbert (1884) reported values are for MgO (Magnesia). Range is for means of three plots. Compare with same grains analyzed in Fan et al. 2008 (Fig. 1). See text

[b] Calculated DW mean of 5 varieties of wheat reported identically in USDA National Nutrient Database for Standard Reference, Release 24 (USDA 2011) and Health-Canada 2012. Wheats analyzed in 1989

[c] Single value from Table 5 of Watt et al. (1963) for "Whole Wheat Grain" Mg content, year and % moisture not reported; DW calculation assumes 12.8 % moisture (mean of 5 WW grains' % moisture from Table 1 of Watt et al. 1963)

[d] DW, calculated from Medical Research Council 1946 reported values using 15 % moisture assumed by table compilers; Range is for English WW flours (106 mgMg/100 g fresh weight (FW)) and Manitoba WW flours (141 mgMg/100 g FW)

[e] Calculated DW value from Paul and Southgate 1978; Must be pre-1978 value for Mg in wheat as England's Voluntary Flour Sampling Scheme program did not analyze for Mg before 1978 (Wenlock 1982)

[f] Calculated DW value from Food Standards Agency 2002 (FW value=120 mgMg/100 g at 14 % moisture)

[g] Calculated DW mean of six English WW flours milled commercially in 1942 as per McCance et al. 1945, supporting paper of (but not reported in) (Medical Research Council 1946)

[h] Wenlock 1982, supporting paper for Holland et al. 1988 which supports Food Standards Agency 2002

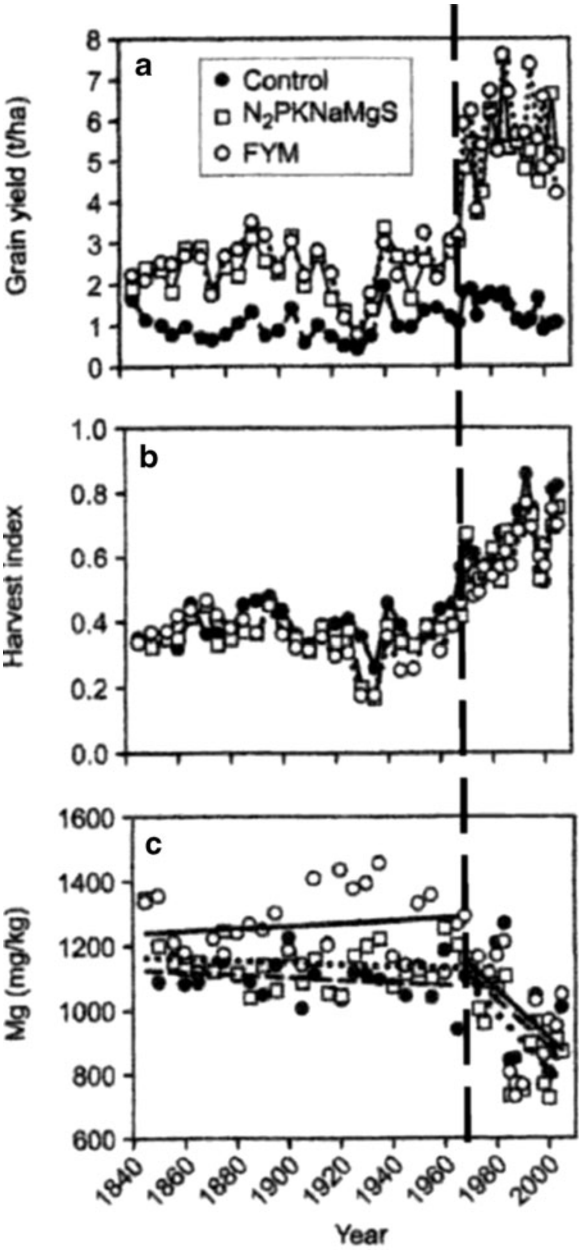

Fig. 1 Trends in wheat grain yield (at 85 % dry matter) (**a**), harvest index (**b**) and Mg concentration (**c**) over 160 years from three plots of the Broadbalk Experiment at Rothamsted, England. *Dotted line* indicates 1968, the year that short-straw cultivars were first introduced. Modified from Fan et al. (2008) with permission

farmyard manured plots, and on plots with ammonium salts alone for each year from 1848 to 1863. The Lawes & Gilbert values appear higher than the results from atomic emission spectroscopy shown by Fan et al. 2008 in Fig. 1 for these same grain samples, but when recalculated for elemental Mg from a presumed MgO result (see Table 1), there is good agreement with the modern analytical results. The Fan et al. 2008 results are not directly comparable with the Lawes & Gilbert results since the latter is an average of 16 yearly crops while the former is reported in 5-year intervals. In addition, Lawes & Gilbert reported minerals in wheat grains grown on 3 types of plots, only one of which was included in the 7 Rothamsted plots selected for analysis by Fan et al. 2008. However, such close agreement, given this calculation for elemental Mg from a presumed MgO analysis, gives a bit of confidence in using Mg concentration values from historic analytical studies. Acknowledging that historic analyses may be for endpoints other than elemental Mg, a situation best discerned by an analytical chemist, we cannot ignore analyses of crop Mg concentrations only because they did not use modern techniques. In this regard McCance and Widdowson guide us with their statement in the forward to their 6th edition (Food Standards Agency 2002), that although several historic food values were "obtained by what are regarded nowadays as very primitive methods . . . Those were no less accurate than the modern automated ones, but they took a much longer time." Indeed, we can only admire the work of Mr. R. Richter who executed about 700 complete analyses of the ashes of various products, animal and vegetable, prepared at Rothamsted (Lawes and Gilbert 1884, p. 4) along with that of the chemist(s) who analyzed 1755 wheat samples reported in the Greaves and Hirst (1929) study (Table 2). If we imagine a human being with a practiced hand and a favorite buret, we know that we cannot wholly ignore (nor fully accept) historical results of Mg crop analyses just because they were performed before the advent of atomic absorption/emission spectroscopy.

Lower Mg concentration of wheat as reflected in food tables

Foodstuffs are not always reanalyzed for each edition of USA or English food tables. Nonetheless, historic food table and supporting historic analyses for Mg in wheat appear generally higher than modern Mg concentration values in the food tables of the USA (USDA 2011), Canada (Health-Canada 2012) and England (Food Standards Agency 2002). (See Fig. 3, Table 2). The Mg drop of 14 % in English whole wheat flours and

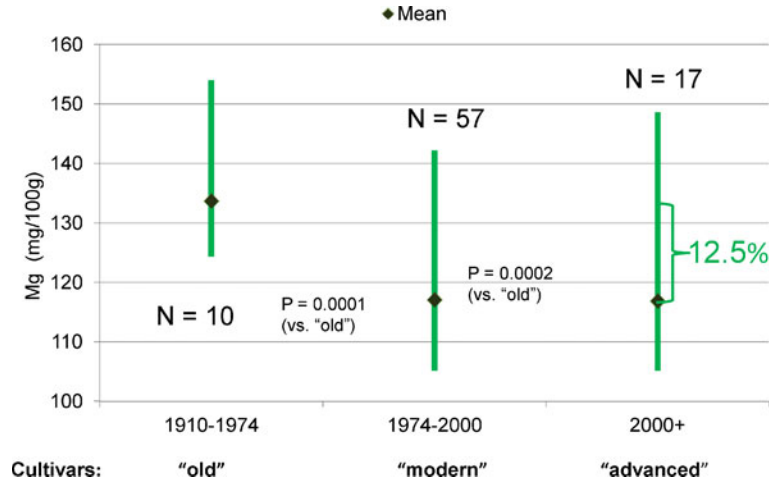

Fig. 2 Mg concentration of "old", "modern" and "advanced" Italian durum wheat cultivars. (Data from Ficco et al. 2009)

27 % in North American whole wheat grains (Fig. 3) compare well with the 12.5 to 19.6 % drops in Mg concentration in the Fan et al. 2008 and Ficco et al. 2009 studies discussed above. For refined wheat products, the downward trend in Mg concentration is not discerned. Both USA and English food tables show no real change in Mg concentration for white breads and white flours (data not shown) between earlier and latest editions. USA food tables show a rise in Mg concentration of wheat bran and decline in wheat germ between 1962 (Watt et al. 1963) and 1989 (USDA 2011), on both DW and FW bases, but the historic figures from 1963 are unreliable. Early English food tables do not list wheat bran or wheat germ, and English tables show no change in wheat bran from 1975 forward (Paul and Southgate 1978; Food Standards Agency 2002). Later English tables show a higher Mg concentration DW and FW for patent flour than the earliest edition (Medical Research Council 1946; Paul and Southgate 1978; Food Standards Agency 2002), but this rise may easily be due to changes in milling procedures.

Declining Mg concentration of vegetables

In addition to cereal grains, fruits, vegetables, nuts and legumes have been rich and usual sources of Mg in human food. Welch and Graham (1999) suggested that level rather than increased production of such non-grain plant foods has been a limitation to providing adequate essential nutrients to the growing human

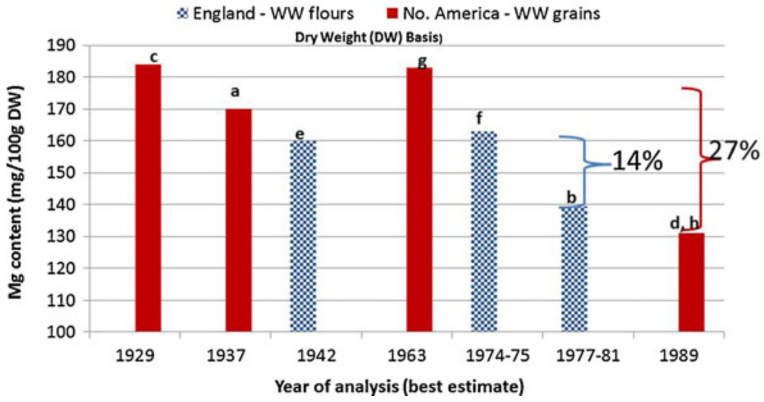

Fig. 3 Historical comparison of changing Mg concentrations, dry weight basis, of whole wheat (WW) grains and whole wheat (WW) flours over time in USA, Canadian and English food tables and published sources. (Data from *a* Beeson 1941; *b* Food Standards Agency 2002; *c* Greaves and Hirst 1929; *d* Health-Canada 2012; *e* McCance et al. 1945 and Medical Research Council 1946; *f* Paul and Southgate 1978; *g* Watt et al. 1963; *h* USDA 2011)

population. Could this possible decrease in per capita vegetable Mg supply be exacerbated due to lessening Mg concentration of fruits and vegetables?

Using food tables, three studies have attempted to determine if fruit and vegetables have changed in Mg concentration over the past 50+ years. These are summarized in Table 3. Both White and Broadley (2005) and Mayer (1997) used English food tables with values generally assumed to be from the 1930s (Medical Research Council 1946) and the 1980s (Food Standards Agency 2002). White and Broadley (2005) calculated "new"/"old" ***mean*** DW mineral values for 26 vegetables and 38 fruits from these two English food tables, and both calculations were reanalyzed using "new"/"old" ***median*** DW mineral values by Davis (2009). White and Broadley (2005) also calculated and compared "new"/"old" mean DW mineral values for 15 USA vegetables using values published in Beeson (1941) and the USDA National Nutrient Database for Standard Reference, Release 16 which was first published in May, 2004. Years for the source references given in Beeson 1941 are used for these 15 USA vegetables in Table 3; source years for USDA food tables were not available with Release 16 and

Table 3 Comparisons of Mg concentrations for produce sampled from the market in different periods; used for re-calculating change in Mg available to USA food supply, 1900–2006 (see Fig. 4a)

Crop	Date[a] of "old" Mg concentration value	Date[a] of "new" Mg concentration value	% change in Mg concentration	Dry weight (DW) or fresh weight (FW) basis	Reference
Vegetables					
26 English vegetables	1930s	1980s	−19 %	DW	White and Broadley 2005
26 English vegetables, barely n.s.	1930s	1980s	−18 %	DW	Davis 2009[b] analysis of White and Broadley data
20 English vegetables	1930s	1980s	−35 %	FW[c]	Mayer 1997
20 English vegetables	1930s	1980s	−23 %	DW	Davis 2009[b] analysis of Mayer data
15 USA vegetables (reanalyzed by Davis w/1 fruit)	1913–1937	2004[a]	0 %	DW	White and Broadley 2005
15 USA vegetables + 1 USA fruit	1913–1937	2004[a]	−15 % (n.s.)	DW	Davis 2009[b,c] analysis of White and Broadley data
15 USA vegetables	1913–1937	1984–2002[d]	−15 %	DW	Rosanoff expansion & analysis of White and Broadley data
Fruits					
38 English fruits	1930s	1980s	0 %	DW	White and Broadley 2005
38 English fruits	1930s	1980s	0 %	DW	Davis 2009[b,c] analysis of White and Broadley data
20 English fruits	1930s	1980s	−11 %	FW[c]	Mayer 1997
20 English fruits	1930s	1980s	0 %	DW	Davis 2009[b] analysis of Mayer and

[a] Both White and Broadley (2005) and Mayer (1997) used English food tables with values generally from 1930s (Medical Research Council 1946) and 1980s (Food Standards Agency 2002). For USA produce, White and Broadley (2005) used values published in Beeson (1941), a gathering of several published and unpublished sources with source referenced dates shown here. For "new" USA values, White and Broadley (2005) used the USDA National Nutrient Database for Standard Reference, Release 16 of May, 2004, actual dates not available. See note d. below

[b] Davis 2009 reanalyzed studies that compared new:old means by comparing new:old medians

[c] Mayer (1997) did not calculate DW Mg concentrations; "new" to "old" vegetable moisture contents did not change significantly, but water content of "new" to "old" fruits increased significantly. Both were reanalyzed on a DW basis by Davis (2009)

[d] Rosanoff (unpublished) extended the White and Broadley (2005) data for 15 USA vegetables, using Mg concentrations DW values from Beeson (1941) and calculating DW Mg concentrations from the USDA National Nutrient Database, Standard Release 24, 2011 (USDA 2011) from which actual dates of analyses are available here

first became available with Release 24 (USDA 2011). Davis 2009 reanalyzed these 15 USA vegetables along with 1 USA fruit (lemon) calculating the DW median ratio using White & Broadley's data. Mayer (1997) used fresh weight values (FW) for 20 English vegetables and 20 English fruits from the same tables used by White and Broadley (2005). Both Mayer calculations were reanalyzed by Davis (2009) who used median "new to old" ratios rather than mean ratios and reanalyzed the Mayer data on a DW basis. Results are summarized in Table 3.

English vegetables, 1930s to 1980s

White and Broadley (2005) found a statistically significant decline in the DW Mg concentrations of 26 English vegetables and 8 dry fruits. Further analysis of the vegetable data by Davis (2009) quantified a DW Mg change of −18 % in the 26 English vegetables, 1930s to 1980s. Using the same sources on a FW basis, Mayer reported a 35 % drop in Mg concentration for 20 English vegetables, and the Davis analysis of her study (using the median rather than the mean "new-to-old" quotient of Mg concentration and a DW basis) reported this as a 23 % decline in Mg.

USA vegetables, 1940s to 2004

White & Broadley's comparative analysis for 15 USA vegetables' Mg concentrations published in 1941 (Source dates range from 1913 to 1937) and in 2004 (no source dates available) show no overall change in DW Mg concentration. Davis (2009) reanalyzed this data (including one fruit—lemon) in his analysis using medians rather than means, and found a non-significant 15 % decrease in DW Mg concentration in the "new" produce vs. the "old". We expanded the White and Broadley (2005) study of 15 USA vegetables using Release 24 of the USDA food composition table (USDA 2011), which allowed us to include years of source data reported in Table 3. As noted above, foodstuffs are not always reanalyzed for each edition of USA and English food tables, and our analysis of 15 USA vegetables showed only 5 differed in Mg values in Release 24 (USDA 2011) compared with Release 16 values reported in White and Broadley (2005). We found decreases in DW Mg values for 12 vegetables and increases for three vegetables from the 1913–1937 to the 1984–2002 analyses and a mean DW drop of 15 % overall. Changes in DW Mg concentration by as much as −83 % (celery) to +59 % (rutabaga) in 47 to 64 years, respectively, show the difficulties in assessing genuine changes of nutrient composition in foods over time.

Has Mg in the food supply changed over time?

To quantify any change in food Mg supplied from the farms of the world over the last century is a difficult task. FAO Stat sheets quantify countries' food supplies (FAO 2012b) available for human consumption, but calculate only energy, protein and fats available per capita in a given time frame. The USA is the only country for which I have found both historical Mg supply and health data. This report from the United States Department of Agriculture (USDA), Nutrient content of the U.S. Food Supply, 1909–2000 (Gerrior et al. 2004) with its 2000–2006 supplement (Hiza and Bente 2011) has calculated several essential vitamins and minerals, including Mg, available from the food supply for consumption by the USA population between 1900 and 2006. It shows that grain and vegetable supply, two major sources of nutritional magnesium, changed in the United States (USA) between 1900 and 2006. Grain supply per capita dropped steadily from 136 kg (300 lb) per year in 1900 to about 63.5 kg (140 lb) per year in 1972, climbing again after 1980 to 91 kg (200 lb) per year in 2000–2006. Per capita vegetable supply dropped from about 181 kg (400 lb) per year in 1900 to about 118 kg (260 lb) per year in 2000. According to this report, these changes lowered the Mg in the USA food supply from about 385 mg/day per person in 1900 to around 330 mg per day per person between 1950 and 1979, rising to approximately 375 mg/day per person in 2000. However, this USDA report uses modern food values for calculating all Mg contents, not taking into account the changes in wheat and vegetable Mg concentrations over the past 50+ years (Tables 2 and 3). A recalculation is necessary.

Recalculation of the Food Mg available to this estimate of Mg in the US food supply was performed assuming that grain Mg concentration dropped 7 to 25 % (as per Table 2) and vegetables dropped in Mg concentration by 15–35 % (as per Table 3). The recalculation was performed only for decades previous to 1970. The results are shown in Fig. 4a, and show a decline of Mg supply to USA from more likely 400–450

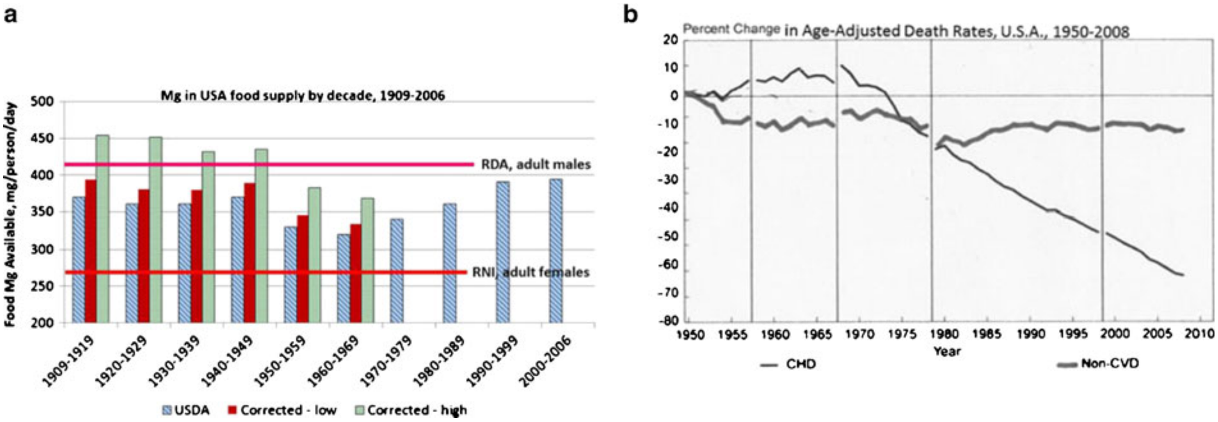

Fig. 4 Coronary Heart Disease (CHD) mortality peak in USA coincides with nadir of USA Mg in food supply. **a** Mg in USA food supply per capita per day by decade, 1909-2006, with recalculation using crop %Mg declines summarized in Tables 2 and 3. USDA data from Gerrior et al. 2004 and Hiza and Bente 2011: Data recalculated with data from Fan et al. 2008; Ficco et al. 2009; Murphy et al. 2008; White and Broadley 2005; Davis 2009; Rosanoff 2012 (unpublished). **b** Change in age adjusted death rates for cardiovascular (CHD) and non-cardiovascular diseases, USA, 1950-2008. Adapted, with permission (NIH 2012)

rather than 385 mg/day per capita in 1900, declining steadily due to less availability of both grains and vegetables until early 1980s when grain supply again rose (along with miscellaneous sources of Mg), albeit providing less Mg than early in the century due to post-1968 drops in Mg concentration. This estimate of farm output of Mg assumes a 7–25 %Mg concentration loss in all grains, even though historical Mg data on grains other than wheat have not been found, and it is not known what % of USA grain supply came from refined wheat. It also assumes no change in Mg concentration of fruits, nuts, and legumes including soy. Mg concentrations in various crops are often (but not always) lower in higher-yielding, modern genotypes than in lower-yielding older genotypes (Farnham et al. 2000; Broadley et al. 2008; White et al. 2009).

Have changing Mg concentrations of food crops affected human health?

How does this USA food Mg supply history compare with USA CVD mortality? Figure 4b shows that CVD mortality rate peaked in the USA in 1968 (NIH 2012), the same year that Mg in the USA food supply reached its nadir (Fig. 4a). As food Mg supply rose after 1968, CVD mortality rates began a long, gradual decline which continues today. Food Mg is not included in analyses of this decline in CVD mortality, and Ford (Ford et al. 2007) estimates that 6 % is due to unknown sources; medical treatments and medications can account for 77 % of the decrease, and success in pro-exercise and stop-smoking campaigns account for 17 % of the decline. Ford estimates that other countries' "unexplained" reductions in CVD mortality account for 5–25 % of their declines. We see much evidence that as societies transition from traditional diets to modern processed food diets, their rates of CVD mortality, obesity, metabolic syndrome and NCDs rise substantially (Popkin 1994, 2001; Gault et al. 1996; Rowley et al. 1997; Fraser et al. 1990, 2001; Zhai et al. 2007 with Liu 2007) while their Mg intakes decline (Abu-Saad et al. 2009). It might be assumed that these rising negative trends are due solely to loss of Mg and other essential nutrients due to modern food processing, but lower Mg concentrations of wheat, vegetables and perhaps other grains of the Green Revolution might also have impact.

Human Mg requirements and ranges of Mg intakes

Figure 4a shows the range of current accepted Mg human requirements, i.e. the daily Mg intake necessary for 97.5 % of healthy persons to maintain their Mg balance. The range spreads from a low of 270 mg/day for women in England (RNI 1991) up to 420 mg/day for men in USA (DRI 1997). Mg requirements outside this range have been reported and are summarized in Table 4. Hunt and Johnson (2006) recently reported a lower adult Mg requirement of 237 mg/day. This estimate was based upon a healthy human requirement of 2.36 mg/kg/day, much lower than other human balance studies, using pooled data from 27 controlled balance studies all conducted at the

Table 4 Range of measured human Mg requirements

Requirement to maintain Mg balance (mg/kg/day)	Intake range for healthy adult men (mg/day)	Intake range for healthy adult women (mg/day)	Source
2.36	237	237	Hunt and Johnson 2006
–	300	270	(England) RNI 1991
4.3	400–420	310–320	(USA) DRI 1997
7–10	530–760	427–610	Seelig 1964

metabolic unit at Grand Forks Human Nutrition Research Center in North Dakota, USA. The Hunt & Johnson subjects (*n*=243) spent typically 6 months in the metabolic ward and were very carefully selected to have no Mg deficit symptoms, including "extensive in-house psychological history." Depression and anxiety as well as other neurotic behaviors have been associated with Mg status (Eby and Eby 2006; Jung et al. 2010; Papadopol and Nechifor 2011). In contrast to Hunt and Johnson (2006), Seelig (1964) reported human Mg needs to be much higher, that intakes of Mg at 7 to 10 mg/kg body weight/day are necessary to maintain optimal health, and are not to fall below 6 mg/kg body weight/day (Table 4). Seelig's guidelines translate into RDAs of 427 to 610 mg/day for women and 530 to 760 mg/day for men. Such "high" Mg intakes have been shown to be "usual" in pre-modern food diet communities (see Table 5) in India (Basu and Malakar 1940) Ceylon (Cullumbine et al. 1950), and in Chinese upper classes (Chu et al. 1941) as well as in underprivileged communities of rural India as late as the 1990s (Kapil et al. 1998) and modern Bedouins still consuming their traditional diet (Abu-Saad et al. 2009). These high Mg intakes were in "undeveloped" societies consuming a traditional, non-Western diet based upon legumes, vegetables, seeds and whole grains as the main dietary constituents. In contrast, current Mg intakes in "Western" cultures and "modern" cultures in transition consuming elements of the processed food diet show lower Mg intakes

Table 5 Range of measured human Mg intakes

Population/year	Mean Mg intake, adult males (mg/day)	Mean Mg intake, adult females (mg/day)	Reference
Healthy, young Chinese upper class, 1941	473	392	Chu et al. 1941
Ceylon med students, 1950	425 Range: 351–641	–	Cullumbine et al. 1950
Rural India, underprivileged/1998	641	460	Kapil et al. 1998
Bedouin, traditional, 2009	490[a]	490[a]	Abu-Saad et al. 2009
Bedouin, transitional, 2009	262[a]	262[a]	Abu-Saad et al. 2009
USA adults, 2003	278–352	202–256	Ford and Mokdad 2003
Caucasian	352	256	
African-Am	278	202	
Mexican-Am	330	242	
Canadian adults, 2004	364	296	Health-Canada 2004
Turkish teens, 2008	258	198	Garipagaoglu et al. 2008
England, adults, 2008–9	302	229	Bates et al. 2010
10 European countries, EPIC/2009	354 Range of means: 347–467	292 Range of means: 258–402	Welch et al. 2009
Saudi pregnant women, 2012		232	El-kholy et al. 2012

[a] Mean of all adults, both male and female; transitional Bedouins have added white bread to diets

(Table 5). The recent EPIC study (Welch et al. 2009) reports comparable nutrient intake data currently for European nations and shows adult males' mean Mg intakes below 420 mg/day in about half of the areas studied, with all being above the adult male RNI of 300 mg/day. Women in the EPIC study showed mean Mg intake to be below the RNI for women (270 mg/day) in two of 27 areas with 12 of the areas' mean Mg intake below the RDA for their age group. For all groups in this EPIC study, mean Mg intake was above the Hunt & Johnson low-requirement estimate and well below the high requirement proposed by Seelig.

Summary

Human traditional diets are high in legumes, whole grains, seeds, vegetables and often fish rather than meats—diets that have been assessed for their Mg content in the 500–750 mgMg/day range (Kapil et al. 1998; Seelig 1964). As populations move from their traditional diets to modern processed foods, their diets start including refined grains, oils extruded from oil seeds and fewer fruits, vegetables, legumes and nuts. As this transition occurs, their levels of daily Mg intake approach the much lower intakes of the 'developed' world, i.e. 100–575 mg/day (Broadley and White 2010; Bates et al. 2010; Welch et al. 2009; Moshfegh et al. 2005, table A11, 2001–2). Obesity, diabetes, cardiovascular risk factors, metabolic syndrome and NCD death rates go up as their intakes of dietary Mg decline. If they return to their traditional diets, their health returns. Overall global trend is toward the low Mg modern processed food diet.

Mg concentrations of wheat have declined since 1968 with the advent of high-yield, short straw cultivars, and vegetable crops may be lower in Mg than they were 50 years ago. We are limited in our Mg intake data for several countries as well as in historical Mg levels for many food crops. This makes our task of assessing the degree to which these changes in food crop Mg are enabling the global rise in NCDs unfinished and speculative at this time. Current Mg range for modern wheats is wide, 80 to 1886 mg/100 g dry weight (Oury et al. 2006), showing the potential of selecting for high-Mg-concentration wheats which, however, must be balanced with yield. Mg concentrations in edible portions of many crops vary widely and can be increased not only by cultivating an appropriate genotype but also by applying Mg fertilizer (White and Broadley 2009). It is probably a true statement to say that increasing Mg concentrations of food crops to at least their pre-Green Revolution levels will not hurt and may make all the difference. Processing such crops into adequate Mg foods is certainly a large part of the challenge.

Others have noted the 'Green Revolution' health consequences of high yield cereal crops with lower Zn, Fe, I, Se and vitamin A concentrations (Welch 2002); this paper has attempted to assess possible health consequences of lower crop Mg concentrations that came with the Green Revolution to see if the new paradigm for world agriculture i.e. meeting human needs (Welch and Graham 1999), with regards to Mg, seems possible and warranted.

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