# Human Health Depends on Soil Nutrients

By John Duxbury, Graham Lyons and Tom Bruulsema

**The composition of soils influences the composition of crops, in turn influencing the quality of food, its contribution to human nutrition, and ultimately, human health. Agricultural management options for improvement include diversifying cropping systems and correcting deficiencies through fertilization.**

Courtesy Fernando Calle and Hernan Ceballos, CIAT

**Fertilizing cassava** with Se, Zn and I at the International Center for Tropical Agriculture (CIAT) in Colombia, South America.

Human nutrition remains in crisis. While the prevalence of hunger has declined by 21% since 1990, at least 805 million still go hungry. Among children under five, 161 million are estimated to be stunted (low height for age). Micronutrient deficiencies due to lack of dietary vitamins and minerals affect around 2 billion people, with multiple adverse health impacts and often impairing both physical and mental development of children. As atmospheric levels of carbon dioxide increase, Zn deficiencies are likely to increase (Myers et al., 2014).

Most plant nutrients are human nutrients too. Dietary Reference Intakes for human nutrition are provided for every nutrient element considered essential to plants (NAS, 2014). Boron is not fully recognized as essential, but some evidence indicates roles for it in bones, rickets and mental functions. Several roles for Ni are recognized, though its human dietary need is considered to be <100 µg/d (Welch and Graham, 2012).

**Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; B = boron; Cu = copper; Fe = iron; I = iodine; Mo = molybdenum; Mn = manganese; Ni = nickel; Se = selenium; Si = silicon; Zn = zinc; As = arsenic; ppm = parts per million.**

Fertilization with Zn, Ni, I, Mo, and Se increases their concentrations in cereal seeds and in vegetative tissues. On the other hand, fertilization with Fe, Cu, Mn, and Si has little effect on their concentrations in grain. In general, plant tissue has higher levels of micronutrients than grain on a dry weight basis, and thus can be relevant to animal nutrition, and to the nutritional value of food products derived from animals.

Iron, Zn and I are the most important mineral micronutrient deficiencies. For the major staple grains, the Zn content of wheat and maize can be increased two-fold by foliar, and less by soil, fertilization, but gains with rice are generally less

**Table 1.** Examples of effects of fertilization with Zn on grain Zn concentration in rice and wheat.

| | | | Wheat grain Zn, mg/kg | | |
|---|---|---|---|---|---|
| Source | Soil pH | No Zn | Soil | Foliar | S+F |
| 1 | 7.0-8.2 | 25 | 35 | - | - |
| 2 | 7.8 | 10 | 18 | 27 | 35 |
| 3 | 5.5 | 24 | 40 | 48 | - |
| | | | Brown rice grain Zn, mg/kg | | |
| Source | Soil pH | No Zn | Soil | Foliar | S+F |
| 4 | 8.2 | 20 | 29 | - | - |
| 5 | 4.8-8.8 | 19 | 21 | 24* | 26* |
| 6 | 7.0 | 20 | 22 | - | 25 |

*Potential contamination as second Zn application 1 week after flowering and unhusked rice had high Zn.
Sources: 1) Malakouti, 1998; 2) Yilmaz et al., 1997; 3 & 6) Bodruzzman and Duxbury, unpublished; 4) Shivay et al., 2014; 5) Phattarakul et al., 2012

than 50% (Tariq et al., 2014; **Table 1**).

The FAO, and many others, have been emphasizing that good nutrition requires sustainable, equitable and resilient food systems. Diversity in cropping systems is important. Pulses and legumes generally contain higher levels of micronutrients than cereals, but their availability relative to that of cereal grains has decreased since the Green Revolution. A notable exception is the growth of soybean cultivation in Bangladesh, expanding from near zero in 1980 to over 40,000 ha in 2010. Sustainable diets for the global human family require the design of agricultural systems to provide better human nutrition.

Vast areas of global soils have low pH, restricting the uptake of Ca and Mg, two macronutrients very important to human health. Simple additions of dolomitic limestone can increase the concentration of these two mineral elements, particularly in vegetables, and thus prevent diseases like rickets. Work supported by Cornell University in Bangladesh has demonstrated yield increases (10 to 50%) and quality improvements in more than 40 crops including: groundnuts, radishes, garlic, cabbage, cauliflower, eggplant, and turmeric, resulting in adoption of liming on over 86,000 ha by over 280,000 farmers. Addition of iodate to irrigation canals has been successfully used in China and Mongolia to address human I deficiency where iodized salt was not accepted (Ren et al., 2008). The fortified irrigation water spread the added I widely through the food system, increasing levels in soils, crops and animal products (meat, eggs and milk). This led to dramatic human health gains, including a 50% decrease in infant mortality. Animal productivity was also greater, emphasizing the benefits of improving the nutritional quality of animal feeds as well as plant foods.

Victor Moritz Goldschmidt (1888-1947), the father of modern geochemistry, introduced the term "biophile" for elements found at high absolute or relative concentrations in living organisms. They include N, S, P, K, Se, I, Zn, and B. This concept points to the importance of managing the soil-plant system for these nutrients for plants, animals and humans.

Selenium and S are strongly biophile elements. As selenate and sulfate they are very leachable. As a consequence of fires, especially on savannahs, they can also be lost to the atmosphere in the form of $SeO_2$ and $SO_2$ (Christophersen et al., 2012). When the soil is S-deficient, plant protein content declines, especially for the S-rich proteins. In the more humid parts of sub-Saharan Africa, there are large areas where the human diet is deficient in S amino acids. This deficiency arises from both low protein intake and soil S deficiency. Plant-available Se is very low in many soils in Zambia, Malawi, Rwanda, Burundi, and other sub-Saharan African countries, with common levels less than 20 µg/kg (Hurst et al., 2013). A survey of Zambian maize grain conducted in 2012 revealed a median S concentration of only 1,030 mg/kg and N:S ratios of 13-15 (Lyons et al., 2014), values equivalent to only 60% of critical deficiency levels (Reuter and Robinson, 1997). In programs addressing the primary NPK fertility needs of the soils of sub-Saharan Africa, S and Se need strong additional consideration.

In many studies, selenate has been found to be around five times more effective than selenite in increasing grain/seed Se concentration in cereal (barley, bread and durum wheat) and pulse (chickpeas, peas) crops. An inverse relationship between yield (due to climatic variation) and grain Se concentration, has been observed, indicating a dilution/concentration effect of yield (McGrath et al., 2013).

Decades of experience and research in Finland have documented strong benefits to human Se status from programs of enrichment of fertilizers with Se starting in the 1980s. In the 1970s the per capita dietary intake of Se was 30 µg, of which 70% came through meat and milk. Animal Se deficiency was widespread, but inorganic Se added to animal diets did not transfer much Se to meat or milk. The low levels of Se in food and feed crops were due to strong binding of Se anions to oxides in the typically acid soils. Starting in 1984, selenate was added to all NPK fertilizers for forage crops (Se added at 16 mg/kg) and cereal grains (6 mg/kg) as a strategy to achieve nutritionally adequate and safe levels in humans. The rates were changed to 6 mg/kg for all crops in 1990, and then increased to 10 mg/kg in 1996. The changes were associated with changes in Se levels in foods and with dietary intake (**Table 2**). Outcomes included a doubling of human serum Se levels,

**Table 2 .** Fertilization with Se affected Se levels in foods and dietary intake in Finland (data assembled from Eurola, 2005).

| Year | 1984 | 1991 | 1996 | 2002 |
|---|---|---|---|---|
| Forage fertilizer Se, mg/kg | 16 | 6 | 10 | 10 |
| Cereal fertilizer Se, mg/kg | 6 | 6 | 10 | 10 |
| Spring cereal* Se, mg/kg | 0.01 | 0.28 | 0.07 | 0.18 |
| Milk Se, mg/kg | 0.05 | 0.20 | 0.14 | 0.22 |
| Meat Se, mg/kg | 0.20 | 0.90 | 0.38 | 0.60 |
| Dietary intake, µg/d | 40 | 110 | 80 | 80 |

*Winter wheat and rye Se were much lower (0.02 to 0.07 mg/kg) as added selenate was reduced to selenite over winter, but increased to approximately 0.1 mg/kg when added during crop growth.

and, while other factors were also involved, the mortality rates from heart disease decreased by about two-thirds from 1982 to 1997 (Laatikainen et al., 2005). Effects on cancer rates varied from none to moderate.

Micronutrient availability can be influenced by macronutrient additions. When phosphate fertilizers are added to different soils, Se availability to plants may be increased or decreased, as a result of soil sorption and precipitation reactions. Even though marine phosphorites (sedimentary phosphate rock) contain much more Se than igneous phosphate ores (e.g., from the Kola Peninsula), their Se/P concentration ratio is often not as high as that of the topsoils of natural terrestrial ecosystems (McConnell, 1979). The application of commercial fertilizers may lead to a reduction of the total Se/P concentration ratio in the soil (depending on the Se/P ratio of the fertilizer), which would also lead to reduction of the Se/P ratio of food and forage plants. What this points to, as a general principle for management of soil fertility, is that when fertilizers are used to supply the most limiting nutrient, there may be long term implications for the uptake of other nutrients into plants. Continued application of P fertilizer, without regard to other nutrients, risks the development of soil deficiencies in nutrients like S, Se and Zn.

Use of As-contaminated groundwater for household and irrigation purposes in the Bengal basin has led to increased levels of As in both drinking water and in the irrigated crops produced. It is estimated that 140 million people worldwide are at risk for As-related diseases, the majority in Bangladesh. Recent research on animal models has shown a potential role for Se enrichment in countering As toxicity. Feeding lentils of varying Se content (Saskatchewan lentils with 0.3 ppm Se compared to northwestern USA lentils with <0.01 ppm Se) to rats, Sah et al. (2013) found that Se played a role in reducing the retention and increasing the excretion of As, resulting in lower levels of liver damage. The relevance of these findings for human nutrition needs to be confirmed by clinical trials. However, biofortification of Se in lentils through plant breeding and fertilization, and/or selection of foodgrains based on the Se level of the soils in which they were grown, could potentially play a role in addressing the huge human health concern posed by excess As.

*Dr. Duxbury is Professor of Soil Science and International Agriculture, Cornell University, Ithaca, NY, USA; e-mail: jmd17@cornell.edu. Dr. Lyons is Research Associate, School of Agriculture, Food and Wine, University of Adelaide, South Australia, Australia; e-mail: graham.lyons@adelaide.edu.au. Dr. Bruulsema is Director, IPNI North America, located in Guelph, ON, Canada; e-mail: tom.bruulsema@ipni.net.*

## References

Christophersen, O.A., G. Lyons, et al. 2012. *In*, B.J. Alloway (ed.). Heavy Metals in Soils: Trace Elements and Metalloids in Soils and their Bioavailability 3rd edition. Dordrecht: Springer.

Eurola, M. (ed.). 2005. Agrifood Research report 69, MTT Agrifood Research, Finland.

Hurst, R., E.W. Siyame, et al. 2013. Scientific Reports 3:1425. doi: 10.1038/srep01425

Laatikainen, T., J. Critchley, et al. 2005. Am. J. Epidemiology. 162:764-773

Lyons, G.H., C. Gondwe, et al. 2013. *In*, G.S. Banuelos, Z-Q. Lin, X. Yin (eds.). Selenium in the Environment and Human Health. Leiden: CRC Press.

Malakouti, M.J. 1998. Soil and Water J. (Iran) 12:34-43.

McConnell, D. 1979. *In*, P.A. Trudinger, D.J. Swaine (eds.). Biogeochemical cycling of mineral-forming elements. Elsevier.

McGrath, S.P., M.J. Poblaciones, S.M. Rodrigo. 2013. DOI: 10.1201/b15960-52

Myers, S.S., A. Zanobetti, et al. 2014. Nature doi:10.1038/nature13179

NAS. 2014. National Academies of Science. Daily Reference Intakes.

Phattarakul, N., B. Rerkasem, et al. 2012. Plant Soil 361:131–141.

Ren, Q., J. Fan, et al. 2008. J. Trace Elem. Med. Biol. 22:1-8 DOI: 10.1016/j.jtemb.2007.09.003

Reuter, D.J. and J.B. Robinson. 1997. Plant Analysis: An Interpretation Manual. 2nd edition. Melbourne: CSIRO Publishing.

Sah, S., A. Vandenberg, and J. Smits. 2014. Toxicology and Applied Pharmacology 272:256-262.

Shivay, Y.S., R. Prasad, and M. Pal. 2014. J. Plant Nutr. 37:1873–1884.

Tariq, A., S.A. Anjum, et al. 2014. Am. J. Plant Sci. 5:2646-2654.

Welch, R.M. and R.D. Graham. 2012. *In*, T. Bruulsema, P. Heffer, R.M. Welch, I. Cakmak, and K. Moran (eds.). Fertilizing Crops to Improve Human Health: A Scientific Review, IPNI, Norcross, USA; IFA, Paris, France.

Yilmaz, A., H. Ekiz, et al. 1997. J. Plant Nutr. 20:461-471 .