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Invited Review

Soil, food security and human health: a review

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Summary

Direct effects of soil or its constituents on human health are through its ingestion, inhalation or absorption. The soil contains many infectious organisms that may enter the human body through these pathways, but it also provides organisms on which our earliest antibiotics are based. Indirect effects of soil arise from the quantity and quality of food that humans consume. Trace elements can have both beneficial and toxic effects on humans, especially where the range for optimal intake is narrow. We focus on four trace elements (iodine, iron, selenium and zinc) whose deficiencies have substantial effects on human health. As the world's population increases issues of food security become more pressing, as does the need to sustain soil fertility and minimize its degradation. Lack of adequate food and food of poor nutritional quality lead to differing degrees of under-nutrition, which in turn causes ill health. Soil and land are finite resources and agricultural land is under severe competition from other uses. Relationships between soil and health are often difficult to extricate because of the many confounding factors present. Nevertheless, recent scientific understanding of soil processes and factors that affect human health are enabling greater insight into the effects of soil on our health. Multidisciplinary research that includes soil science, agronomy, agricultural sustainability, toxicology, epidemiology and the medical sciences will facilitate the discovery of new antibiotics, a greater understanding of how materials added to soil used for food production affect health and deciphering of the complex relationships between soil and human health.

> *'Upon this handful of soil our survival depends. Husband it and it will grow food, our fuel, and our shelter and surround us with beauty. Abuse it and the soil will collapse and die, taking humanity with it'*
> *Vedas Sanskrit Scripture, 1500 BC.*

Introduction

Soil affects human health directly through the ingestion, inhalation and absorption of soil or its constituents and indirectly through the quantity and quality of food that is derived from soil-based agriculture. Some of these effects can be detrimental to health if toxic substances or pathogenic organisms enter the food chain and are passed to humans (Brevik, 2009; Brevik & Burgess, 2013).

Links between the environment and human health were reported in Chinese medical texts of the third century BC. Hippocrates (approximately 460–377 BC) also recognized that environmental factors affected the distribution of disease (Foster, 2002). Medical geology has a strong history dating from the 1960s, but it has focused on relationships between elements and their effects on human health. Soil and human health has a broader remit because it embraces not only the effects of elements, but also the sustainability of agriculture and effects of soil degradation, food quality and security. The literature of medical geology is large (see Selinus *et al.*, 2013, as an example of its scope), whereas that for soil and human health is less. A recent book by Brevik & Burgess (2013) partly fills this gap in knowledge.

Oliver's (1997) review paper on soil and human health emphasized the multidisciplinary nature of the topic and indicated that we knew little about (i) the constituents and behaviour of the soil, (ii) the pathways by which soil constituents move into the body and (iii) the mechanisms by which soil constituents, once in the body, can harm health. A dominant theme in many studies has been the effects of micronutrients in the soil on health, possibly because their behaviour in soil has a prolonged history of study (Oliver, 1997; Abrahams, 2002; Steinnes, 2010; Taylor *et al.*, 2010).

The geographical incidence of some diseases is strongly associated with soil properties: for example anaemia in sedentary

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populations is linked to micronutrient deficiencies in soil, whereas other diseases with long latencies arise from either cumulative exposure or conditions in early life (for example cancers linked to radon; Oliver & Khayrat, 2002). Hough (2007) focused on the epidemiology of human health and soil from the perspective of single outcomes caused by multiple factors, but found little evidence that specific soil contaminants caused diseases in individual people. He concluded that more studies of individuals were required to determine dose-effect relationships for risk assessment and regulation.

The world's population reached 7.2 billion in 2013, and it is forecast to increase to around 9.6 billion (based on the medium-variant projection; within the range 8.3–10.9 billion) by 2050, after which the growth is expected to stabilize (United Nations, 2013). Soil and land are finite resources; they provide most of our food, fodder for animals and, in some parts of the world, fuel. The soil also filters water and supplies essential minerals. Agricultural land is under increasing competition from other uses. While the population has almost tripled over the last 50 years, the world's cultivated land area has increased by only 12% (FAO, 2011), so that, on average, the arable land available per person has decreased from about 0.45 to 0.25 ha over the same period (Bruinsma, 2011). The quantity and nutritional quality of food underpins human health, and in turn most food production depends on the soil.

Technological advances, such as in irrigation, might extend the area of cultivatable land (the irrigated area doubled in the last 50 years; FAO, 2011). However, the increase is forecast to be small, and future increases in agricultural production will come largely from increased productivity of existing agricultural land. It is expected that by 2050 food production will have to increase by 70% globally, and by up to 100% in developing countries, compared with 2009 (FAO, 2011).

In this review we build on Oliver's (1997) injunction that research should be directed towards preventing ill health rather than curing it. We examine some direct effects of soil pathogens on health *via* the pathways of skin, inhalation and ingestion, soil-based medicines, and indirect effects through interactions between soil, the nutritional value of foods and human health. The potential of the soil as a resource for new medicines has barely been exploited although it has been the source of many well-known antibiotics. We focus on four micronutrients that have large effects on human health and where soil scientists can play a substantial role. We conclude with some effects of soil degradation on food security and human health, and the potential role of soil scientists in interdisciplinary research with health professionals. The review illustrates the importance and complexity of relations between soil and human health, and the variety of ways in which soil affects our health (Figure 1).

Direct effects of soil on human health

Soil pathogens

The risk of infection by organisms in the soil has been known for centuries (Jeffery & van der Putten, 2011). For example, Hippocrates in the fourth century BC writes beware of '… the soil too, whether bare and dry or wooded and watered, hollow and hot or high and cold'. Soil microbes interact with one another and also adapt to extreme conditions of temperature, pH and moisture in soil, and, as a consequence, genotypic and phenotypic modifications can occur that alter their virulence (Cassadevall, 2006). Pathogenic organisms in soil enter humans by three pathways, ingestion (for example *Clostridium botulinum*), inhalation (*Aspergillus fumigatus*), and through the skin (hook worm) and skin lesions (*Clostridium tetani*). Figure 2 is a scanning electron micrograph of an asexual *Aspergillus* sp. fungal fruiting body; the conidia are released into the environment and when inhaled by humans can cause respiratory problems.

Pepper *et al.* (2009) describe soil pathogens as geo-indigenous (pathogens indigenous to soil that can metabolize, grow and reproduce), geo-transportable (transport of pathogens can be enhanced by soil) or geo-treatable (for example, viruses, bacteria, protozoa or helminths introduced into soil by humans and animals; see Pepper, 2013, and his Table 2 for a comprehensive list) and are usually inactivated rapidly in soil by biological and abiotic factors. Of the geo-indigenous pathogens, the spore-forming ones, which can survive in soil for a long time, have the most serious effects on human health. They include *Clostridium tetani* (tetanus), *Bacillus anthracis* (anthrax) and many others. Once in anaerobic human tissues *Clostridium tetani* spores revert to the vegetative form and multiply and produce a neurotoxin, tetanospasmin (Baumgardner, 2012).

Fungal pathogens that affect humans tend to be geophilic (proliferate under specific soil and climatic conditions), for example *Coccidioides immitis*, which forms spores and causes 'valley fever' (coccidioidomycosis) in south western USA (Pepper *et al.*, 2009). The yeast-like fungi *Cryptococcus neoformans* and *C. gattii* occur in the soil of tropical and subtropical regions (Sorrell, 2001). Inhalation of their spores leads to cryptoccocosis in humans, which can affect the nervous system as cryptoccocal meningitis or the lungs as pneumonia (Redshaw *et al.*, 2013). Over the past decade or so outbreaks of disease associated with *C. gattii* have occurred in temperate regions of Canada and the USA (MacDougall *et al.,* 2007); these might be a response to a warming climate.

Protozoa, single-celled eukaryotic organisms, are common in soil (Loynachan, 2013); they feed on bacteria and fungi and are important for nutrient recycling. Most protozoa are not harmful to humans, but *Cryptosporidium parvum*, *Entomoeba histolytica* and *Giardia lamblia* can cause diarrhoea; however, they are short-lived in soil (Loynachan, 2013). Several bacteria that cause diseases in humans seem to be carried by amoeba in soil (W. Gaze, personal communication, 2014), for example *Chlamydia* (urogenital tract diseases), *Legionella* (Legionnaire's disease) and *Mycobacterium* spp. (tuberculosis).

Geo-transportable pathogens are spread by water through the soil matrix or in the atmosphere as aerosols. Geo-indigenous soil pathogens that form spores or geo-treatable pathogens from land contaminated by faeces can be transported in this way (Kellogg & Griffin, 2006). Hantavirus, which is excreted by rodents, and *Coccidioides immitus* can be transported by wind (Brevik, 2009). Viruses introduced into soil from biosolids include norovirus

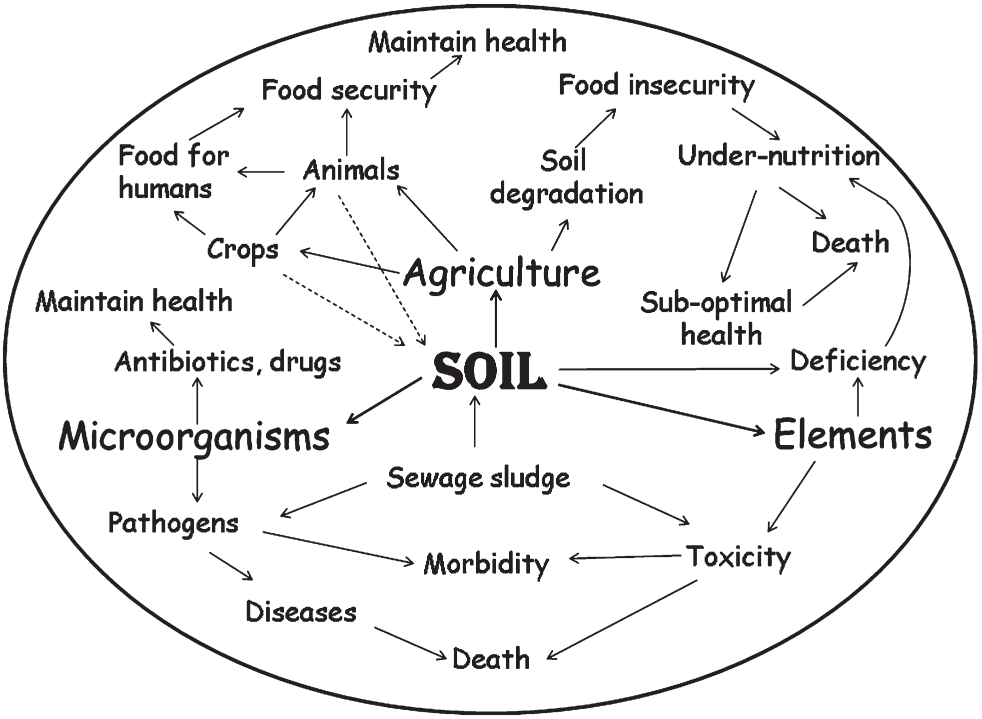

Figure 1 The relationships between soil constituents, agriculture, soil fertility and human health.

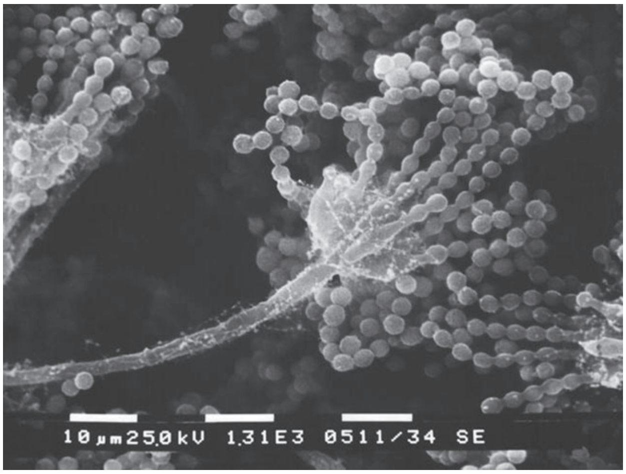

Figure 2 A scanning electron micrograph of an asexual *Aspergillus* sp. fungal fruiting body composed of a septate filament known as a conidiophore, which is topped by chains of conidiospores (credited to J. H. Carr and provided by R. Simmons, obtained from the Public Health Image Library of the Centres for Disease Control and Prevention, Atlanta, GA, USA).

(Norwalk virus) and hepatitis A, which are mobile in the soil solution and can contaminate ground-water (Abbaszadegan *et al.*, 2003).

Enteric bacteria (geo-treatable) such as *Campylobacter*, *Escherichia coli* and *Shigella* spp. are gram-negative, do not form spores, and cause 4–6 million deaths per year. They are the second most common cause of infant mortality (Jeffery & van der Putten, 2011). The usual source for ingestion of these bacteria is food or water contaminated by soil.

Helminths, in contrast to many geo-treatable pathogens, can survive in soil for several years. Pepper *et al.* (2009) estimate that 2 billion people worldwide are infected by helminths, and Bultman *et al.* (2013) that 130 000 deaths per annum are caused by nematode infections. Most helminths are nematodes; they include hookworm, round worms, whipworms and pinworms. They enter the body through ingestion or through the skin depending on their form. Hookworm larvae enter through skin lesions and pores and travel to the intestine, where they hook on to the intestine wall and cause bleeding, which leads to anaemia, and lay eggs that are defecated and pass into the soil for the cycle to begin again (see Abrahams, 2002, for a life-cycle diagram). Hookworm larvae thrive in warm moist soil with a particle-size distribution that includes clay and also organic matter (Mabaso *et al.*, 2004). Figure 3 shows a hookworm filariform larva. *Ascaris lumbricoides* (round worm), which causes ascariasis (an infection of the small intestine) is the largest and most widespread nematode. Infections result from poor sanitation and infected soil is ingested either directly or from dirty vegetables and fruit.

Prions

The term prion was coined by Prusiner (1982) for an infectious protein particle associated with transmissible spongiform encephalopathies (TSEs) that affect humans and animals. The infectious prion agent is a misfolded isoform (PrP^{Sc}) of the normal cellular prion protein (PrP^{C}); they have identical amino acid sequences

Figure 3 A hookworm filariform lava (provided by Dr M. Melvin and obtained from the Public Health Image Library of the Centres for Disease Control and Prevention, Atlanta, GA, USA).

(Prusiner, 1998; Johnson *et al.*, 2006) but exist as distinguishable strains that lead to different diseases (Soto, 2010).

The TSEs in animals include scrapie in sheep, bovine spongiform encephalopathy (BSE) in cattle, chronic wasting disease in deer and also variant Creutzfeldt–Jacob disease (vCJD) in humans. Johnson *et al.* (2006) consider that soil is a reservoir for TSE infectivity and that prion-contaminated soil might allow intra-species transmission of TSEs through soil ingestion. They showed that montmorillonite had a greater capacity for adsorption than kaolinite and quartz for $\mathrm{PrP^{Sc}}$, and that the prions remained infective when bound. Furthermore, Johnson *et al.* (2007) showed that prions bound to montmorillonite are orally bioavailable and have enhanced oral transmissivity. Prions appear to persist in soil for several years (Seidel *et al.*, 2007), have limited mobility (Smith *et al.*, 2011) and appear to be unaffected by other microorganisms and enzymes (Booth *et al.*, 2013). However, Saunders *et al.* (2012) suggested that prions in sandy soil might be transported more readily to the subsoil and into ground and surface waters. The environmental transmission of TSEs and epidemiological analysis of the risk factors to animal and human health (Saunders *et al.*, 2012) require further research into the behaviour of prions in soil.

Although prion diseases are rare, the key importance of misfolded protein aggregates can also be seen in common conditions, including Alzheimer's disease (beta amyloid) and Parkinson's disease (alpha synuclein in Lewy bodies), together with more than 20 other human disorders (Soto, 2001; Chiti & Dobson, 2006). At present no direct link between prions in soil and human disorders has been identified, but an indirect link is possible through transmission from animals to humans, as shown by the relationship between BSE and vCJD (Hill *et al.*, 1997).

Medicines from soil

Antibiotics

The most significant medical use of soil has been in the isolation of antibiotics from soil organisms. Selman Waksman and his team at Rutgers University in the 1940s were the first to isolate antibiotics (actinomycin, neomycin and streptomycin) from soil actinomycetes, which are gram-positive organisms that have many properties in common with both bacteria and fungi. Waksman (1952) found that some microbes compete with one another for survival by secreting defensive chemicals (antibiotics) to gain a competitive advantage in the soil ecosystem (Ratnaddass *et al.*, 2006). Waksman received a Nobel Prize for Physiology or Medicine in 1952, the only soil scientist to date to receive this award (American Chemical Society, 2005).

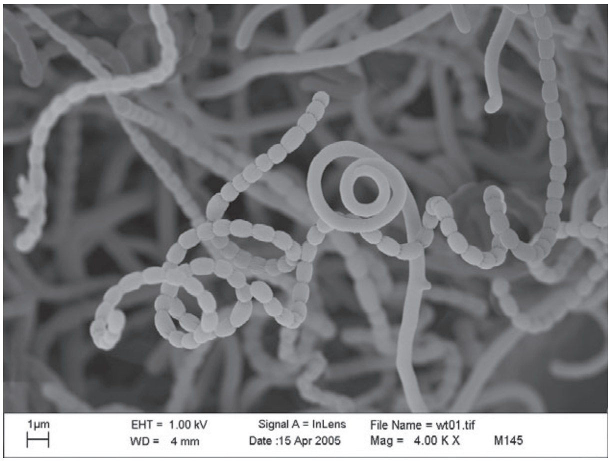

Figure 4 A photomicrograph of *Streptomyces* sp. recorded by Dr K. Findlay (John Innes Centre, Norwich, UK) with a Zeiss Supra 55 VP FEG-SEM and a Gatan Alto 2500 cryo-system.

Concepcion *et al.* (2001) indicated that 78% of antibiotic agents approved between 1983 and 1994 had their origins in natural products from microorganisms. Gans *et al.* (2005) suggested that more than 1 million distinct genomes occurred in pristine soil, which might be vital to human health in the future, especially as infectious agents become increasingly resistant to existing medicines. Nevertheless, despite the potential diversity of soil antibiotics, more than 50% of current antibiotics come from the genus *Streptomyces* (Kieser *et al.*, 2000); Figure 4 shows a photomicrograph of *Streptomyces*.

Soil fungi, for example the cephalosporin group, are also major sources of antibiotics. The successful immunosuppressant cyclosporine is derived from the fungus *Tolypocladium inflatum* (Borel & Kis, 1991). Although penicillin (isolated by Sir Alexander Fleming in 1929) was not discovered from the soil itself, it forms from a soil-borne fungus.

Pepper *et al.* (2009) indicated that recent research has focused on rhizosphere bacteria and endophytic microbes as new sources of antibiotics or other compounds to aid human health. For example, endophytic *Streptomyces* sp. strain NRRL 30562, an endophyte associated with black coral pea (*Kennedia nigriscans*, Schwarze Korallenerbse), provides wide-spectrum antibiotics known as munumbicins, which are effective against drug-resistant *Mycobacterium tuberculosis* (Castillo *et al.*, 2002).

Concepcion *et al.* (2001) reported that more than 60% of all cancer drugs approved from 1983 to 1994 had been developed from natural products in soil. Anti-cancer agents such as Paclitaxel, discovered by the US National Cancer Institute in 1967, are produced by endophytic fungi associated with the Pacific yew (*Taxus brevifolia* Nutt.). Natural products from endophytes have been used to produce bioinsecticides (Findlay *et al.*, 1997), and they are also a source of immunosuppressive compounds (Lee *et al.*, 1995), for example the cyclosporines mentioned above.

Clays

The phyllosilicate clays have a long history of medicinal use because of their capacity for adsorption and absorption, and surface charge. Kaolin has long been used in diarrhoea medicines, but in the USA attapulgite, another non-swelling clay, is now used. Smectites adsorb aflatoxins, which are naturally occurring carcinogenic mycotoxins (toxic secondary metabolites) produced by several Aspergillus species (commonly known as moulds) (Richard, 2007). Otto & Haydel (2013) examined antibacterial properties of natural clay mixtures *in vitro* and tests on their samples showed that *Escherichia coli* and methicillin-resistant *Staphylococcus aureus* (MRSA) were killed in 24 hours. They considered that the antibacterial properties result from adsorbed ions on the clays, namely iron (Fe^{2+}), copper (Cu^{2+}) and zinc (Zn^{2+}).

Kaolin is also used in ointments as an emollient. Haydel *et al.* (2008) describe treatment by a French aid worker in Burundi who used clay minerals to treat Buruli ulcers (caused by *Mycobacterium ulcerans*) in children successfully without any need for surgical intervention. Haydel *et al.* (2008) used iron-rich smectite and illite clays, one enriched with magnesium and potassium and the other with calcium, which showed natural antibacterial properties.

Soil and food security

The most commonly used definition of food security is the state when ‘all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life’ (FAO, 1996). Food security is underpinned by systems that comprise producing, processing, packaging and distributing food, and retailing and consumption, in a sustainable way (Ericksen, 2008). Recent assessments show that achieving food security for all people is complex (UK Foresight, 2011; Beddington *et al.*, 2012). The soil is at the core of food production, markedly affecting its availability and quality. Soil must be protected and preserved from degradation for plants and animals to thrive (FAO, 2011). It also directly influences accessibility and social preferences for certain foods. For example, in Asia, different types of rice grown on different soil types and with specific growing systems have become politically, socially and commercially important as sources of cultural capital (Greenland, 1997).

Soil, food production and food quality

Soil fertility determines the quantity and quality of food that can be grown on a given area of land, and its productivity determines our health indirectly (Gregory, 2012). Agriculture plays a central role in both food availability and food quality, and is also the main source of income and livelihood for 70–80% of people who currently suffer from hunger in developing countries. In the immediate future, these people will depend on agriculture remaining an ‘engine of growth, vital to economic development, environmental services and central to rural poverty reduction’ (FAO, 2011). Food security, environmental balances and land degradation are strongly linked and must be addressed together for any improvement in food security (Eswaran *et al.*, 2001).

It has been appreciated for centuries that the inherent properties of different types of soil have marked effects on crop productivity (see, for examples, the writings of Cato and Pliny the Elder; Rackham, 1950) and that some soil types are inherently more fertile and productive than others. Inherent soil fertility embraces nutrient availability, stable porous structure, large available water content and microbial and faunal communities that facilitate root and shoot growth. Fertility can be, indeed usually is, improved by management practices that maintain structure and through additions of manures and fertilizers (Stockdale *et al.*, 2013).

During the last 50 years the population has tripled and production of the major cereal grains (maize, wheat, rice and barley) has also tripled. Production of potato and cassava has increased by about 40%, and as diets have changed to consume more meat the number of chickens has increased by 4.5 times and that of pigs by 2 times (Godfray *et al.*, 2010). Much of this increased production can be accounted for by the Green Revolution (Tinker, 2000), when average yields of the major cereal grains increased from 1.35 to 3.35 $\mathrm{t\,ha^{-1}}$ between 1961 and 2007 (Gregory, 2012). However, yields of several grains ceased to increase from the mid-1990s. The technological innovations of the second half of the last century, together with institutional and market reforms, increased the soil’s productivity and intensified production, but they have had some adverse effects on the environment. For example, excessive applications of nitrogen and phosphorus have polluted fresh and coastal waters, and vegetation clearance has resulted in enhanced rates of soil erosion (Vitousek *et al.*, 2009; Powlson *et al.*, 2011). Soil degradation through the effect of water, tillage and wind is now estimated to result in global soil erosion of 5 (±10) $\mathrm{Pg\ year^{-1}}$ or about 5 $\mathrm{t\ year^{-1}}$ for every person (Quinton *et al.*, 2010). Soil erosion leads to the loss of about 10 million $\mathrm{ha\ year^{-1}}$ (Pimentel, 2006) and salinization to the severe damage of a further 10 million $\mathrm{ha\ year^{-1}}$ (Pimentel & Wilson, 2004), both of which diminish food security. Degradation also adds to the poverty of farmers in developing nations because they lack the resources to remedy the losses, which leads to greater food insecurity and under-nutrition.

The use of crop rotations, crop residues, animal and green manures and other organic wastes can improve soil fertility and mitigate soil degradation. However, organic farming alone is rarely a solution to issues of food security because of its generally smaller yields compared with the inclusion of inorganic fertilizers into cropping systems. Farming systems that use integrated management with rotation and organic and mineral fertilizers (Marsh, 2000) can maintain both human and soil health.

The nutritional value of many foods is also markedly affected by the soil. This can have important consequences for human health where food is produced and consumed locally. The effects are less evident in more complex food chains with food from different sources and in which processed foods are often supplemented with essential minerals and vitamins to make good any deficiencies. Crops require 14 mineral elements (listed in Table 1) and deficiency in any one restricts plant growth and reduces crop yields (Marschner, 2012). In addition to these elements essential for plants, humans require small amounts of several other trace elements also given in Table 1. Humans get most of these elements from plants (White & Brown, 2010; Table 1).

Mineral deficiencies occur worldwide (see below), but some elements occur in potentially toxic concentrations that diminish crop yields (Hodson & Donner, 2013). Potentially toxic elements may be taken up by plants and animals and accumulate in the food chain with detrimental consequences for human health. On acid soil, which occupies about 40% of the world's agricultural land, toxic concentrations of manganese (Mn) and aluminium (Al) limit crop production, whereas on sodic and saline soils (5–15% of agricultural land) too much sodium, boron and chloride frequently reduce crop production. Toxic concentrations of Mn and Fe can occur in waterlogged or flooded soil. Excessive concentrations of nickel (Ni), cobalt (Co), chromium (Cr) and selenium (Se) can limit plant growth on soil derived from certain geological formations, such as serpentine, and toxic concentrations of arsenic (As), cadmium (Cd), Cu, mercury (Hg), lead (Pb) and zinc (Zn) have accumulated in agricultural soil in some areas as a result of the mining and manufacturing industries (Hodson & Donner, 2013).

Under-nutrition

Some causes of under-nutrition can be attributed to the soil or agriculture, whereas others are social and political (Table 2). The FAO (2011) considers that almost a billion people are under-nourished, most in sub-Saharan Africa (239 million) and Asia (578 million). These areas often have soil that can support only poor yields because it is either inherently infertile or requires the addition of fertilizers. Poverty in these areas contributes directly to under-nutrition because people cannot afford to buy food even if it is available and indirectly because they cannot afford to maintain soil fertility.

The link between under-nutrition and the soil arises from insufficient food, food of poor quality and food lacking in essential elements (Table 2). Insufficient food leads directly to 'protein–energy' malnutrition caused by a lack of carbohydrates, proteins and fats in the diet; there is also a deficit in all major macronutrients (United Nations World Food Programme, 2014). Under-nutrition leads to stunted growth, wasting of muscle and fat reserves, and an increased risk of diabetes and cardiovascular disease in adulthood (Jamison *et al.*, 2006). It impairs the immune system so that the body is more susceptible to diseases, in particular malaria and tuberculosis (UNSCN, 2009). It also enhances the effects of toxic elements, for example lead, on humans. Black *et al.* (2008) stated that maternal and child under-nutrition is the underlying cause of 3.5 million deaths and about 35% of the disease burden in children <5 years. Under-nutrition also leads to poor health and disability in both the long and short terms (Black *et al.*, 2008).

The trace elements required by humans cannot be synthesized; therefore, there is a direct link between soil, food and under-nutrition (McMillian, 2002). The diets of more than two-thirds of the world's population lack or are deficient in one or more of these essential mineral elements (White & Broadley, 2009), with more than 60% deficient in Fe, >30% in Zn, almost 30% in iodine (I) and about 15% in S. Dietary deficiencies of calcium (Ca), Cu and magnesium (Mg) are also prevalent in many countries.

Mineral or nutrient malnutrition results from crops produced on soil with poor phytoavailability of the elements essential to human nutrition (Table 2). For example, alkaline and calcareous soils (25–30% of all agricultural land) have small availabilities of Fe, Zn and Cu (Broadley *et al.*, 2007; White & Greenwood, 2013), coarse-textured, calcareous or strongly acidic soils contain little Mg, mid-continental regions have little I and soil derived mostly from igneous rocks contains little Se (Gregory, 2012). Consequently, crops also have inherently small concentrations of certain elements (Karley & White, 2009; White & Broadley, 2009). Although plant breeding has increased the calories and protein in human diets, the nutritional health of many people, particularly in developing countries, has deteriorated (Welch & Graham, 2004). Graham *et al.* (2012) consider that this has resulted from the emphasis on cereal crops, which have small concentrations of micronutrients, at the expense of pulses and other dicotyledons that have larger concentrations.

The bioavailability of minerals to humans can also be affected by dietary fibre consumed in the same meal as food containing minerals, mineral–mineral interactions and vitamin–mineral interactions (McMillian, 2002).

Nutrient deficiencies can have far-reaching consequences for human health, but they are often disregarded because they can be difficult to identify, except for iodine. They can result in anaemia, diseases of the immune system, mental retardation and cardiovascular diseases, to name but a few, and have more impact during pregnancy, lactation and periods of rapid growth, such as early childhood (Bellamy, 1998). Nutrient deficiencies are most likely to be evident in developing countries because of poor soil, poverty and local sources of food (Oliver, 1997). Nevertheless, they might be an underlying factor in many diseases in developed countries, in particular Se (Rayman, 2000) and Zn (Hotz & Brown, 2004).

Selected trace elements

Table 2 summarizes the soil and related factors that affect human health and what their effects are.

Iron

Soil affects the amount of iron in food, but its absorption by humans is complex and depends on many factors (Table 2). Animal products

Table 1 Essential mineral nutrients (in addition to carbon, hydrogen and oxygen) in plants and mammals, together with their recommended daily allowance (RDA) or adequate intake (AI – where no RDA has been established) in humans and function in mammals

	Essentiality			
Element	Plants	Mammals	RDA or AI / mg	Function in mammals
Primary element				
Calcium (Ca)	Yes	Yes	1300	Essential constituent of bones and required for synthesis and function of blood cells, and function of muscle, heart and digestive system
Nitrogen (N)	Yes	Yes	105	Essential constituent of DNA, RNA and proteins
Phosphorus (P)	Yes	Yes	700	Essential constituent of bones, cells and energy processes plus other functions
Potassium (K)	Yes	Yes	4700	A systemic electrolyte and essential in regulating ATP with sodium
Secondary element				
Magnesium (Mg)	Yes	Yes	420	Required for bones and processing ATP
Sulphur (S)	Yes	Yes	–	Constituent of amino acids – diets with sufficient protein contain adequate sulphur so there is no RDA
Chlorine (Cl)	Yes	Yes	2300	Pump functions of cells and hydrochloric acid in stomach
Trace element				
Boron (B)	Yes	Yes	–	Has role in some animals in vitamin D activation, but uncertain whether this is a nutritional effect. Helps to build and maintain bones and is involved in Ca and Mg metabolism
Iron (Fe)	Yes	Yes	18	Required for many proteins and enzymes, particularly haemoglobin in blood
Manganese (Mn)	Yes	Yes	2.3	A cofactor in enzyme reactions
Copper (Cu)	Yes	Yes	0.9	Required component of many redox enzymes
Zinc (Zn)	Yes	Yes	11	Required component of many enzymes
Nickel (Ni)	Yes	Yes	–	Suggested role in some animals in enzyme function and iron adsorption and metabolism in humans
Molybdenum (Mo)	Yes	Yes	0.045	Component of several oxidase enzymes
Sodium (Na)	Beneficial	Yes	1500	A systemic electrolyte and essential in regulating ATP with potassium
Selenium (Se)	Beneficial	Yes	0.055	An essential cofactor of antioxidant enzymes
Cobalt (Co)	Beneficial	Yes	–	Required in the synthesis of vitamin B_{12}(cobalamine), which is synthesised by bacteria
Minimum trace element				
Aluminium (Al)	Beneficial	–	–	No known function in healthy humans, but known toxic effects
Silicon (Si)	Beneficial	Possibly	–	Possible beneficial role in human bone health and wound healing
Human trace element only				
Iodine (I)	–	Yes	0.15	Essential for the synthesis of thyroid hormones, possibly as an antioxidant and for the functioning of mammary and salivary glands
Fluorine (F)	–	–	–	Not an essential nutritional element, but helps in the prevention of dental cavities
Human minimum trace element				
Lithium (Li)	–	Possibly	–	Physiological function unknown, but feeding studies have suggested benefits in some animals
Vanadium (Va)	–	Possibly	–	Not essential, but is a cofactor that enhances or inhibits some enzymes
Chromium (Cr)	–	Possibly	–	Not essential although some studies suggest a role in sugar metabolism
Toxic trace element				
Arsenic (As)	–	Possibly	–	May play a role in DNA methylation and cancer prevention, but also toxic effects
Cadmium (Cd)	–	–	–	No known function in healthy humans, but known toxic effects
Lead (Pb)	–	–	–	No known function in healthy humans, but known toxic effects

provide 10–20% more available Fe than plants, and ferrous iron (Fe^{2+}) is more available than ferric iron (Fe^{3+}) in the body (Otten *et al.*, 2006). The amount of Fe absorbed from plants depends on other foods eaten during the same meal; vitamins A, B_{12} and C, folic acid, protein and Cu can enhance its absorption (World Health Organization, WHO, 2001), whereas Ca, phytates, whole grains and dairy products can decrease its absorption.

Availability of Fe to plants is limited by its solubility in soil, which decreases from the amorphous iron oxides to ferrihydrate to goethite to haematite and is linked to soil type. Iron deficiency reduces crop yields because Fe is a catalyst in many oxidation and reduction reactions, is involved in chlorophyll production, and is an activator for several enzymes involved in electron transport (Irmak, *et al.*, 2012).

In anaerobic conditions, toxic concentrations can result at redox potentials <0.5 V, with the reduction of Fe^{3+} to Fe^{2+}. In lowland rice systems, Fe^{2+} concentrations in the soil solution can range from 10 to >2000 mg l^{-1}, resulting in yield losses of 15–30%, but the

Table 2 A summary of the soil and other associated factors that affect human health

	Human health	Soil factors	Other factors	Food sources of elements
Food insecurity Under-nutrition	Protein-energy malnutrition, stunted growth, disability, immunocompromised, death.	Poor soil, poor nutrient status and maintenance, organic matter and biodiversity depletion, salinization, sodification, acidification, drought, desertification, compaction, wind and water erosion.	Transport and distribution, poverty, politics, economics, loss of agricultural land to other uses.	–
Food quality - elements				
Hidden hunger				
Iron	Present in haemoglobin, myoglobin. Iron deficiency anaemia (IDA) – cognitive development in children, pregnancy, reduced immunity and thyroid function.	Poor bioavailability – Fe^{2+} more available than Fe^{3+}. Deficiency occurs in aerobic, sandy, calcareous and alkaline soil types. Toxicity occurs in anaerobic and acid ($pH < 5.5$) soil. Availability depends on redox potential, pH and microbiology (siderophores and phytosiderophores).	Deficiency in food affects humans. Deficiency and toxicity reduce crop yields. Fertilizers can maintain Fe status, but expensive. Zinc enhances Fe absorption by humans.	Red meats, liver, egg yolk, dried fruits, beans, lentils.
Iodine	Hypothyroidism - goitre, irreversible brain damage, cretinism, mental retardation and perinatal mortality.	Dry and wet deposition from atmosphere, volatilization from soil and re-deposition. SOM, microbial activity, texture, Eh and pH affect I fixation. Bioavailability depends on redox potential and pH – IO_3^- (iodate) more available than I^- (iodide).	Deficiency in humans – deficiency in food and presence of goitrogens. Selenium involved with I in synthesis of thyroxine.	Cod, shellfish, eggs, seaweed, milk, cranberries.
Selenium	Deficiency – reduces antioxidant and redox functions. Linked to coronary diseases, miscarriage, malignancies. Toxicity –selenosis.	Deficiency is more widespread than toxicity. Microbial processes, pH and redox potential affect Se status. Selenate generally more available than selenite, but Li *et al.* (2008) challenge this.	Fertilizers effective in supplementing Se (see example from Finland).	Brazil nuts, cashew nuts, shellfish, tuna, swordfish, seeds, whole grains, meats.
Zinc	Metabolic promoter. Gene expression. Deficiency affects physical growth, immune system, reproductive health, dermatological conditions and neurobehavioural problems.	Deficient in leached tropical, sandy, calcareous, alkaline and flooded soil types. Toxic in soil with $pH < 4$ and deficiency common in soil with $pH > 7$ and large concentrations of phosphate. Redox status affects form.	Cu inhibits Zn uptake in plants.	Meats, shellfish, whole grain cereals, sesame and pumpkin seeds, pulses, cashew nuts.

Table 2 Continued.

	Human health	Soil factors	Other factors	Food sources of elements
Environmental factors				
Elemental contamination	As (vascular disorders), Cd (kidney and liver disease), F (fluorosis), Pb (neurological damage and haematological effects), Zn (reproductive effects).	Toxicity by metals may relate to geology, mining, industrial activity, fertilizers, pesticides, windborne dusts, sewage sludges, irrigation. May accumulate in plants and be ingested or may be ingested directly from soil by mouth or inhalation.	Soil degradation can lead to increased wind and water transport over long distances of soil pollutants.	–
Organic chemical contamination	Carcinogenic, neurological and immune problems.	PCBs, PAHs, carbamates, furans accumulate in soil from industry, pesticides and applied biosolids. Some persist in soil (POPs) and enter food chain.	Sources food, windborne dust and soil. Children are most susceptible.	–
Pharmaceutical contamination	Emasculation resulting from oestrogen in environment. Antibiotic resistance from environmental effects. Unknown human effects from additive effects of mixtures of compounds.	Sewage water and sludges applied to land contain a range of pharmaceutical agents.	Antibiotics and other drugs given to animals enter the environment from sewage sludges with largely unknown effects.	–
Soil pathogens	Bacteria (anthrax, tetanus), fungi (valley fever), protozoa (diarrhoea), helminths (anaemia, ascariasis), prions (transmissible spongiform encephalopathies).	Occur naturally in soil, some related to anthropogenic activity. Transported long distances by wind. Ingestion by mouth, skin lesions and inhalation.	Desertification and salinization: poor crop cover resulting in greater soil transport of dust containing pathogens.	–

crop may also fail completely when concentrations become toxic (Becker & Asch, 2005).

In aerobic soil, the activity and availability of Fe^{3+} is enhanced by many soil bacteria and fungi (Neilands, 1995); these organisms produce siderophores, which enhance the bioavailability of Fe to plants. Graminaceous plants can synthesize siderophores in their roots (phytosiderophores, non-protein amino acids that can bind Fe); they operate similarly to those derived from microorganisms.

Effects of iron on human health. Iron deficiency in soil, plants and animals results in too little Fe in the human diet. Zinc is a critical element in the control of intestinal Fe absorption and zinc-enriched diets enhance its absorption (Chang *et al.*, 2010; Graham *et al.*, 2012). Zinc deficiency appears to be related to a significant proportion of iron-deficiency anaemia (IDA).

Iron is indispensable to human health. It is a component of haemoglobin and myoglobin, which bind molecular oxygen, and is an essential component of many enzymes that catalyse metabolic processes. Iron-deficiency anaemia (IDA) is one of the most severe effects of nutritional deficiencies in the world (WHO, 2001), affecting some 25% of the world's population and about 47% of pre-school children (WHO, 2008). The incidence of IDA is large in developing countries, but it also occurs in industrialized countries; every age group is vulnerable (WHO, 2002). It impairs the cognitive development of children from infancy to adolescence and immunity, leading to increased susceptibility to infectious diseases and mortality. The greatest effects of IDA are in pregnancy and during periods of rapid growth, such as infancy, and infants with less than half the normal iron reserves are prone to perinatal mortality (WHO, 2001). Iron-deficiency anaemia also impairs thyroid function by decreasing thyroid production, which can reduce metabolism and energy.

Iodine

Iodine was the first element to be recognized as essential to human health when the French chemist Chatin (1851) identified its relationship with goitre. He observed that goitre was more frequent in the Alps than near the sea; a difference explained by the iodine content of soil and water. However, goitre was known to the Chinese possibly as early as 2700 BC, and around the fourth century AD they realized that seaweeds provided a cure (Ellis, 2001).

The main source of I in soil is from the oceans *via* atmospheric deposition in either rain or dry deposition (Table 2). There is no simple correlation between I in soil and distance from the sea, although the largest concentrations are typically 0–50 km from the sea (Johnson, 2003b). Iodine deficiency occurs worldwide; it is most pronounced in high mountain areas, inland areas of continents and some alluvial plains. The soil's potential to fix iodine affects its I concentration (Johnson, 1980), which depends principally on soil organic matter content, but also on other soil properties given in Table 2 (Johnson, 2003a). The bioavailable fraction (Table 2) important for health (Johnson, 2003a) is iodide, which is the most mobile and volatile form of I and is favoured by acidic and anaerobic conditions. Iron and sulphate-reducing bacteria can reduce iodate to iodide (Councell *et al.*, 1997), showing the effect of Eh. In general <25% of soil iodine is in a soluble form and therefore immediately available (Fuge, 2013). The less mobile iodate occurs in dry, oxidizing, alkaline conditions, such as in calcareous soil (see figure 7 in Johnson, 2003a). Iodate in calcareous soil does not re-volatilize (Fuge & Ander, 1998), suggesting that it is fixed and not bioavailable. Figure 5 summarizes the main features of the iodine cycle.

Soil organic matter plays a major role in retaining I and humus might be the main reservoir of I (Shetaya *et al.*, 2012). Yamaguchi *et al.* (2010) showed that iodide transformed more rapidly to organic forms than iodate. Shetaya *et al.* (2012) considered that inorganic adsorption of iodide and iodate play a minor and transient role, and Yu *et al.* (1996) also showed that inorganic solutes of iodine did not adsorb on silicate clays because of their negative charge.

The volatilization of methyl iodide (CH_3I) from the biological methylation of iodine in soil by a variety of bacteria plays an important role in the geochemical cycling of I (Muramatsu & Yoshida, 1995; Amachi *et al.*, 2001) and its transfer to the biosphere (Fuge, 1990). Amachi *et al.* (2001) suggested that methylation occurs especially at oxic–anoxic interfaces, such as in flooded rice fields, peat bogs and swamps, but not in strictly anoxic sediments or the subsoil. Volatilization depends on the soil's Eh and pH; iodine gas forms from iodide in acid soil conditions, but this is unlikely in alkaline conditions. Iodine can be lost from soil by volatilization, but dry deposition of I on to plant leaves contributes to the total I content of the edible parts of plants.

Effects of iodine on human health. Insufficient I in crops, animal products and drinking water is the primary cause of iodine deficiency diseases, but other factors such as goitrogens also affect iodine availability. Goitrogens are derived from cyanogenic glycosides in some vegetables such as brassicas, lima beans, bamboo shoots, sweet potatoes, cassava, maize and millets (WHO, 1996).

The effects of iodine deficiency on human health are among the most serious of the trace element deficiencies, especially for pregnant women and young children. Although I deficiency has decreased (WHO, 2007), it remains a serious problem in South-East Asia and Europe. It can occur in unexpected places, such as coastal areas, large cities and developed countries (WHO, 2007).

Iodine is required in only minute amounts, but it is essential in the thyroid gland for the synthesis of thyroxine, which is essential for growth and development. Selenium-dependent enzymes (iodothyronine deiodinases) are also required to convert I to the biologically

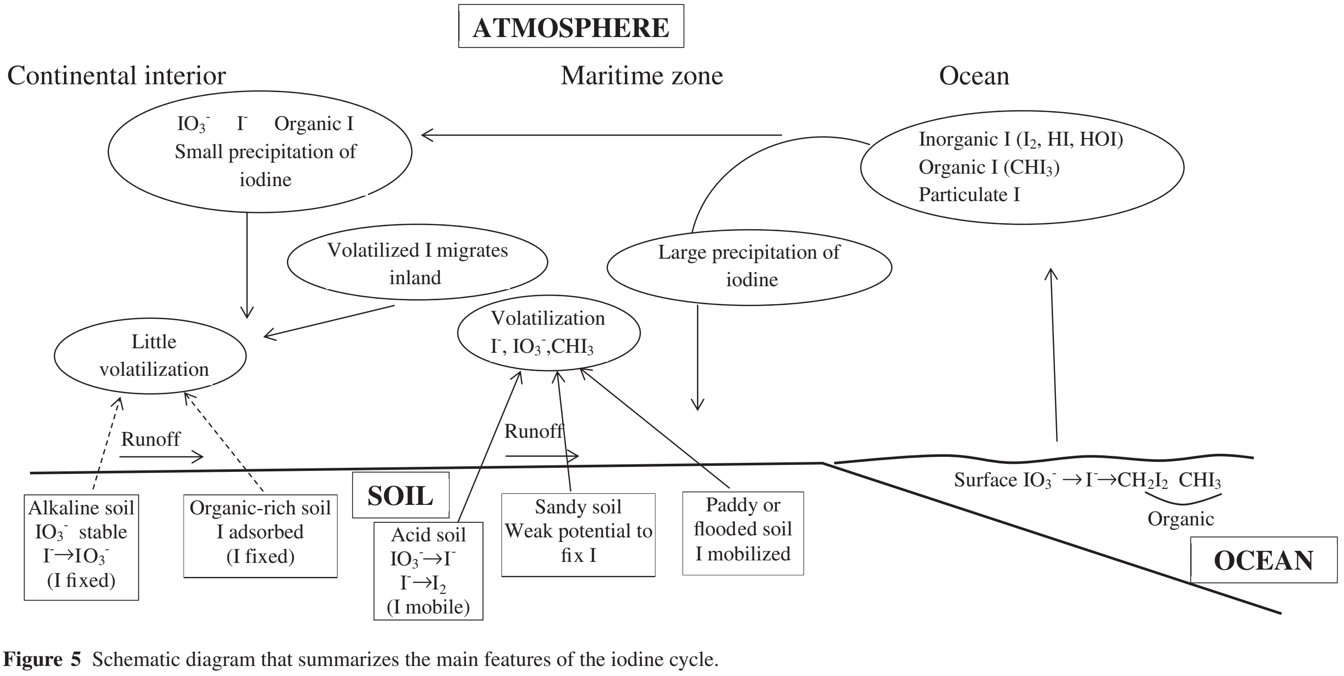

Figure 5 Schematic diagram that summarizes the main features of the iodine cycle.

active thyroid hormone, triiodothyronine (Levander & Whanger, 1996). Deficiencies of vitamin A or iron might also exacerbate the effects of iodine deficiency (Zimmermann *et al.*, 2008).

Iodine deficiency results in hypothyroidism and functional and developmental disorders (see Table 1 of WHO, 2004). Goitre is the most obvious effect, but the more insidious effects are mental retardation, cretinism and perinatal mortality. Cretinism may affect 5–15% of the population in areas of endemic I deficiency (WHO, 2004). Qian *et al.* (2005) confirmed Bleichrodt & Born's (1994) work on the effect of I deficiency on IQ from 37 studies of 12 291 children in China: those with iodine deficiency had up to 12.5 IQ points fewer than those with sufficient I.

Selenium

Selenium deficiency as a causal factor in animal diseases was identified in the late 1950s (Shwartz & Foltz, 1957). It is associated with a wide range of problems, such as reproductive impairment, subdued growth and white muscle disease, a myopathy of the heart and skeletal muscle that mainly affects lambs and calves (Rayman, 2000). The Se available to animals and humans comes from food that depends on Se in the soil.

Selenium occurs in soil as selenide (H_2Se), selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), elemental Se and organic forms such as selenomethionine and selenocysteine. The cycling between these oxidation states depends on microbiological processes (Fellowes *et al.*, 2013), both dissimilatory (respiratory) and non-dissimilatory (Winkel *et al.*, 2012). Selenium-reducing organisms can produce elemental Se nanoparticles (Lenz *et al.*, 2011). The transfer of organic groups such as ethyl and methyl to selenium atoms (biotic alkylation) forms volatile compounds that can increase the atmospheric transport and deposition of Se. Inorganic Se exists in soil in three phases (Fairweather-Tait *et al.*, 2011), fixed, adsorbed and soluble; the latter two phases are available for plant uptake. Figure 6 summarizes the main features of the selenium cycle.

Selenite is more strongly adsorbed by soil, and is less soluble and more stable than selenate. Acid conditions favour the stability of selenite (Se^{4+}), and it is adsorbed by clays and strongly fixed by iron hydroxides by ligand exchange (Coombs, 2001a) to form a ferric iron–selenite complex that is only slightly available to plants (Gupta & Gupta, 2010). Adsorption of Se by Fe oxides generally exceeds that by clay minerals (Fordyce, 2013). Alkaline conditions favour the stability of selenate (Se^{6+}) ions, which are not fixed in soil. Chilimba *et al.* (2011) showed that grain concentrations of Se were 10 times greater on calcareous Eutric Vertisols in Malawi with the greater availability of selenate than on other soil types.

Redox potential in combination with pH also affects Se speciation; at low redox potential selenate is reduced to selenite, when it is moderate selenite dominates and when ≥400 mV selenate dominates. Although selenate is generally regarded as being the more available form of Se to plants under most soil conditions (Fairweather-Tait *et al.*, 2011), Li *et al.* (2008) challenged this by suggesting that selenite is the most available form for plant uptake in aerobic soil. Zhang *et al.* (2003), amongst others, have shown that selenite is taken up by plants at a similar or faster rate than is selenate. Borowska & Koper (2011) showed that soil enzymes and

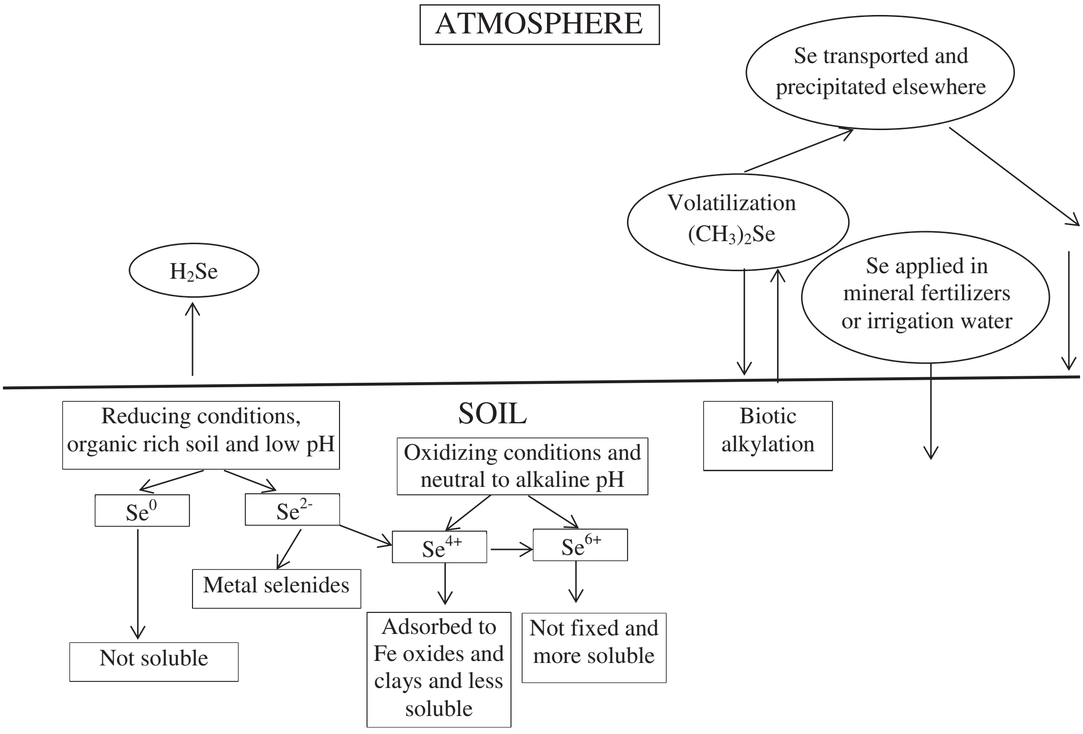

Figure 6 Schematic diagram that summarizes the main features of the selenium cycle.

organic matter affected Se status in soil and plants. In organic-rich soil with low pH and redox potential, elemental Se, selenides and SeS_2 are present that are not bioavailable to plants (Fordyce, 2013). Johnsson (1991) showed that an increase in organic matter content fixed Se as organometallic complexes and decreased its concentration in wheat grains from 1350 to 160 μg kg^{-1}. However, decomposing organic matter can be a source of Se for plant uptake (Zawislanski & Zavarin, 1996).

Phosphate and sulphate ions also affect Se availability because they compete for fixation sites in the soil and plant (Fordyce, 2013). Sulphate inhibits Se uptake by plants, and the effect is greater for selenate than selenite. Selenate is taken up by sulphate transporters (Terry *et al.*, 2000), whereas selenite is taken up by other transporters and so is little affected by sulphate. Phosphate may increase Se availability to plants because it displaces selenite in soil. Phosphorus deprivation can increase selenite uptake in wheat, but its presence inhibits it (Li *et al.*, 2008).

Selenium is not an essential nutrient for higher plants (Terry *et al.*, 2000) although Zhou (1990) indicated that Se deprivation reduced the growth of rice, and Peng *et al.* (2000) that it reduced wheat growth. More recently, Lyons *et al.* (2009) have shown the benefit of Se in *Brassica rapa* L. treated with sodium selenite, resulting in an increase in seed production of 43%.

Effects of selenium on human health. Selenium is an essential trace element for humans with a narrow range between dietary deficiency (<40 μg Se day^{-1}) and toxicity (>400 μg Se day^{-1}) (Winkel *et al.*, 2012). Severe human deficiency in Se is rare; the main examples are in China, where Keshan and Kashin–Beck diseases are evident (see Oliver, 1997; Coombs, 2001b). Many people, however, have too little Se in their diet; Haug *et al.* (2007) suggested that 0.5–1 billion people are directly affected by Se deficiency. Selenium in many animal products is only poorly available to humans, whereas selenomethionine and selenocysteine in plant materials are bioavailable and incorporated into selenoproteins (Coombs, 2001b).

There are some 35 selenoproteins (Rayman, 2000) that are critical in thyroid function, redox homeostasis and antioxidant defence (Hurst *et al.*, 2013). As a redox centre, Se reduces hydrogen peroxide and damaging lipid and phospholipid hydroperoxides to water and alcohols, which are harmless (Rayman, 2000; Joseph & Loscalzo, 2013). Selenium deficiency is implicated in a wide range of medical conditions (Table 1). It reduces the antioxidant and redox functions of selenoproteins, making people more prone to viral infections (Fairweather-Tait *et al.*, 2011), inflammation and environmental pollutants (Coombs, 2001a). Selenium also seems to be a crucial micronutrient for people infected with HIV (Baum *et al.*, 1997).

Selenium has been added to fertilizers since 1984 in Finland, and Fairweather-Tait *et al.* (2011) indicated that average intake in the population rose from 25 μg day^{-1} in 1975–1976 to 124 μg day^{-1} in 1989. Over the same period the intake from cereals increased from 9 to 30 μg day^{-1}, and that from fruit and vegetables increased from 0.4 to 4 μg day^{-1}. Age-adjusted mortality from ischaemic coronary heart disease declined by 55% in men and 68% in women between 1972 and 1992 in Finland (Vartiainen *et al.*, 1994), but this research did not investigate the effects of fertilizers supplemented with Se. Coombs (2001a) further suggested that adequate Se can be expected to reduce the rates of cancer worldwide.

Selenium toxicity in humans, which can cause selenosis, is much less common than deficiency. Concentrations of Se in the diet at which toxicity occurs are difficult to establish because it depends on the form available and probably the effects of other components in the diet (Fairweather-Tait *et al.*, 2011). Toxic concentrations, >3 mg Se kg^{-1}, can occur locally on seleniferous parent materials and can also result from irrigation with Se-rich water, as in the Punjab and San Joaquin Valley in California (Wu, 2004).

Zinc

Zinc has the most ubiquitous deficiency of any micronutrient, especially in certain types of soil (Table 2). The solubility of Zn is generally small (Shuman, 2005) and is pH dependent (Table 2). Zinc can be fixed by clays, and its adsorption by soil colloids increases as pH increases, resulting in smaller availability (Alloway, 2009).

Factors affecting Zn availability to plants are total Zn content, pH, contents of organic matter, clay and calcium carbonate, redox conditions, microbial activity in the rhizosphere, soil moisture status, concentrations of other trace elements and macronutrients, especially P, and climate (Alloway, 2008). Plant-available Zn occurs as Zn^{2+} and $ZnOH^+$, organically complexed Zn in solution and easily desorbed Zn on the surfaces of colloids (Kiekens, 1995). At $pH < 7.7$ Zn^{2+} predominates, at $pH > 7.7 < 9.11$ $ZnOH^+$ is the main species and at $pH > 9.11$ $Zn(OH)_2$ dominates (Alloway, 2008). Copper inhibits Zn uptake because they share common transporters for absorption, and it also affects the redistribution of Zn in plants (Alloway, 2008). Large phosphate concentrations in soil also cause Zn deficiency (Zhu *et al.,* 2001). Alloway (2008) suggested that crops respond to Zn and N together, but not to Zn alone. Cakmak *et al.*, (2010) indicated that Zn and N act synergistically in increasing Zn concentration in grain.

Although Zn is not susceptible to oxidation or reduction, the soil's redox status can affect its form in soil. In waterlogged soil Zn can precipitate as the sulphide, ZnS (Alloway, 2008), or there may be an increase in Zn-organic complexes that make it unavailable (Shuman, 2005), for example in paddy fields. Organic matter affects Zn availability: solid forms have negative adsorption sites that bind Zn and decrease its availability, whereas soluble organic matter forms complexes with Zn in the soil solution that enhance its availability (Shuman, 2005).

Effects of zinc on human health. Zinc is essential for animal and human health although the effects of its deficiency in humans were not recognized until the 1960s (Prasad *et al.*, 1961). It binds with 925 different proteins in humans (Graham, 2008). The International Zinc Consultative Group considers that Zn deficiency affects about a third of the world's population (Hotz & Brown, 2004) and might be linked to about 800 000 deaths per annum and about 20% of perinatal mortality worldwide (Nriagu, 2007). The recommended daily intake for humans is 3–6 mg Zn day^{-1}; the precise amounts depend on age, sex, type of diet and so on.

Zinc is the most important metabolic promoter among the nutrients known to be essential to humans (Graham *et al.*, 2012). It can function as an antioxidant and stabilize membranes and modulate oxidative stress (Castro & Freeman, 2001). Zinc is also important in human gene expression, in cell growth and differentiation, and in processes of genetic stability. It is also involved in DNA and RNA synthesis.

Graham (2008) considered Zn deficiency to be the ultimate hidden hunger. Zinc deficiency in humans is closely associated with its deficiency in their food. The bioavailability of Zn from grains is substantially reduced by phytate (inositol hexaphosphate), especially when the phytate:zinc molar ratio exceeds 15 (Alloway, 2008). Zinc deficiency can be overcome by its addition to fertilizers, which increases Zn bioavailability in the diet (Cakmak, 2008).

Zinc deficiency in children causes stunted growth, and learning, psychomotor and neurobehavioural problems (Nriagu, 2007). It also affects the formation and maturation of spermatozoa and foetal development. Zinc deficiency affects the immune system (Shankar & Prasad, 1998). Severe Zn deficiency gives rise to acrodermatitis enteropathica (a genetic disorder), pustular dermatitis, alopecia, diarrhoea, emotional disorders, weight loss, infections, immune dysfunctionsm, hypogonadism in males, neurosensory disorders and problems with the healing of ulcers (Prasad, 2008). Moderate Zn deficiency is associated with growth retardation, rough skin, poor appetite and mental lethargy, for example.

Maintenance of soil fertility and human health

Soil degradation–including the depletion of nutrients and organic matter, declines in cation exchange capacity, structure and water-holding capacity, increases in leaching, acidification, compaction, erosion, salinization, sodification and desertification–resulting from man-induced processes is widespread on land used for agriculture. Of the total agricultural land, 40% (2 billion ha) is degraded (Global Environmental Facility, 2009). These adverse and cumulative changes reduce the soil's capacity to support crop growth and animals and thereby impair food security. Reduction in the quantity and quality of food directly affects human health (Lal, 2009), whereas pollution of surface waters by fertilizers and pesticides is an indirect effect (Pimentel *et al.,* 2007). Pimentel (2006) considered that about 80% of the world's agricultural land is moderately to severely eroded, mainly by water but also by wind, resulting in reduced rooting depth, aggregate stability, nutrient availability and microbial activity, which lead to a loss of plant-available water and crop yields. Some are irreversible, such as reduced rooting depth from accelerated soil erosion (Eswaran *et al.*, 2001).

Salinization in arid and semi-arid regions from irrigation and restricted and internal drainage (Keren, 2005) reduces biodiversity, efficiency in nutrient cycling and productivity, which increases food insecurity and plant, animal and human diseases (Jardine *et al.*, 2007). Salinity, desiccation and drought reduce crop cover and increase wind-borne dust, which leads to bronchitis (Schenker, 2000) and asthma (Park *et al.*, 2005). Such dust often contains fungi and pathogens that affect humans, such as anthrax, *Mycobacterium tuberculosis*, influenza viruses and hantavirus (Griffin *et al.*, 2001; Taylor 2002). Elements such as Hg, Se and Pb from Asia and Africa have been linked to larger concentrations of these metals in soil elsewhere due to wind transport (Garrison *et al.,* 2003). Increased salinization in SW Australia appears to be associated with an increase in the extent of the mosquito, *Aedes camptorhynchus* (Horwitz *et al.*, 2001), the major vector for Ross River Virus (RRV).

Excess metal concentrations in soil from industrial manufacturing, mining, pesticides and fertilizers, traffic and so on can cause toxicity that affects crop growth and human health directly (Table 2) (Oliver, 1997; Morgan, 2013). Phosphate fertilizers manufactured from rock phosphate can add Cd to the soil (Alloway, 1995), and some pesticides contain As, Pb and Cu (Morgan, 2013). Arsenic and Cu can also contaminate soil through their use in animal feeds to control growth and disease (Bradford *et al.*, 2008). Irrigation in Bangladesh by arsenic-enriched water has led to large concentrations in rice and vegetables, resulting in several adverse health effects such as hyperkeratosis (blackfoot), malignancies and cardiovascular disease (Tseng, 1999, 2002). Organic chemicals (Table 2), such as polychlorinated biphenols (PCBs), polybrominated biphenols, polychlorinated dibenzofurans, polycyclic aromatic hydrocarbons (OAHRs), organophosphate and carbamate insecticides, herbicides, organic fuels, especially petrochemicals and those from municipal biosolids, also contaminate soil (Burgess, 2013). Persistent organic pollutants (POPs) may be deposited far from their sources and resist environmental, chemical, physical and biological degradation (Teran *et al.*, 2012) leading to bioaccumulation through the food web (http://ec.europa.eu/environment/pops/index_en.htm (accessed July 2014)). Young children are most susceptible to POPs from airborne dust, soil and food (Wilson *et al.*, 2003). Even background concentrations (WHO, 2010) can increase rates of cancer, neurological and reproductive problems, and endocrine and immune diseases (Bhatia *et al.*, 2005; Aneck-Hahn *et al.,* 2007).

Pharmaceutical products in soil such as antibiotics, hormones and antiparasitic drugs result from the application of biosolids (Albihn, 2002). Redshaw *et al.* (2008) suggested that 3000 pharmaceutical ingredients in use in the European Union can potentially enter sewage systems and then soil from sewage sludge applied to agricultural land (Table 2). They showed that drugs such as fluoxetine HCl (Prozac®), diazepam (Valium®) and their major human metabolites persisted in soil amended with sewage sludge. Potentially harmful effects on humans and agricultural ecosystems of veterinary pharmaceuticals in soil from sewage sludge and manures need to be assessed (Song *et al.*, 2010). Gaze *et al.* (2011) showed that sewage sludge and animal slurries contained large numbers of class 1 integrons (genetic elements that carry antibiotic and quaternary ammonium compound resistance genes, resistant to detergents and biocides). Bacteria carrying class 1 integrons in sewage sludge added to soil can increase the reservoir of antibiotic-resistant bacteria in humans. Exogenous bacteria are now mixing with antibiotic-producing bacteria that occur naturally in soil (Wellington *et al.*, 2013), which can result in horizontal gene transfer that produces antibiotic-resistant genes. Plants can take up antibiotics from soil treated with animal manure (Kumar *et al.*, 2005), and humans may be exposed to antibiotics, antibiotic-resistant genes or antibiotic-resistant bacteria through crops, water and animal products (Wellington *et al.*, 2013).

Humans are exposed to mixtures of compounds in both the environment and food that are at safe concentrations individually (Feron *et al.*, 2002), but may contain mixtures that can have additive, even synergistic, effects that could be harmful. Legislation to determine 'safe' concentrations of chemicals in the environment must take the effects of mixtures of chemicals into account to allow for potentially adverse effects on human health.

Where do we go from here?

Links between the environment and human health were reported in Chinese medical texts of the third century BC. Hippocrates (about 460 to 377 BC) also recognized that environmental factors affected the distribution of disease (Foster, 2002). However, many of the points made by Oliver (1997) about understanding the relations between soil and human health remain and are still at an elementary stage because of the difficulties of quantification and of ascertaining which of the profusion of factors contribute to ill health. Identifying and understanding the factors, and their confounding effects, that affect human health are vital. Penetrating statistical analyses that take confounding effects into account are required to assess the risks to health from the effects of the soil.

Geostatistics provides methods for mapping both health and soil properties. Oliver *et al.* (1998) showed how geostatistics could be applied to estimate the risk of childhood cancer by binomial cokriging. Goovaerts & Gebreab (2008) stated that this approach still remained little known, whereas the Besag, York and Mollie (BYM) model (Besag *et al.*, 1991), a Bayesian approach, is widely used despite its drawbacks. Goovaerts & Gebreab (2008) showed that Poisson kriging, which can incorporate varying population sizes and varying sizes and shapes of administrative units, is more flexible for modelling the spatial risk and results in less smoothing.

Furthermore, there is a need for international and multidisciplinary research that includes soil science, agronomy, toxicology, epidemiology and the medical sciences to understand the risks to human health that are linked to soil. Many individual disciplines have information, but often it is not readily transferrable. The European Union recognized the importance of the environment and human health by establishing The European Centre for Environment and Health at the University of Exeter (UK) in 2011.

The fate of pharmaceuticals in the environment is largely unknown because of the lack of fundamental data on their chemical behaviour, transport and bioavailability (Kümmerer, 2010). Technological advances in the analysis of trace compounds in environmental matrices have shown that pharmaceuticals in biosolids used to amend soil are present in irrigation water. Studies have shown that some pharmaceuticals can be taken up by some plants (Manuel Cortes *et al.*, 2013), but we know little about the processes, the metabolites formed and the bioavailability to humans and animals (Kümmerer, 2010).

Food security to ensure adequate and nutritious food is vital. Many chronic diseases suffered by western societies are caused by under-nutrition related to essential elements, but this is masked by the many confounding factors that affect food; the effects in developing nations are also widespread (Graham *et al.*, 2012). Precision agriculture has the technology to enable better economic and environmental use of agricultural land at all spatial scales (Oliver *et al.*, 2013), and it can provide detailed information related to soil and crop conditions.

Graham *et al.* (2012) recommended that for all soil types the limiting nutrients should be supplied by fertilizers, animal and green manures and other organic wastes. Zinc is effective in fertilizers (Cakmak, 2009), as is Se as illustrated in Finland. Cao *et al.* (1994) showed that by additions of I to irrigation water in China, soil iodine content increased up to three-fold. Precision agriculture has the technology to apply fertilizers and to irrigate selectively once soil concentrations are known. Furthermore, Welch & Graham (2004) indicated that crops can be bio-fortified with micronutrients by plant breeding and or transgenic approaches, which use micronutrient enrichment traits within plant genomes that do not affect crop productivity; for example, ferritin-Fe-enriched rice grains. Synchrotron-based X-ray absorption fine-structure (XAFS) spectroscopy is a potential tool for such research because it can be used *in situ* in soil to identify element species and their availability (Winkel *et al.*, 2012). The nanoscale secondary ion mass spectrometer (nano-SIMS) is another potential tool because it enables high spatial resolution mapping of elements and their isotopes (Winkel *et al.*, 2012). Moore *et al.* (2010) used it in combination with synchrotron X-ray fluorescence (s-XRF) to map Se in cereal grains and showed that it was concentrated in the protein around starch granules in the endosperm cells.

The soil is a reservoir of potentially new antibiotics because bacteria are continuously developing new ones to resist new stresses. Until recently, however, the physiology and genetic make-up of only a few bacteria have been studied because most (>99% according to the Handelsman Laboratory, 2010) cannot be cultured in the laboratory. Now metagenomics can treat the collective genomes of the microbial population as a single entity, and enable the physiology and genetics of microbes that cannot be cultured to be determined. Functional metagenomics is a further development (Handelsman, 2004) that identifies clones that express a function, and this has enabled the rapid identification of novel antibiotics and antibiotic-resistant genes.

We still have only a rudimentary understanding of the forces between diverse microbial populations that coexist in soil (Vos *et al.*, 2013) and the degree to which microbial populations vary at the nano-, millimetre- or centimetre-scale (Lehmann *et al.*, 2008). Imaging techniques and functional metagenomics are increasingly available to soil scientists to explore spatial heterogeneity in soil at these scales. Future research at such scales should link

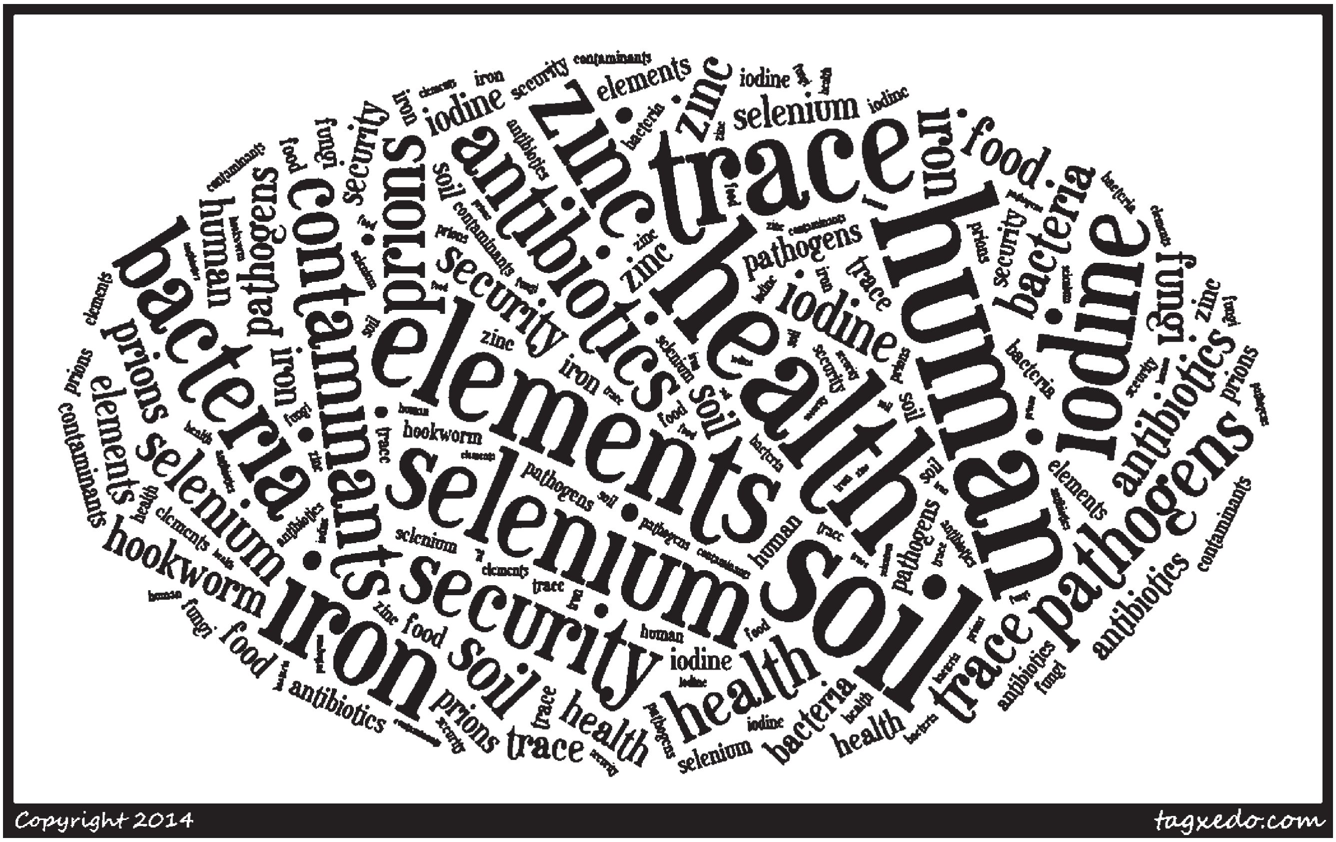

Figure 7 Word cloud to express the multiplicity of factors involved in soil and human health (Produced with software by tagxedo: http://www.tagxedo.com).

with microbiologists in their search for bacteria to provide new antibiotics.

The potential for soil scientists to contribute significantly to debates on the bioavailability of elements, limiting soil degradation and food security to improve human health should encourage us to broaden the already large scope of our subject. We leave you with Figure 7 which expresses the multiplicity of factors involved in understanding how soil affects human health.

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