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The effect of soil on human health: an overview

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Abstract

Soil has a considerable effect on human health, whether those effects are positive or negative, direct or indirect. Soil is an important source of nutrients in our food supply and medicines such as antibiotics. However, nutrient imbalances and the presence of human pathogens in the soil biological community can cause negative effects on health. There are also many locations where various elements or chemical compounds are found in soil at toxic levels, because of either natural conditions or anthropogenic activities. The soil of urban environments has received increased attention in the last few years, and they too pose a number of human health questions and challenges. Concepts such as soil security may provide a framework within which issues on soil and human health can be investigated using interdisciplinary and transdisciplinary approaches. It will take the contributions of experts in several different scientific, medical and social science fields to address fully soil and human health issues. Although much progress was made in understanding links between soil and human health over the last century, there is still much that we do not know about the complex interactions between them. Therefore, there is still a considerable need for research in this important area.

Keywords

elemental toxicity; xenobiotic organic chemicals; essential nutrients; human pathogens; urban soil; antibiotic resistance

Introduction

Soil has a profound effect on the health and well-being of humans. Depending upon the condition of the given soil and the interactions of interest, this effect can be either positive or negative and direct or indirect. Soils that affect human health include natural soil, which usually has little anthropogenic contamination, and soils in agroecosystems, urban areas, mines, oil and gas extraction areas, landfill sites and other locations where anthropogenic contamination is more likely. People in professions that work closely with soil, such as farmers, construction workers or miners are at a greater risk of health problems that involve

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direct contact with soil, but everyone's health is affected by soil to some extent. This is because soil provides many of the nutrients we require and can pass on harmful substances through the food that we eat. Some dusts generated from soil can travel thousands of miles and affect people long distances from where they originated. Although recent advances in the role soil plays in human health are being made and continue to be investigated, few people probably think about soil having an effect on their health. This paper will give a brief, general overview of the topic of soil and human health. Other excellent papers on this topic have been published recently and we encourage the reader to find additional details on many of these topics in other related publications (e.g. Pepper, 2013; Brevik & Burgess, 2015; Oliver & Gregory, 2015; Cakmak & Kutman and Li *et al*. in this issue).

History

Probably the first recorded depiction of the relation between human health and soil occurs in 1400 BC in the Bible in the book of Numbers where Moses directs the people to "see what the land is like….how is the soil…fertile or poor?" (Numbers 13:18–20). In 400 BCE Hippocrates published a list of things that should be considered part of a proper medical evaluation, a list that included the nature of the ground (Hippocrates, 2010) and in 60 BCE Columella wrote about hidden diseases from marshes (Sylvia *et al*., 1998); in each case advancing the idea that soil is important to human health. However, it was not until the early 1900s that the idea that soil could affect human health started to gain widespread acceptance. McCarrison (1921) concluded that the fertility of a soil determines the nutrient content of food crops, and therefore the health of humans who ate the crops. In the late 1930s, the USDA Yearbook of Agriculture (USDA, 1938) included discussion on the importance of soil as the origin for many of the essential elements necessary for human health in at least three of its chapters, and in 1940 the USDA established the Plant, Soil and Nutrition Research Unit (PSNRU) at Cornell University which still continues to do research into soil and human health (PSNRU, 2008). In the 1940s, individuals such as Sir Albert Howard (1940), Lady Eve Balfour (1943) and J. I. Rodale (1945) offered opinions on the links between soil and human health, in particular the effect of soil fertility on the nutrient content of foods grown in a particular soil was a common theme. The 1950s brought about the realization that soil could supply toxic amounts of elements to the human diet (USDA, 1957). André Voisin published extensively on the potential links between soil and human health in 1959, a study that was probably the most comprehensive on the subject up to that time. From these first realizations, studies into the relation between soil and human health have continued to increase and several of the areas of investigation will be described below in summary. Brevik & Sauer (2015) recently reviewed the history of the soil–human health field and we direct readers to this review for more detail.

Routes of exposure

There are three common ways that humans are exposed to soil materials: (i) ingestion, (ii) respiration and (iii) skin absorption or penetration (Brevik, 2013). Ingestion can occur deliberately, known as geophagy, or incidentally, such as during hand to mouth contact (particularly children) or when raw fruits or vegetables are consumed without adequate washing. Ingestion of soil is especially common in children (von Lindern *et al*., 2016) and pregnant women. Ingested soil can potentially supply essential nutrients, but it can also lead to exposure to heavy metals, organic chemicals or pathogens and in large amounts can cause an intestinal obstruction (Henry & Cring, 2013). Respiration involves inhaling soil materials. Some serious problems are linked to inhalation, such as coccidioidomycosis (Bultman *et al.*, 2005; Stockamp & Thompson, 2016), acute inflammation of the bronchial passages, chronic bronchitis, emphysema and fibrotic changes from breathing in soil-derived dust (Zosky *et al.*, 2014), and mesothelioma from breathing in naturally occurring asbestos minerals from soil-derived dust (Buck *et al.*, 2016). Absorption or penetration of the skin can expose an individual to pathogens and soil chemicals (Brevik, 2013). It can also cause podoconiosis (endemic non-filarial elephantiasis), which is a non-infectious disease found in subsistence farmers who frequently go barefoot. This is due to long-term contact with volcanically-derived clay in the soil which obstructs the lymph system (Deribe *et al.*, 2013). Prevention is as simple as wearing shoes, and the condition has ceased to occur in countries where it was once found such as in France, Ireland and Scotland once the use of shoes became commonplace (Deribe *et al.*, 2013).

Element toxicity

There are many ways that soil can adversely affect human health. The soil may be contaminated either naturally or through anthropogenic activities with chemical elements and substances that are in toxic amounts when ingested or inhaled. A supply of any element may result in human toxicity, even elements that are essential for life. For any essential element there is an optimal range of concentration in humans, falling below this optimal range results in deficiency, whereas, concentrations above the optimal range create toxicity. Thus, the level of any essential element in humans can be deficient, adequate or toxic depending upon the concentrations of these elements in the soil and the degree of exposure. Both deficiency and toxicity can result in morbidity and in some cases mortality. There are many examples, reports and research publications on the risk of toxicity from substances in soil and the risk to human health, although some have been studied more than others. There are also elements that can be present in soil that have no known benefit for human health such as lead and mercury, but can cause problems with toxicity even at very small concentrations (Combs, 2005; Brevik & Burgess, 2015). Herein we briefly overview several elements of particular interest. The reader is referred to other papers on the supply of elements by soil, such as Steinnes (2011), Green *et al.* (2016) and Cakmak & Kutman (this issue), for additional information.

Lead

Lead is probably the single largest soil contaminant worldwide because it has been widely introduced into soil from anthropogenic sources such as leaded petrol (gasoline), lead-based paint, lead mining and smelting, and other industrial activities. The effects of lead, especially on children and adolescents, is well documented (Deckers & Steinnes, 2004; Balabanova *et al.*, 2017) and has led to multiple public health problems and concerns. Lead in urban soil, where children are especially at risk for contact and contamination, is a particular problem (Filippelli & Laidlaw, 2010; Li *et al.*, 2015). Mass lead poisoning was recently reported in Senegal (Haefliger *et al.*, 2009) and Nigeria (Lo *et al.*, 2012) in villages that participated in informal recycling of used lead-acid batteries and gold ore processing, respectively. The recycling and gold processing activities resulted in lead contaminated soil, with dust from such soil being inhaled, ingested or both, causing lead poisoning. Such studies demonstrate the challenges that many developing countries still face with regard to soil contamination by heavy metals and human health (Wu *et al.*, 2015).

Arsenic

In addition to lead, arsenic poisoning remains a concern over large parts of the world. Arsenic is a naturally occurring element that can concentrate in drinking water, especially water obtained from wells (Helmke & Losco, 2013; Ayotte *et al.*, 2015). Millions of people worldwide are exposed to potentially toxic levels of arsenic each day. Moreover, another common source of arsenic exposure is from the wood found in and around homes, especially in wood preservatives used in pressure treated timber (lumber). Arsenic can concentrate in the soil around structures made with this treated wood where it creates an exposure hazard, especially to children (Gardner *et al.*, 2013). Another problem is the use of arsenic contaminated water to irrigate rice crops; the arsenic then accumulates in people who consume the rice (Brammer & Ravenscroft, 2009; Kwon *et al.*, 2017). Rice is the dietary staple for about half the world’s population, and for most of these people rice also represents their primary exposure to arsenic (Zhao *et al.*, 2010).

Cadmium

Cadmium contamination can be caused by industrial activities or by fertilization with sewage sludge or superphosphate (Nordberg *et al.*, 2015). Cadmium is the most common heavy metal contaminant in the soils of China (Zhao *et al.*, 2015). Large concentrations of cadmium in soil can lead to corresponding large concentrations in plant tissues (Hunter, 2008), which results in toxicity to humans when foods grown in such soil are consumed. The classic example of health problems caused by soil cadmium was the itai-itai disease outbreak in Japan in the first half of the 1900s (Nordberg *et al.*, 2015). Mining in the Toyama Prefecture of Japan released large quantities of cadmium into the Jinzu River, which was used for rice irrigation. Rice absorbed cadmium from the water, and people who consumed the rice subsequently developed itai-itai disease. Itai-itai means “it hurts-it hurts” in Japanese, and the disease is characterized by weak, brittle bones, pain in the legs and spine, coughing, anaemia, and kidney failure. However, large cadmium concentrations in soil do not necessarily produce such symptoms because other soil and dietary conditions are important. Cadmium bioavailability is affected by soil aeration status (Zhao *et al.*, 2015), soil pH and the concentrations of other elements present in a soil. The effect on humans is affected by the concentrations of nutrients such as iron and zinc present in the local diet (Brevik, 2013; Morgan, 2013). Residents of the village of Shipham, in England have large cadmium concentrations in their soil, but do not appear to suffer any adverse health effects because of low bioavailability of the cadmium in their soil and large soil zinc concentration (Chaney, 2015). More in-depth discussions of itai-itai soil interrelations are provided by Morgan (2013) and Brevik & Sauer (2015).

Nitrate

Soil is the primary nitrogen source for plants, and given that nitrogen is required for human health, nitrate is an essential nutrient; however, because of its importance plants can quickly diminish nitrate concentrations in soil. For production agriculture to succeed, the nitrogen consumed has to be replaced frequently, and this is usually with the use of chemical fertilizers. Properly managed, this does not endanger human health and increases crop production. However, improper use and overuse can lead to leaching of excess nitrate into groundwater or surface water (Zhang *et al.*, 2015). Nitrate-contaminated water can cause serious toxicity when the gut microflora convert nitrate into nitrite. Nitrite then reacts with haemoglobin to form methemoglobin, which prevents oxygen from being carried throughout the body. The condition is called methemoglobinemia, and while it can occur in adults it is a bigger problem in infants (Bryan and Ivy, 2015). With the decrease in oxygen concentrations in the blood, infants can become cyanosed with a bluish colouring of the skin. Nitrate has also been identified as a risk factor in the development of stomach cancer (Nagini, 2012). Therefore, proper use of nitrogen fertilizers is vital to prevent public health concerns over nitrate (Richard, 2014).

Mercury

Mercury occurs naturally in soil formed from parent materials with a large organic content; mercury has a strong affinity for organic matter. However, anthropogenic contamination through the mining of gold, burning of coal or chlorine production can cause mercury contamination of soil over large areas. Mercury can be methylated by soil organisms causing it to become mobile in the soil leading to surface water contamination or methyl-mercury can be taken up by plants (Xu *et al.*, 2015). Subsequent human exposure occurs through consumption of contaminated water, plants, animals or both. Therefore, the general public is more likely to encounter large concentrations of mercury through ingestion of fish when the water source is contaminated with methyl-mercury, the consumption of vegetation grown in mercury contaminated soil or the improper handling and disposal of compact fluorescent light bulbs (CFLs) (Boerleider *et al.*, 2017; Liang *et al.*, 2015).

Radionuclides

Soil can be contaminated with radioactive elements naturally or through anthropogenic activity. There is a wide range of radioactive elements that occur naturally and cause concern (Cygan *et al.*, 2007); radon represents the largest natural radiation dose to humans (Appleton, 2007). Radon is a naturally occurring radioactive gas found in many parts of the world that accumulates in basements and other underground structures (Appleton, 2007). It is known to cause lung cancer in individuals (Islami *et al.*, 2015), and because it is inherent to the soil, proper ventilation of basements to reduce the radon concentration or proper sealing to prevent the entry of radon are the only remedies (Khan & Gomes, 2017).

In addition to naturally-occurring radiation such as radon gas, the anthropogenic release of radionuclides into the environment, including soil, poses an immediate and long lasting threat to human health. Anthropogenically generated radionuclides are often the by-product of medical waste, nuclear waste, nuclear power disasters, or fallout from the testing, use or both of nuclear weapons or dirty bombs that contaminate the soil in the vicinity of or downwind from these point sources (Hu *et al.*, 2010). These forms of radioactive pollution can occur by accident or purposefully. Probably the most publicized releases of radionuclides have been from nuclear power plant disasters, the most recent was the Fukushima Daiichi nuclear plant in Japan related to the earthquake and tsunami in 2011 (Chino *et al.*, 2011). The Chernobyl nuclear disaster in the Ukraine (former USSR) in 1986 was another large accidental release that received considerable attention and which has several implications for human health related to radioactive fallout into soil (Brevik, 2013). The effect of radionuclides on human health can be through either direct exposure to the radioactive materials, which leads to various cancers and genetic mutations (Magill & Galy, 2005), or indirect exposure through the creation of soil nutrient imbalances because of antagonism between elemental nutrients (Brevik, 2013).

Xenobiotic organic chemicals

Xenobiotic organic chemicals are carbon based compounds that are synthesized and therefore unnatural. They are referred to as xenobiotic from the Greek term ‘xeno’ for strange. The differences between these synthesized organic compounds and their natural parent compounds are the common insertion of halogen atoms (chlorine, fluorine, bromine) or multivalent nonmetal atoms (such as sulphur or nitrogen) into the structures (Calabrese & Baldwin, 1998; Salem *et al.*, 2017). Because these xenobiotic compounds contain types of atoms in locations that do not occur in natural compounds, organisms have not evolved adequate pathways of biotransformation to metabolize them. Therefore, the synthetic organic compounds are very resistant to biological decay and are usually markedly toxic to organisms even at extremely small doses. Soil contamination with organic chemicals is a serious problem in all nations (Aelion, 2009). A common hazard from these organic chemicals comes from the application of pesticides in both rural and urban areas, with a large percentage of the applied chemicals reaching the soil (Figure 1). For example, when pesticides were applied to a forest area about 25% reached the tree foliage, about 1% reached the target insect and about 30% reached the soil, with the remainder ending up in the atmosphere and surface or groundwater. Application of pesticides to crops increased the percentage of pesticide reaching the soil compared to application to the forest area (Calabrese & Baldwin, 1998).

Soil pollution with organic chemicals is not limited to farming areas. Soil in urban areas is also polluted with organic chemicals from medicines, industrial activities, coal burning, motor vehicle emissions, waste incineration, sewage and deposition of solid wastes (Leake *et al.*, 2009). Both farming and urban areas have soil contamination that includes a complex mixture of organic chemicals, metals and microorganisms from municipal and domestic septic system waste, farm animal waste and other biowastes (Pettry *et al.*, 1973; Saha *et al.*, 2017). A more recent health concern includes pharmaceutical waste derived from antibiotics, hormones and anti-parasitic drugs used to treat humans and domestic animals (Albihn, 2001; Aust *et al.*, 2008; Crofts *et al.*, 2017).

These xenobiotic organic chemicals are typically very diluted, they can form chemical mixtures in the upper layers of the soil. We have very little toxicological information about the health effects of these chemical mixtures (Carpenter *et al.*, 2002; Fan *et al.*, 2017).

Because of the long half-lives of many organic chemicals, they are referred to as ‘persistent organic pollutants’ (POPs). Twelve POPs were identified by the Stockholm Convention in 2001 (Xu *et al.*, 2013) and 14 additional POPs were added in amendments to the Stockholm Convention in 2009, 2011, 2013 and 2015 (Stockholm Convention, 2015) (Table 1). These POPs resist decomposition in the environment and bioaccumulate as they move up the food chain. An example of a POP is 1,1,1-trichloro-2,2-bis(p-chlorophenyl)ethane (DDT), which was shown to disrupt the hormonal systems of raptors causing eggshells to be too thin to support the chicks (Vega *et al.*, 2007).

Essential nutrients

There are 14 elements essential for plant growth that come from the soil, and many of these elements are also essential for human health (Combs, 2005). These essential nutrients end up in the human diet either directly through the consumption of plants or indirectly through the consumption of animal products (Abrahams, 2002). Hydrogen, oxygen, carbon, nitrogen, sodium, potassium, calcium, magnesium, phosphorous, sulphur and chlorine make up 99.9% of the atoms in the human body, with all but hydrogen, oxygen and carbon having soil as their major source (Brevik, 2013). However, the remaining 0.1% consists of approximately 18 additional elements known as micronutrients or trace elements that are essential in small amounts to maintain human health (Combs, 2005). Therefore, soils that provide plants with the proper nutrients for growth also contain many of the elements that are necessary for human health as well. Herein, we focus briefly on some important micronutrients that can cause fairly commonly seen health issues; major sources of selected human nutrients are given in Table 2. We refer the reader to Shetty (2009) for additional details.

Iodine

Iodine deficiency has been identified as the single most preventable cause of brain damage world-wide by the World Health Organization (WHO, 2007a). Other health effects include goitre, hypothyroidism, spontaneous abortions and stillbirths, congenital anomalies, impaired mental function and delayed physical development (WHO, 2007a). Deficiencies are common in regions where soil does not supply adequate iodine to the crops grown in it, and although widespread, they are most common in the high altitude interiors of continents (Combs, 2005). Considerable progress has been made in correcting iodine deficiency disorders through the ‘Universal Salt Iodization’ programme that started in 1994 (WHO, 2007a).

Iron

Iron deficiency causes anaemia because it is an essential component of haemoglobin. About two billion people are estimated to have iron deficiency worldwide making it one of the most common nutrient deficiencies (WHO, 2007b). Iron deficient soil can lead to small iron concentrations in plants and in humans who consume them (Combs, 2005). This is especially problematic in arid soils and in populations whose diets rely on a large intake of cereal grains, but have few meat products (Deckers & Steinnes, 2004). Excessive iron, however, can lead to genetic and metabolic diseases (Fraga, 2005).

Selenium

Selenium is an essential micronutrient for humans because it has critical roles in thyroid function and immunity (Fairweather-Tait *et al*, 2011). Selenium concentrations in soil vary greatly throughout the world depending on geological and climatic factors and, therefore, the concentration of bioavailable selenium in plants varies considerably (Haug *et al.*, 2007). Most of the world's population consumes suboptimal amounts of selenium and is therefore at increased risk of cancer, heart disease, other diseases caused by increased oxidative stress (Combs, 2001) and a weakened immune system (Fraga, 2005). Conversely, selenium toxicity in humans can occur in regions where the soil or drinking water has large concentrations of selenium (Fordyce, 2013). The effects of selenium toxicity in humans are not well understood, but it is considered a probable carcinogen that targets the liver and kidneys (Hardman, 2006) and causes brittle hair and nails, hair and nail loss, gastrointestinal problems, fatigue and nerve damage (Fordyce, 2005; Fraga, 2005).

Zinc

Zinc is a critical component of several enzymes, in cellular growth and in tissues that have a rapid differentiation and turnover, such as in the gastrointestinal tract and immune system (WHO, 2006). Zinc deficiency is suspected to be common in developing countries (Fraga, 2005), but the exact level of the problem is not well known because of the lack of reliable and well-accepted indicators of zinc deficiency (WHO, 2006). Deficiency negatively affects the healing of wounds, immune system response and the ability to taste and smell (Fraga, 2005), and is also suspected of causing stunted growth (WHO, 2006). About half the world's soils are deficient in zinc, with strongly leached acidic soil and calcareous soils being the most likely to be deficient (Combs, 2005; Abrahams, 2002).

Human pathogens

In addition to soil affecting the nutrient quality of foodstuffs and exposing humans to contaminants, it is also a vast heterogeneous habitat for millions of macroscopic and billions of microscopic organisms. Although the majority of these organisms do not cause disease in humans, several species of bacteria, fungi, protozoa, viruses and prions can cause disease depending upon many factors including the condition of the soil, climate, location, land use and other variables that upset the normal microbial biomass. A set of tables that give a good overview of pathogens found in soil, including the diseases caused, geographic distributions, problems caused and incidence is given in Loynachan (2013). Herein, we provide two examples of how soil can affect human health through contact with soil microorganisms directly or indirectly by promoting either antibiotic resistance or by producing antibiotics. Other excellent papers on this topic have been published recently and we encourage the reader to obtain additional details on many of these topics in other related publications (e.g. Adegoke *et al*. 2017; Baumgardner, 2012; Wall *et al.*, 2015).

Coccidioidomycosis

Coccidioidomycosis, also called Valley Fever (Figure 2), is caused by the fungus *Coccidioides* spp. which lives in soil of the southwestern United States and areas further south into Mexico and Central and South America (Brevik, 2009). The fungus usually enters humans through the respiratory route by inhalation of microscopic fungal spores. The fungus can grow under extreme environmental conditions including extreme temperatures, high salinity and very alkaline conditions that most other microorganisms cannot tolerate. However, they compete poorly with other soil fungi and bacteria, which often limits *Coccidioides* spp. to soils with properties that are not suitable to many other organisms (Bultman *et al.*, 2005; Reyes-Montes *et al.*, 2016). These fungi grow and reproduce in and above the soil. Any natural (earthquake or dust storm) or anthropogenic (construction or tillage) soil disturbance in these endemic areas can cause aerosolization of the fungus and infect humans and animals. Epidemics can occur after heavy rains that promote mycelial growth followed by drought and windy conditions. Although uncommon, the fungus can also directly infect skin or bone through contamination by a penetrating object, but inhalation is a much greater threat (Stockamp & Thompson, 2016). This disease is expected to increase in prevalence because of population growth in areas where *Coccidioides* is endemic. Soil maps have been used successfully in an epidemiological study that sought to identify areas where people were susceptible to contracting valley fever (Tabor *et al.*, 2011).

Antibiotic resistance and antibiotics

Antibiotic resistance by definition occurs when an antibiotic no longer effectively controls or kills bacterial growth (an increase in the minimum inhibitory concentration); thus the bacteria are said to be resistant to the antibiotic and are difficult or impossible to treat. Antibiotic resistance continues to be a major concern in infectious disease control because of the large increase in antibiotic resistant bacteria that is being seen worldwide (Tanwir & Khiyani, 2011). Accordingly, physicians are running out of therapeutic options with which to fight these bacterial species as several of these so called superbugs are resistant to many of the most potent antibiotics available (Khan & Khan, 2016). There are several reasons why antibiotic resistance develops. First, antibiotics are often overprescribed or prescribed inappropriately by physicians or are obtained ‘over-the-counter’ when the patient does not have a bacterial infection or for the prophylactic prevention of an infection before a dental or medical procedure. Second, when prescribed appropriately, patients will begin to feel better and will discontinue the use of the antibiotic before it has completely eliminated the pathogenic bacteria. This leads to bacterial adaptations by which the organisms can survive at small concentrations of the antibiotic, potentially acquire antibiotic resistance genes, upregulate antibiotic resistance mechanisms or both. These bacteria are then able to transmit resistance genes between bacteria (intra- or inter-species transfer) leading to antibiotic resistance through a variety of mechanisms (Blair *et al.* 2015). The heterogeneous habitat of the soil environment favours the exchange of genetic material between organisms, many of which confer antibiotic resistance (Forsberg *et al.*, 2012; Woolhouse & Ward, 2013). Soil is known to contain gene pools which promote the emergence of antibiotic resistance, similar to antibiotic resistant genes in a hospital setting (Nesme *et al.* 2014). The role of the soil is to provide an environmental niche for both the emergence and dissemination of antibiotic resistance genes (Vas-Moreira *et al.* 2014). Adegoke *et al.* (2017) and Nesme & Simonet (2015) have recently reviewed the role of soil in contributing to antimicrobial resistance and we refer the readers to these publications and others for more information. Many anthropogenic factors such as the use of organic fertilizers on crops, antibiotic use in humans and livestock and antibiotic use on crops (typically through the application of manures or waste water that contain antibiotics to crops (Palacios *et al.*, 2017; Prigitano *et al.*, 2017)) increase the incidence and persistence of antibiotic resistance genes and antibiotic resistant species in the soil (Adegoke *et al.* 2016; McManus *et al.* 2002; Popowska *et al.* 2011; Wang & Tang 2010). Whether this poses direct harm to the health of humans remains under investigation (D'Costa *et al.*, 2011; Forsberg *et al.* 2012; Pepper, 2013; Udikovic-Kolic *et al.* 2014); however, the emerging evidence of increased antimicrobial resistance lends credence that it is and will continue to pose a risk to human health. Nevertheless, the increase in antibiotic resistance has led to a burst of research to discover new antibiotics. Not only is the soil a source of antibiotic resistance, but it is also a source of natural antibiotics. Soil organisms often increase production of antibiotic-like compounds during times of stress (Swiecilo *et al.* 2013) and perhaps because of the increased stresses on soil worldwide new antibiotics are being discovered, although at a slower rate than the emergence of antibiotic resistance in the same stressed soil (Martinez *et al.* 2008). Many of the bacteria and actinomycetes found in soil naturally secrete compounds to ward off other bacteria and actinomycetes to give them a survival advantage in the competitive soil environment. However, it is difficult to isolate and grow these organisms in the laboratory environment, which hampers the ability of scientists to discover new antibiotics quickly. The recent discovery of Teixobactin using new culture isolation methods for soil organisms (Ling *et al.* 2015) provides hope that more antibiotics can be discovered by soil and medical microbiologists and other fields of medicine and chemistry working together.

Urban soil

The study of urban soil has received increased attention recently, including processes that create and modify it (Lehmann & Stahr, 2007), the vertical and horizontal spatial distribution of soil properties (Howard & Orlicki, 2015) and the ability to predict such property distributions so that they can be mapped (Howard & Shuster, 2015). These studies have revealed that urban soils are very heterogeneous and strongly affected by anthropogenic activities, which supports the suggestion by some soil scientists that soil should now be considered a human–natural body rather than just a natural body (Richter *et al.*, 2011).

The anthropogenic effects that make urban soils so heterogeneous can also introduce a number of contaminants that may have adverse effects on human health. For example, while only 2% of 0–5 year old children in the USA are poisoned with lead, it is 15–20% in Eastern and Midwestern USA city centres because of the close contact that children have with lead contaminated urban soil (Filippelli & Laidlaw, 2010). The contamination now found in urban soil came from sources such as the combustion of leaded petrol, use of lead-based paints (Filippelli & Laidlaw, 2010), smelting and other industrial operations, recycling and disposal of wastes, application of lawn chemicals (Burgess, 2013; Morgan, 2013), and even the use of pressure treated wood in the construction of playground equipment (Gardner *et al.*, 2013) in the past. Although active contamination has been greatly reduced in many developed countries, urban soils still bear the burden of contamination from previous activities (Filippelli & Laidlaw, 2010; McClintock, 2015), and in many developing countries contamination actively continues (Trujillo-González *et al.*, 2016).

Given the large numbers of people who live in urban centres (over 54% of the world's population as of 2014 and increasing, particularly in developing countries (WHO, 2016)) and the close contact between people and urban soil, there is large potential for negative health effects because of exposure to contaminated soil in the urban environment. There has also been a growing urban garden movement in recent years (Philpott *et al.*, 2014), providing the potential for the transfer of containments into the human food supply through soil–plant interactions (Beniston *et al.*, 2015; Roy & McDonald, 2015). Therefore, connections between urban soils and human health will be likely to be a growing area of research in the near future.

Soil security

The concept of soil security has been advanced recently in an effort to put policies concerning soil on to a similar level as those focused on food and water security (Koch *et al.*, 2012). The description of soil security provided by Koch *et al.* (2012) coincides in many ways with commonly accepted definitions of soil quality or soil health (Karlen *et al.*, 1997). There are definite ties between the concepts (Brevik *et al.*, 2017), but soil security goes further than the soil quality and health concepts in that soil security integrates economic, social and political aspects (McBratney *et al.*, 2014).

McBratney *et al.* (2014) identified five dimensions of soil security, and each of them have links to human health (Brevik *et al.*, 2017) (Table 3). There are also interconnections between many of the dimensions. For example, the condition (dimension 2) of a soil affects that soil's capability (dimension 1) to provide services, such as growing nutritious foods. Another example is how people connect (dimension 4) with soil affects how a given society tends to treat or manage their soil, which affects its condition (dimension 2). Codification (dimension 5) can also affect soil condition (dimension 2) through its effect on management choices by land managers. Therefore, the concept of soil security provides a platform that can be used to explore links between soil and human health in a transdisciplinary way, combining and merging aspects of the physical and biological sciences with those of the social and medical sciences.

Dimension 4, connectivity, provides an excellent example of a potential transdisciplinary approach highlighted by the concept of soil security. Societies tend to take care of things that matter to them and to neglect things that do not; the connectivity dimension includes making connections between the soil that supports society and items that matter to them (McBratney *et al.*, 2014). In this respect, the concept of *terroir* may be particularly useful. Originally *terroir* established a connection between the soil that produces a given wine and wine connoisseurs, but more recently *terroir* has been expanded to include many other food products (Vaudour *et al.* 2015) and even the sources of water (springs, artesian aquifers, glaciers, etc.) (Capehart, 2015). Establishing connections between people and soil through products that they value, such as favourite foods, might create greater concern for the soil resource, ultimately leading to better treatment and management of our soils and through that improved human health (Karltun *et al.*, 2013). For a more in-depth discussion of links between soil security and human health see Brevik *et al.* (2017).

Conclusions

Research into all of the above areas and those discussed more fully in the literature needs to continue to understand fully the effect of soil on human health. Interdisciplinary and transdisciplinary studies will be needed in the future because narrowly focused research will be inadequate to address many of the outstanding issues that still need to be understood. Many disciplines including soil science, agronomy, geology, geography (cultural and physical), biology, microbiology, ecology, public health and medicine (amongst others) will need to be involved in these collaborative studies. In addition, the field of soil and human health needs more people within scientific societies and political establishments to convey the importance of and to secure funding for these studies. This special section seeks to help achieve these goals by bringing together specialists from different fields to present original research on topics important to the study of the soil and human health connection.

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Highlights

- Soil is important to human health
- Effects can be positive or negative, direct or indirect
- Advances have been made in recent years
- Inter- and trans-disciplinary research is needed

Figure 1.

Application of agricultural chemicals can lead to considerable interaction between soil and the chemical. (a) Chemicals being applied directly to exposed soil in between the cropped rows as a side effect of treating the crops. Photograph by Jeff Vanuga, USDA–NRCS. (b) Worker sprays pesticides on a garden in an urban area. Photograph by Artemi Cerdà.

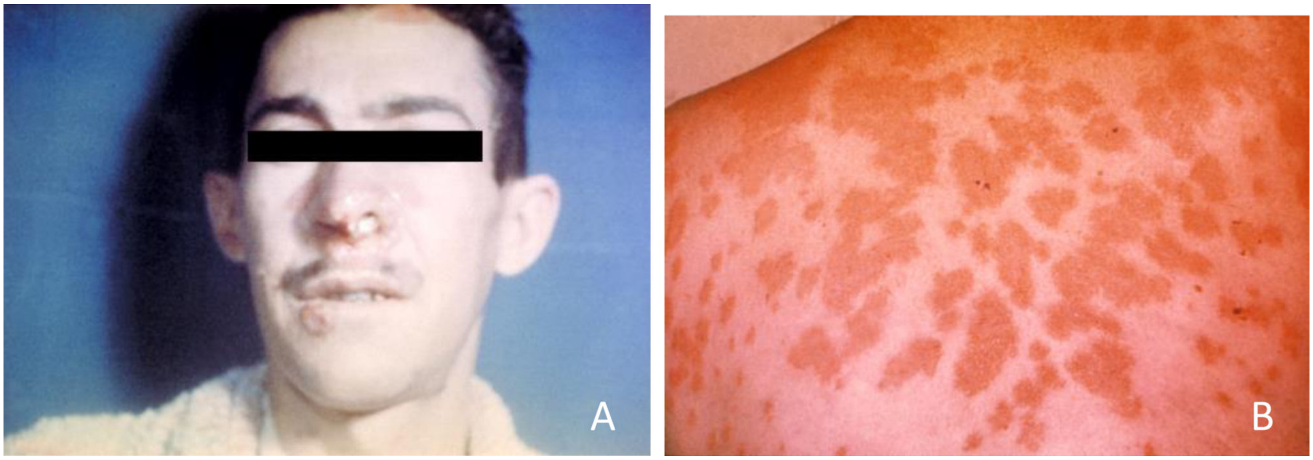

Figure 2.
(a) Paracoccidioidomycosis lesions on the face of a patient and (b) erythema nodosum lesions on skin of the back because of coccidioidomycosis (valley fever) (Courtesy Centers for Disease Control and Prevention, image #4027 and #482).

Table 1

Persistent organic pollutants identified by the Stockholm Convention (SC). Some POPs can still be used for specific purposes as outlined in the SC. Table based on Stockholm Convention (2008; 2015).

Chemical	Year Added	Source*	Annex in SC	Additional Notes
Aldrin	2001	P	A	
Chlordane	2001	P	A	
DDT	2001	P	B	DDT still used against mosquitoes in several countries to control malaria
Dieldrin	2001	P	A	
Endrin	2001	P	A	
Heptachlor	2001	P	A	
Hexachlorobenzene (HCB)	2001	P, IC, BP	A & C	
Mirex	2001	P	A	
Toxaphene	2001	P	A	
Polychlorinated biphenyls (PCB)	2001	IC, BP	A & C	Has specific exemptions under Annex A
Polychlorinated dibenzo-p-dioxins (PCDD)	2001	BP	C	
Polychlorinated dibenzofurans (PCDF)	2001	BP	C	
Alpha hexachlorocyclohexane	2009	P	A	
Beta hexachlorocyclohexane	2009	P	A	
Chlordecone	2009	P	A	
Hexabromobiphenyl	2009	IC	A	
Hexabromodiphenyl ether, heptabromodiphenyl ether	2009	IC	A	Can be used in accordance with the provisions of Part IV of Annex A
Lindane	2009	P	A	Human use for control of head lice and scabies as second line treatment
Pentachlorobenzene	2009	P, IC, BP	A & C	
Perfluorooctane sulfonic acid, its salts and perluorooctane sulfonyl fluoride	2009	IC	B	Acceptable purposes and specific exemptions in accordance with Part III of Annex B
Tetrabromodiphenyl ether, pentabromodiphenyl ether	2009	IC	A	Has specific exemptions under Part V of Annex A
Technical endosulfan and its related isomers	2011	P	A	Exemptions for crop-pest complexes in accordance with the provisions of part VI of Annex A
Hexabromocyclododecane	2013	IC	A	Expanded and extruded polystyrene in buildings in accordance with the provisions of part VII of Annex A
Hexachlorobutadiene	2015	IC	A	
Pentachlorophenol and its salts and esters	2015	P	A	Pentachlorophenol for utility poles and cross-arms in accordance with the provisions of part VIII of Annex A
Polychlorinated naphthalenes	2015	IC, BP	A & C	Can be used for production of polyfluorinated naphthalenes, including octafluoronaphthalene

*P, pesticide; IC, industrial chemicals; BP, by-products

Table 2

Examples of important sources of elements essential to human life, it is important to note that this table does not give a complete list of elements essential to human health (Table based on Combs, 2005; Fraga, 2005; Shegefti *et al.*, 2016).

Element	Important Sources
Ca	Kale, collards, mustard greens, broccoli, dairy products
Cl	Dairy products, meats, eggs
Co	Fish, oysters, eggs, milk, green vegetables, cereals, nuts
Cu	Beans, peas, lentils, whole grains, nuts, peanuts, mushrooms, chocolate, organ meats, oysters, dark chocolate
Fe	Meats, especially red meat, cereals, legume seeds, fruits, vegetables, dairy
I	Vegetables, cereals, fruit
K	Fruits, cereals, vegetables, beans, peas, lentils, dairy products, meats
Mg	Seeds, nuts, beans, peas, lentils, whole grains, dark green vegetables
Mn	Whole grains, beans, peas, lentils, nuts, tea
Mo	Beans, peas, lentils, dark green leafy vegetables, organ meats
Na	Dairy products, meats, eggs
P	Nuts, beans, peas, lentils, grains, meats, eggs, dairy products
Se	Grain products, nuts, garlic, broccoli (if grown on high-Se soil), red meats, seafood
Zn	Nuts, whole grains, beans, peas, lentils, red meats, organ meats, poultry, sea food, dairy

Table 3

Examples of ways that the dimensions of soil security link to human health. Some of the dimensions are interconnected. The examples are based on Brevik *et al.* (2017).

Dimension of Soil Security	**Links to Human Health**
1: Capability	Production of plentiful food
	Ability to pass essential nutrients up the food web
	Waste filtration function of soils, particularly in the supply of clean water
2: Condition	Ability to pass essential nutrients up the food web
	Presence or absence of potentially harmful chemicals or organisms
3: Capital	Ecosystem services that support human health have value
	Soil conditions that negatively influence human health have a cost
	Medicines developed from soils or soil organisms have economic value and save money when they shorten or prevent illness
4: Connectivity	The value that society places on soils influences how soils are managed or treated, which in turn influences soil condition
	The *terroir* concept provides an example of a way to connect people to the soils that produce their food and encourage a more positive image of soil and better management
	Contact with healthy soil has been shown to have potential human health benefits
5: Codification	Government sponsored conservation programs can improve soil and water quality, leading to human health benefits
	Non-binding initiatives such as the United Nations proposed Sustainable Development Goals can positively influence soil and water quality and thus human health through capability and condition