Fundamental and Applied Agriculture
Vol. 5(4), pp. 443–452: 2020
doi: 10.5455/faa.127472

Soil Science | Review Article

Soil health and human well-being: a review

M Jahiruddin

Department of Soil Science, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh

Article Information

Article History
Submitted: 21 Aug 2020
Accepted: 28 Oct 2020
First online: 29 Nov 2020

Academic Editor
M Harun Rashid
mhrashid@bau.edu.bd

**Corresponding Author*
M Jahiruddin
m_jahiruddin@yahoo.com

OPEN ACCESS

Abstract

A range of positive and negative impacts of soil on human health are reviewed in this article. Soil has a variety of positive functions that support human health. It supplies nutrients to the plants and eventually to the human body via food intake. Soil helps purification of water and serves as foundation for buildings. Healthy soils impact carbon sequestration, greenhouse gas reduction, adequate nutrient supply, water retention and efficient biodiversity. Both soil macroorganisms (e.g. earthworms) and microorganisms (e.g. N_2 fixing bacteria) perform great role on soil health, and soil health in turn has good linkage with human health. Nevertheless, soils can exert negative impact on human health. Negative health effects occur when foods are grown in soils that have nutrient deficiencies or toxicities and when toxic heavy metals (e.g. Cd, As, Pb, Hg) are transferred from soils into the plants and then into the human food chain. People are also exposed to toxic chemical substances (e.g. soil insecticides), radionuclides (e.g. ^{137}Cs), soil pathogens (e.g. saprophytic fungi) and soil parasites (e.g. hookworms). Inhalation of airborne dusts causes respiratory trouble (e.g. asthma). Many of the complex interactions between soil and human health are yet to be unveiled. For thorough understanding of the soil ecosystem and its relation to safe and nutritious food production and broadly human health, multidisciplinary approach is needed. Contributions of experts from agriculture, medical and social science fields are needed to address the whole soil and human health issues.

Keywords: Soil health, degradation, pollution, nutrition, productivity

Cite this article: Jahiruddin M. 2020. Soil health and human well-being: a review. Fundamental and Applied Agriculture 5(4): 443–452. doi: 10.5455/faa.127472

1 Introduction

About 78% of per capita calorie consumption depends on crops that grown directly on soil, and nearly 20% on terrestrial food sources that rely indirectly on soil (Brevik, 2012). Decline of the Mesopotamian civilizations and collapse of the Maya Empire (A.D. 600) happened partly due to soil degradation (soil erosion, salinization and nutrient exhaustion) resulting food insecurity (Olson, 1981).The capacity of a soil to continuously support plants, animals and human is termed as soil health (USDA, 2019). Healthy soils continuously produce ecosystem services such as sustaining plant and animal productivity, increasing biodiversity, and maintaining or enhancing the qualities of air and water and thereby support human health (Anonymous, 2018).

Healthy soils impact carbon sequestration, detoxification, water retention, nutrient release and biodiversity (Brevik et al., 2018). Soil nutrient supply, soil pollution and soil organisms are the key determinants of human health. Different aspects soils that influence human health have been well reviewed (Brevik et al., 2020; Steffan et al., 2017; Brevik and Burgess, 2012; Abrahams, 2002). It is the 'negative' general public perception of soil; in fact they often regard it as "dirty thing" rather than "soil," which can produce beautiful thing (e.g. flowers, fruits, vegetables). Link exists between health of soil and health of people who consume foods produced on soils (Friedrichsen et al., 2018).

Human activities may cause physical, chemical and biological degradation of soil (Nieder et al., 2018). Physical degradation includes soil erosion, crusting and compaction, chemical degradation includes soil fertility depletion, acidification and salinization and biological degradation includes loss of soil organic matter and biodiversity. Climate change (global warming) induces soil degradation. Thus, attention is needed for sustainable and profitable soil management to minimize soil degradation and to obtain benefits for human health. Every year, the Earth loses more than 25-40 billion tonnes of topsoil, mainly due to human activity (FAO and ITPS, 2015).

Plants depend on soil for nutrients and both humans and animals depend on plants for food. So, soil can be regarded as the basis of life. The fertility (nutrient status) of a soil determines the nutrient content of food crops, and therefore the health of humans. Of the 17 Sustainable Development Goals (SDGs), no poverty (SDG 1), zero hunger (SDG 2), climate action (SDG 13) and biodiversity (SDG 15) are directly linked with sustainable land and soil management (Akhtar-Schuster et al., 2017; Smith et al., 2017). Thus, proper care is needed for sustenance of healthy soils for providing sufficient, safe and nutritious food for the people.

Soils also negatively impact human health as because many soils contain toxic heavy metals (e.g. Cd, As), organic chemicals (e.g. pesticides) and pathogens (e.g. *Clostridium tetani*). When soil is healthy, plant grown on soil is healthy and consequently man eating plant food is healthy. This article has reviewed how soil health affects human health and welfare.

2 Positive effects of healthy soil

2.1 Soil health and food production

Food production includes production of sufficient amounts of food with adequate nutrient content and absence of toxic substances (Hubert et al., 2010) where soils have a good role. Food security is considered achieved when all people can get sufficient, safe, and nutritious food (FAO, 2003). Soils having good physical, chemical and biological properties can produce good crop with satisfactory yield and quality (Reicosky et al., 2015; Brevik, 2009). Intensification of agriculture to meet the food demand of increasing population has put our soils under pressure, resulting in nutrient depletion, physical degradation, and biodiversity reduction. Thus, degraded soil (low fertility, salinity, acidity, erosion, heavy metals pollution, etc.) causes decreased safe food production and threatens food and nutrition security (Brevik, 2013; Pimentel and Burgess, 2013; Hubert et al., 2010; Lal, 2009). Toxic heavy metals (e.g. Cd, As, Cr) of soils may enter into food chain through crop uptake, leading to unsafe foods (Hubert et al., 2010; Brevik et al., 2018). An estimated 2 billion hectares of land (54% of world's land area) is degraded to some degree (FAO, 2011). The major causes of soil degradation are salinization, waterlogging, pollution, acidification and nutrient depletion. Since degradation reduces the soil productivity, it has been directly linked to the hunger and malnutrition in many parts of the world. Malnutrition affects 815 million people (mostly in sub-Saharan Africa and southern Asia), and world food production must double over the coming half century to meet the needs of 9-10 billion people. The sustainable management of the land resource is an important issue for human and other lives in the earth (Henry et al., 2018).

2.2 Soil as a source of major nutrients

In human body, 99% is constituted by H, O, C, and N, and 0.9% by other elements *viz.* Na, K, Ca, Mg, P, S, and Cl (Combs, 2013). Besides, some trace elements (micronutrients) are also considered essential for human life. However, 17 elements are essential to plants and 14 of them plants take up from soil (Brevik, 2013). Plants obtain C, H and O from air and soil water (Kirkby, 2012). Thus, soil supplies plants most of the nutrients that required for human life (Combs, 2013). However, deficiency, excess, or imbalance in the supply of nutrient elements from dietary sources would have deleterious effects on human health (Mills, 1996).

2.3 Soil as a source of micronutrients

Of the essential micronutrients, the most frequently reported deficiencies for human health are Fe, Zn, I and vitamin A (Welch and Graham, 2004), the reason can be attributed to the smaller amount of micronutrients in cereal grains (Garg et al., 2018) which the people usually more consume and the higher amount of antinutrient substances e.g. phytic acid (White and Broadley, 2009), a substance that inhibits the absorption of mineral elements by the gut. Humans need 14 vitamins which include water-soluble vitamins *viz.* ascorbic acid, biotin, cobalamin, folic acid, niacin, pantothenic acid, pyri-doxine, riboflavin and thiamin and fat-soluble vitamins *viz.* retinoic acid, calciferol, tocopherol, phylloquinone, and menoquinone (Graham et al., 2001). The RDA (recommended daily allowance) of different minerals for humans is: Fe 8.0-18.0, Zn 8.0-11.0, Mn 1.8-2.3, Cu 0.9, I 150, Se 55, Mo 45, Cr 25-35 and F 3-4 mg (White and Broadley, 2009). More than 2 billion people in the world suffer from Zn and Fe deficiency diseases (WHO, 2012), the majority of them are rural poor from developing countries.

Micronutrient deficiency is very common in population where the staple foods are cereals of low nutritional quality (Cakmak, 2009). Cereal-cereal rotation is a common agricultural practice in the South Asia and the major fraction of calorie intake of the population comes from cereals. Therefore, micronutrient malnutrition is the highest and is considered the top-priority health issue here (Shivay et al., 2016). Very recently Jahiruddin (2020) has comprehensively reviewed the biofortification of food crops with a greater emphasis on micronutrient malnutrition in south Asia. In addition to producing enough calories through increasing cropping intensity, use of HYVs and application of modern technology, we also need to enrich our food and feed crops with micronutrients to ensure adequate supply for human and animal health. Two approaches such as breeding and agronomic are the good means to increase micronutrient concentration in food crops. The fertilization strategy (agronomic method) is a rapid was to achieve micronutrient biofortification without incurring loss to crop yield (Jahiruddin, 2018).

Mineral nutrient deficiencies in humans may arise for a variety of reasons. The WHO (WHO, 1996) is particular concern about F, Fe, Zn, I and Se deficiency problems. For Fe, poor diet, blood loss and higher requirements of pregnant women are the most common causes of Fe deficiency (Crommentuijn et al., 1997). Iodine is an essential constituent of the thyroid hormones; 'goitre' arises due to I deficiency (WHO, 1996). Keshan disease is found in areas of high soil Se (Johnson et al., 2000). The itai-itai disease in Japan is reported to occur due to excess Cd concentrations in food crops when cultivated in soils treated with sewage sludge, phosphatic fertilizers and industrial effluents (Alloway and Ayres, 1993).

2.4 Soil harbors beneficial organisms

Biological diversity of soil ecosystems is fundamentally important for soil and human health. Soil microorganisms offer positive effects on quality and security of food systems that subsequently influence human nutrition and health. Plant growth-promoting (PGP) bacteria or fungi can play an important role to increase crop yield and nutritional quality (Martínez-Hidalgo et al., 2019). For example, inoculation of maize plants with PGP rhizobacteria (*Pseudomonas*, *Bacillus* and *Mycobacterium*), inoculation of lettuce with *Trichoderma* fungus and arbuscular mycorrhizal fungi (AMF) colonization of rapeseed (*Brassica napus*) roots increased crop growth and nutrient uptake in low fertile soils (Egamberdiyeva, 2007; Poveda et al., 2019). In addition to addressing nutrient deficiency, AMF have been reported to control the absorption of heavy metals by plants from toxic soil (Sarkar et al., 2015a,c,b, 2017). Soil arbuscular mycorrhizal fungi also help controlling soil borne plant diseases (Sarkar et al., 2015d; Talukder et al., 2019). Soil macroorganisms are important component of soil health, and soil health has direct ties to human health (Kemper and Lal, 2017; Pepper, 2013). The role and impact of earthworms, ants, mites, and other arthropods are important in agroecosystems (Rousseau et al., 2010; Romig et al., 2015). Earthworms plays an important role in recycling organic material, increasing nutrient availability. They incorporate organic materials into the soil and release nutrients held within dead animals and plant matter. Microrganisms also improve soil structure and influence the habitat and activities of other organisms.

2.5 Ecosystem services of soils

Soil health determines the extent to which a soil can provide ecosystem services. Dominati et al. (2010) listed the following ecosystem services that can be achieved from a healthy soil:

Productivity: A healthy soil provide nutrients to plants and sustain their growth.

Filter and reservoir: Soils filter polluted water through fixing and storing the solutes passing through it.

Structural: Soils provide mechanical support to plants and support infrastructure such as buildings and roads for human.

Resources: Soils provide raw materials such as sand, peat and clay for bricks, roads and buildings.

Biodiversity conservation: Soils provide habitat for thousands of macro- and microorganism (flora and fauna) of which are beneficial such as those important for pest, disease and waste management.

Soil is an important source of medicines such as antibiotics. Soil microorganisms could be the main producers of natural antibiotics, penicillin produced from fungus and streptomycin from bacteria (Streptomyces) being the good examples. S. A. Waksman was awarded the Nobel Prize in 1952 for discovery of streptomycin which is active against Mycobacterium tuberculosis.

2.6 Other uses of soil

Soil has ability to purify wastewater. Soils can remove contaminants through physical trap as the water moves downward through the soil profile, through chemical sorption to soil solid surfaces, and through biodegradation carried out by soil microbes (Helmke and Losco, 2012). Soil (clay type) is also used to make earthen pots and utensils. Earthen pots are used for potting plants (especially flowering plants), storage of water and cooking of foods. An earthen pot is a fundamental cooking utensil for poor and old people. Water in the earthen pots remains cool which is important in the summer days. Although cooking in earthen pots takes relatively more time, the porosity and natural insulation properties of soil clay cause heat and moisture to circulate throughout the food.

Soil is directly used to make building materials, such as brick. Historically, many houses and other structures were made from soil. Selection of sites with the best soil is an important engineering decision for construction of a building. Builders find loamy soils to be adequate for building. Red soil has a great impact on strength, imperviousness and anti pest control.

3 Effects of soil degradation

3.1 Heavy metal pollution

Although some metallic elements *viz*. Fe, Zn and Cu in smaller amounts are essential for plant growth, their excessive uptake can produce toxic concentration in plants and that plant foods become unsafe for human consumption (Jarup, 2003). The heavy metals (density 5 g cm^{-3}) of greatest concern for human health include: As, Pb, Cd, Cr, Cu, Hg, Ni, and Zn (Hu and McCally, 2002; Fergusson, 1990). Both natural and anthropogenic sources (human activities) are the reasons for heavy metals pollution in soils. Heavy metals may accumulate in soils naturally through weathering of rocks and minerals and by human activities. For example, weathering of arsenopyrite (FeAsS) mineral is responsible for arsenic occurrence in soils and eventually in groundwater. These metals may come from different wastes (industrial, municipal and household wastes) and sewage sludge. Use of fertilizers, manures, and pesticides also contribute to the accumulation of heavy metals in soils (Kabata-Pendias and Pendias, 1992; Senesil et al., 1999). Elements such as Ag, As, Be, Cd, Hg and Pb are regarded as potentially harmful elements (PHEs) that known to have adverse physiological effects even at low concentrations (Plant et al., 2000). The maximum permissible addition (MPA) of metals and metalloids in soil is shown in Table 1. The WHO's provisional maximum tolerable daily intake (MTDI) for As is 2.1 µg d^{-1} kg body wt^{-1} WHO (2012). Daily intake of these heavy metals from rice is estimated as 18.6-214 µg for As, 2.6-119 µg for Cd and 25.0-241 µg for Pb, based on 400 g daily rice consumption for 60 kg Bangladeshi adult people, and rice component of the diet alone may contribute up to 46%, 57% and 50% of the Maximum Tolerable Daily Intake (MTDI) for As, Cd and Pb, respectively (Jahiruddin et al., 2017). Among the cereals, rice (*Oryza sativa* L.), is one of the leading staple crops for half of the world's population. In country like Bangladesh rice is the staple food and the crop covers about 75% of agricultural land use. MSW compost amendment may result in a significant enhancement of heavy metal loadings in the amended top soils. As reported by Achiba et al. (2009), a 5-year application of MSW compost increased the organic matter and N content, while increasing the heavy metal concentration in the soil.

3.2 Organic chemical pollution

Soil contamination with organic chemicals is a great concern in many countries (Aelion, 2009). A major source of these chemicals is the use of different types of pesticides in crop production. Pesticides include insecticides, nematicide, rodenticide, bactericide, fungicide and herbicides. Biopesticides could be microbial pesticides and biochemical pesticides. Pesticides are found as common contaminants in soil, air and water. They can also affect beneficial microbes and insects in soils. In urban areas the soils may become polluted because of coal burning, motor vehicle emissions, waste dumping and pharmaceutical waste deposition (Leake et al., 2009; Albihn, 2001). The most common types of organic chemicals that present in soil are polyhalogenated biphenyls, aromatic hydrocarbons, insecticides, herbicides and fossil fuel combustion emitting e.g. Pb (Burgess, 2012). Some organic chemicals such as DDT can resist decomposition in the environment which known as 'persistent organic pollutants' (Vega et al., 2007). Herbicides such as glyphosate (trade name 'round up') are commonly used to make the weed free field before a crop is planted, this chemical could be carcenogenic for humans and wildlife (Bai and Ogbourne, 2016).

3.3 Radionuclide

High concentrations of radionuclides may naturally occur in soil or they can build up due to anthropogenic activities such as uncontrolled disposal of medical and nuclear wastes. These radioactive compounds can cause fatal diseases such as cancer and leukemia (Mittal et al., 2018) to human due to direct exposure or by entering in the food chain. The Chernobyl Nuclear Power Plant (April 26, 1986) and Fukushima Daiichi Nuclear Power Plant (March 11, 2011) accidents are the good examples of radionuclides' impacts on human health (Steffan et al., 2017). In Chernobyl, ^{137}Cs contamination of farm products occurs due to the concentration of the radionuclide in the soil since crops and cattle are raised on those soils (Takatsuji et al., 2000). Apart from nuclear plant disaster, Bhopal gas tragedy (2–3 December night, 1984) happened at the Union Carbide India Limited pesticide plant in Bhopal, India. Besides the human and animal death, there was a serious environmental impact. The heavy gas (methyl isocyanate) was absorbed into local rivers, making the water undrinkable and poisoning the fish.

3.4 Soil pathogens

The presence of human pathogens in the soil biological community can cause negative effects on human health. Bacteria are most abundant microbe in soil. Saprophytic soil fungi that absorb nutrients from decaying organisms can cause disease in humans

Table 1. Maximal permissible addition (MPA) of heavy metals and metalloids in soil (Crommentuijn et al., 1997; Vodyanitskii, 2016)

Metal/metalloid	MPA (mg kg^{-1})	Metal/metalloid	MPA (mg kg^{-1})
Beryllium (Be)	0.0061	Chromium (Cr)	3.8
Selenium (Se)	0.11	Arsenic (As)	4.5
Thallium (Tl)	0.25	Barium (Ba)	9.0
Antimony (Sb)	0.53	Zinc (Zn)	16
Cadmium (Cd)	0.76	Cobalt (Co)	24
Vanadium (V)	1.1	Tin (Sn)	34
Mercury (Hg)	1.9	Lead (Pb)	55
Nickel (Ni)	2.6	Molybdenum (Mo)	253
Copper (Cu)	3.5		

† MPA = Maximum permissible addition; Highly hazardous (MPA <1 mg kg^{-1}) : Be, Se, Tl, Sb & Cd; Moderately hazardous (MPA 1-10 kg^{-1}) : V, Hg, Ni, Cu, Cr, As & Ba; Low (MPA >10 mg kg^{-1}) : Zn, Co, Sn, Ce, Pb & Mo

Table 2. Soil pathogens and associated human diseases (Brevik et al., 2020)

Pathogen	Organism	Human disease	Transmission	Soil niche/carrier
Clostridium perfringens	Bacteria	Gas gangrene	Skin trauma	Permanent
Rhodococcus equi	Bacteria	Pneumonia	Inhalation or wound contamination	Incidental, livestock feces
Escherichia coli	Bacteria	Gastroenteritis	Ingestion	Incidental, cattle feces
Salmonella typhi	Bacteria	Typhoid fever	Ingestion, zoonotic	Incidental, chicken feces
Campylobacter jejuni	Bacteria	Dysentery	Ingestion	cattle/ poultry manure
Clostridium tetani	Bacteria	Tetanus	Ingestion, skin trauma	Permanent
Burkholderia pseudomallei	Bacteria	Melioidosis	Ingestion, skin trauma, inhalation	Permanent
Bacillus anthracis	Bacteria	Anthrax	Ingestion, skin trauma, inhalation	Periodic
Leptospira spp.	Bacterial	Leptospirosis	Ingestion, skin trauma	Incidental, urine of infected animals
Coxiella burnetii	Bacterial	Q Fever	Inhalation	Infected animals
Histoplasma capsulatum	Fungi	Histoplasmosis	Inhalation	Bird feces
Coccidioides immitis	Fungi	Coccidioidomycosis	Inhalation, skin trauma	Permanent
Exserohilum rostratum	Fungi	Fungal meningitis	Inhalation	Permanent
Taenia saginata	Parasite	Tapeworm	Ingestion	Transient
Hookworm	Parasite	Ancylostomiasis	Skin contact	Periodic
Ascaris lumbricoides	Parasite	Ascariasis (round worm)	Ingestion	Transient
Entamoeba histolytica	Protozoa	Amoebic dysentery	Ingestion	Incidental
Giardia intestinalis	Protozoa	Giardiasis	Ingestion	Transient
Toxoplasma gondii	Protozoan	Toxoplasmosis	Ingestion	Cat feces

(Bultman et al., 2013). Some soil protozoa cause human parasitic diseases such as diarrhea and amoebic dysentery (Brevik, 2013). Soil helminths (parasites) may inhabit the human intestines (Bultman et al., 2013). Although soil is not a natural reservoir for viruses, they can survive in soil and may cause hepatitis, polio and meningitis (Hamilton et al., 2007; Bultman et al., 2013). Pathogens often come into soil through contaminated water, human excreta, and municipal and hospital wastes (Loynachan, 2012). Good health education can save human health. For example, the use of footwear can protect the feet from contact with the soil and thus to prevent from podoconiosis (disease in feet, ankles and legs) (Price, 1984). A list of soil pathogens and associated human diseases is given in Table 2.

3.5 Direct exposure to human

Any soil particles adhering to the skin may be ingested; the young children are vulnerable to this situation (Binder et al., 1986; Davis et al., 1990). Foods are often contaminated with soil particles and being consumed without washing (Hallberg and Bjorn-Rasmussen, 1981). Soil dusts when inhaled are retained in the lungs and it causes respiratory problems e.g. asthma, bronchitis (Monteil, 2008; Wagner, 1980). Wind erosion of loose soils from tilled land, earthen roads and construction work sites spread dusts into the atmosphere. This erosion is more active in arid and semi-arid regions. Tetanus and hookworm diseases (e.g. *Ancylostoma duodenale* and *Necator americanus*) are likely to occur due to skin contact with soil (Waldron, 1985; Gilles and Ball, 1991).

3.6 Greenhouse gas emission

Soils act as sources and sinks for greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This corresponds to roughly 21% of the global soil C and N pools. Methane and nitrous oxide have global warming potentials of 21 and 310 times carbon dioxide, respectively. Agriculture practice is responsible for a significant portion of the greenhouse gases (GHGs). Cultivation of wetland rice causes N_2O and CH_4 emissions. The magnitude of these GHGs depends on agronomic management. High yielding varieties of rice tend to have substantially lower CH_4 emissions (Corton et al., 2000; van der Gon et al., 2002) owing to more efficient photosynthate use.

4 Conclusions

Soil has both positive and negative effects on human health. The most significant positive effect is that soils provide nutrients to the plants, and humans eat plant food and food products. Nevertheless, soils may produce detrimental effects on human health. Many soils may contain toxic heavy metals (e.g. Cd, As, Pb) which may enter into human body through plant food chain. Thus, proper care is needed for sustenance of healthy soils for providing sufficient, safe and nutritious food for the people. Soil quality has both direct and indirect effects on human health. There are increasing diverse and complex problems the soil and agricultural research would have to address which has food security and human health implications. Due attention is needed for sustainable and profitable soil management to minimize soil degradation and to obtain benefits for human health. To achieve the goal of long-term food and nutrition security, as well as human health sustainable research is needed to arrest and reverse soil degradation. We do not know fully about the complex interactions between soil and human health. Therefore, innovative research is needed in this area. For thorough understanding of the soil ecosystem and its links to agronomic production and broadly human health, participation of multidisciplinary team consisting of soil scientists, agronomists, chemists, public health experts and sociologists deserves attention.

Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this paper.

References

Abrahams P. 2002. Soils: their implications to human health. Science of The Total Environment 291:1–32. doi: 10.1016/s0048-9697(01)01102-0.

Achiba WB, Gabteni N, Lakhdar A, Laing GD, Verloo M, Jedidi N, Gallali T. 2009. Effects of 5-year application of municipal solid waste compost on the distribution and mobility of heavy metals in a tunisian calcareous soil. Agriculture, Ecosystems & Environment 130:156–163. doi: 10.1016/j.agee.2009.01.001.

Aelion CM. 2009. Soil contamination monitoring. In: Inyang HI, Daniels JL (Eds) Environmental Monitoring. Encyclopedia of Life Support Systems (EOLSS) Publishers, Oxford, England.

Akhtar-Schuster M, Stringer LC, Erlewein A, Metternicht G, Minelli S, Safriel U, Sommer S. 2017. Unpacking the concept of land degradation neutrality and addressing its operation through the rio conventions. Journal of Environmental Management 195:4–15. doi: 10.1016/j.jenvman.2016.09.044.

Albihn A. 2001. Recycling biowaste-human and animal health problems. Acta Veterinaria Scandinavica 95:69–75. doi: 10.1186/1751-0147-43-S1-S69.

Alloway BJ, Ayres DC. 1993. Chemical Principles of Environmental Pollution. Springer Netherlands. doi: 10.1007/978-94-011-2148-4.

Anonymous. 2018. Conference on Connections between Soil Health and Human Health. October 16-17, 2018. Silver Spring, Maryland USA. Accessed from https://soilhealthinstitute.org/humanhealthconference/ on 27 October 2020.

Bai SH, Ogbourne SM. 2016. Glyphosate: environmental contamination, toxicity and potential risks to human health via food contamination. Environmental Science and Pollution Research 23:18988–19001. doi: 10.1007/s11356-016-7425-3.

Binder S, Sokal D, Maughan D. 1986. Estimating soil ingestion: The use of tracer elements in estimating the amount of soil ingested by young children. Archives of Environmental Health: An International Journal 41:341–345. doi: 10.1080/00039896.1986.9935776.

Brevik EC. 2009. Soil health and productivity. In: Verheye W (Ed) Soils, Plant Growth and Crop Production. Encyclopedia of Life Support Systems (EOLSS) Publishers, Oxford, England.

Brevik EC. 2012. Soils and human health. In: Soils and Human Health. CRC Press. p. 29–56. doi: 10.1201/b13683-4.

Brevik EC. 2013. The potential impact of climate change on soil properties and processes and corresponding influence on food security. Agriculture 3:398–417. doi: 10.3390/agriculture3030398.

Brevik EC, Burgess LC. 2012. Soils and human health. CRC Press.

Brevik EC, Pereg L, Steffan JJ, Burgess LC. 2018. Soil ecosystem services and human health. Current Opinion in Environmental Science & Health 5:87–92. doi: 10.1016/j.coesh.2018.07.003.

Brevik EC, Slaughter L, Singh BR, Steffan JJ, Collier D, Barnhart P, Pereira P. 2020. Soil and human health: Current status and future needs. Air, Soil and Water Research 13:1178622120934441. doi: 10.1177/1178622120934441.

Bultman MW, Fisher FS, Pappagianis D. 2013. The ecology of soil-borne human pathogens. In: Essentials of Medical Geology. Springer. p. 477–504.

Burgess L. 2012. Organic pollutants in soil. In: Soils and Human Health. CRC Press. p. 83–106. doi: 10.1201/b13683-7.

Cakmak I. 2009. Biofortification of cereal grains with zinc by applying zinc fertilizers. Biozoom 1:2–7.

Combs GF. 2013. Geological impacts on nutrition. In: Essentials of medical geology. Springer. p. 179–194.

Corton TM, Bajita JB, Grospe FS, Pamplona RR, Asis CA, Wassmann R, Lantin RS, Buendia LV. 2000. Methane emission from irrigated and intensively managed rice fields in central luzon (philippines). In: Methane Emissions from Major Rice Ecosystems in Asia. Springer Netherlands. p. 37–53. doi: 10.1007/978-94-010-0898-3_4.

Crommentuijn T, Polder MD, Van de Plassche EJ. 1997. Maximum Permissible Concentrations and Negligible Concentrations for Metals, Taking Background Concentrations into Account. RIVM Report 601501001, Bilthoven, Netherlands.

Davis S, Waller P, Buschbom R, Ballou J, White P. 1990. Quantitative estimates of soil ingestion in normal children between the ages of 2 and 7 years: Population-based estimates using aluminum, silicon, and titanium as soil tracer elements. Archives of Environmental Health: An International Journal 45:112–122. doi: 10.1080/00039896.1990.9935935.

Dominati E, Patterson M, Mackay A. 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics 69:1858–1868. doi: 10.1016/j.ecolecon.2010.05.002.

Egamberdiyeva D. 2007. The effect of plant growth promoting bacteria on growth and nutrient uptake of maize in two different soils. Applied Soil Ecology 36:184–189. doi: 10.1016/j.apsoil.2007.02.005.

FAO. 2003. Trade Reforms and Food Security: Conceptualizing the Linkages. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2011. The state of the world?s land and water resources for food and agriculture (SOLAW) ?Managing systems at risk. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO and ITPS. 2015. Status of the World?s Soil Resources (SWSR) ? Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

Fergusson JE. 1990. The Heavy Elements: Chemistry, Environmental Impact, and Health Effects, 1st ed. Pergamon Press, Oxford, UK.

Friedrichsen CN, Daroub SH, Monroe MC, Stepp JR, Wani SP. 2018. Mental models of soil management for food security in peri-urban india. Urban Agriculture & Regional Food Systems 3:170002. doi: 10.2134/urbanag2017.08.0002.

Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, Arora P. 2018. Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Frontiers in Nutrition 5. doi: 10.3389/fnut.2018.00012.

Gilles HM, Ball PAJ. 1991. Hookworm Infections. Elsevier, Amsterdam, Netherlands.

Graham RD, Welch RM, Bouis HE. 2001. Addressing micronutrient malnutrition through enhancing the nutritional quality of staple foods: Principles, perspectives and knowledge gaps. In: Advances in Agronomy. Elsevier. p. 77–142. doi: 10.1016/s0065-2113(01)70004-1.

Hallberg L, Bjorn-Rasmussen E. 1981. Measurement of iron absorption from meals contaminated with iron. The American Journal of Clinical Nutrition 34:2808–2815. doi: 10.1093/ajcn/34.12.2808.

Hamilton AJ, Stagnitti F, Xiong X, Kreidl SL, Benke KK, Maher P. 2007. Wastewater irrigation: The state of play. Vadose Zone Journal 6:823–840. doi: 10.2136/vzj2007.0026.

Helmke M, Losco R. 2012. Soil's influence on water quality and human health. In: Soils and Human Health. CRC Press. p. 155–176. doi: 10.1201/b13683-10.

Henry BK, Murphy BW, Cowie AL. 2018. Sustainable Land Management for Environmental Benefits and Food Security: A synthesis report for the GEF. Accessed from https://www.researchgate.net/publication/330263580_Sustainable_Land_Management_for_Environmental_Benefits_and_Food_Security/citation/download on 27 October 2020.

Hu H, McCally M. 2002. Human Health and Heavy Metals Exposure In: Life Support: The Environment and Human Health Michael Mc. Cally. MIT press.

Hubert B, Rosegrant M, van Boekel MAJS, Ortiz R. 2010. The future of food: Scenarios for 2050. Crop Science 50:S–33–S–50. doi: 10.2135/cropsci2009.09.0530.

Jahiruddin M. 2018. Biofortification of zinc and iron in cereals by fertilizer use and variety selection. Project Completion Report (BAS-USDA PALS BAU-CR-10). Department of Soil Science, Bangladesh Agricultural University, Mymensingh, Bangladesh.

Jahiruddin M. 2020. Biofortification of food crops: a novel strategy for reducing micronutrient malnutrition. Fundamental and Applied Agriculture 5:133–146. doi: 10.5455/faa.96078.

Jahiruddin M, Xie Y, Ozaki A, Islam MR, Nguyen TV, Kurosawa K. 2017. Arsenic, cadmium, lead and chromium concentrations in irrigated and rainfed rice and their dietary intake implications. Australian Journal of Crop Science 11:806–812. doi: 10.21475/ajcs.17.11.07.pne408.

Jarup L. 2003. Hazards of heavy metal contamination. British Medical Bulletin 68:167–182. doi: 10.1093/bmb/ldg032.

Johnson C, Ge X, Green K, Liu X. 2000. Selenium distribution in the local environment of selected villages of the keshan disease belt, zhangjiakou district, hebei province, people's republic of china. Applied Geochemistry 15:385–401. doi: 10.1016/s0883-2927(99)00051-7.

Kabata-Pendias A, Pendias H. 1992. Trace Elements in Soils and Plants. 2nd Edition. CRC Press, Boca Raton.

Kemper KJ, Lal R. 2017. Pay dirt! human health depends on soil health. Complementary Therapies in Medicine 32:A1–A2. doi: 10.1016/j.ctim.2017.04.005.

Kirkby E. 2012. Introduction, definition and classification of nutrients. In: Marschner's Mineral Nutrition of Higher Plants. Elsevier. p. 3–5. doi: 10.1016/b978-0-12-384905-2.00001-7.

Lal R. 2009. Soil degradation as a reason for inadequate human nutrition. Food Security 1:45–57. doi: 10.1007/s12571-009-0009-z.

Leake JR, Adam-Bradford A, Rigby JE. 2009. Health benefits of 'grow your own' food in urban areas: implications for contaminated land risk assessment and risk management? Environmental Health 8:S6. doi: 10.1186/1476-069x-8-s1-s6.

Loynachan T. 2012. Human disease from introduced and resident soilborne pathogens. In: Soils and Human Health. CRC Press. p. 107–136. doi: 10.1201/b13683-8.

Martínez-Hidalgo P, Maymon M, Pule-Meulenberg F, Hirsch AM. 2019. Engineering root microbiomes for healthier crops and soils using beneficial, environmentally safe bacteria. Canadian Journal of Microbiology 65:91–104. doi: 10.1139/cjm-2018-0315.

Mills CF. 1996. Geochemical aspects of the aetiology of trace element related diseases. Geological Society, London, Special Publications 113:1–5. doi: 10.1144/gsl.sp.1996.113.01.01.

Mittal S, Rani A, Mehra R, Ramola RC. 2018. Estimation of natural radionuclides in the soil samples and its radiological impact on human health. Radiation Effects and Defects in Solids 173:673–682. doi: 10.1080/10420150.2018.1493482.

Monteil MA. 2008. Saharan dust clouds and human health in the english-speaking caribbean: what we know and don't know. Environmental Geochemistry and Health 30:339–343. doi: 10.1007/s10653-008-9162-0.

Nieder R, Benbi DK, Reichl FX. 2018. Soil Components and Human Health. Springer Netherlands. doi: 10.1007/978-94-024-1222-2.

Olson GW. 1981. Archaeology: lessons on future soil use. Journal of Soil and Water Conservation 36:261–264.

Pepper IL. 2013. The soil health-human health nexus. Critical Reviews in Environmental Science and Technology 43:2617–2652. doi: 10.1080/10643389.2012.694330.

Pimentel D, Burgess M. 2013. Soil erosion threatens food production. Agriculture 3:443–463. doi: 10.3390/agriculture3030443.

Plant J, Smith D, Smith B, Williams L. 2000. Environmental geochemistry at the global scale. Journal of the Geological Society 157:837–849. doi: 10.1144/jgs.157.4.837.

Poveda J, Hermosa R, Monte E, Nicolás C. 2019. Trichoderma harzianum favours the access of arbuscular mycorrhizal fungi to non-host brassicaceae roots and increases plant productivity. Scientific Reports 9. doi: 10.1038/s41598-019-48269-z.

Price EW. 1984. Pre-elephantiasic stage of endemic nonfilarial elephantiasis of lower legs: "podoconiosis". Tropical Doctor 14:115–119. doi: 10.1177/004947558401400306.

Reicosky D, Sauer T, Hatfield J. 2015. Challenging balance between productivity and environmental quality: Tillage impacts. In: Soil Management: Building a Stable Base for Agriculture. Soil Science Society of America. p. 13–37. doi: 10.2136/2011.soilmanagement.c2.

Romig DE, Garlynd MJ, Harris RF. 2015. Farmer-based assessment of soil quality: A soil health scorecard. In: SSSA Special Publications. Soil Science Society of America. p. 39–60. doi: 10.2136/sssaspecpub49.c3.

Rousseau GX, Silva PRDS, de Carvalho CJR. 2010. Earthworms, ants and other arthropods as soil health indicators in traditional and no-fire agro-ecosystems from eastern brazilian amazonia. Acta Zoologica Mexicana 26. doi: 10.21829/azm.2010.262882.

Sarkar A, Asaeda T, Wang Q, Kaneko Y, Rashid MH. 2017. Response of *Miscanthus sacchariflorus* to zinc stress mediated by arbuscular mycorrhizal fungi. Flora - Morphology, Distribution, Functional Ecology of Plants 234:60–68. doi: 10.1016/j.flora.2017.05.011.

Sarkar A, Asaeda T, Wang Q, Rashid MH. 2015a. Arbuscular mycorrhizal association for growth and nutrients assimilation of *Pharagmites japonica* and *Polygonum cuspidatum* plants growing on river bank soil. Communications in Soil Science and Plant Analysis 47:87–100. doi: 10.1080/00103624.2015.1108432.

Sarkar A, Asaeda T, Wang Q, Rashid MH. 2015b. Arbuscular mycorrhizal influences on growth, nutrient uptake, and use efficiency of *Miscanthus sacchariflorus* growing on nutrient-deficient river bank soil. Flora - Morphology, Distribution, Functional Ecology of Plants 212:46–54. doi: 10.1016/j.flora.2015.01.005.

Sarkar A, Asaeda T, Wang Q, Rashid MH. 2015c. Role of arbuscular mycorrhizal fungi on the performance of floodplain *Phragmites japonica* under nutrient stress condition. Chemistry and Ecology 31:402–415. doi: 10.1080/02757540.2015.1039527.

Sarkar A, Das RC, Rashid MH, Ali M, Islam MS, Asaeda T, Wang Q. 2015d. Biocontrol potentiality of isolated *Trichoderma* spp. against *Pestalozzia theae* saw. in tea. Acta Phytopathologica et Entomologica Hungarica 50:179–186. doi: 10.1556/038.50.2015.2.3.

Senesil GS, Baldassarre G, Senesi N, Radina B. 1999. Trace element inputs into soils by anthropogenic activities and implications for human health. Chemosphere 39:343–377. doi: 10.1016/s0045-6535(99)00115-0.

Shivay YS, Prasad R, Singh U. 2016. Micronutrient Fertilizers for Zinc and Iron Enrichment in Major Food Crops: A Practicable Strategy. In: Singh U., Praharaj C., Singh S., Singh N. (eds) Biofortification of Food Crops. Springer India, New Delhi, India. doi: 10.1007/978-81-322-2716-8_17.

Smith P, Lutfalla S, Riley WJ, Torn MS, Schmidt MWI, Soussana JF. 2017. The changing faces of soil organic matter research. European Journal of Soil Science 69:23–30. doi: 10.1111/ejss.12500.

Steffan JJ, Brevik EC, Burgess LC, Cerdà A. 2017. The effect of soil on human health: an overview. European Journal of Soil Science 69:159–171. doi: 10.1111/ejss.12451.

Takatsuji T, Sate H, Takada J, Endo S, Hoshi M, Sharifov VF, Veselkina II, Pilenko IV, Kalimullin WAF, Masyakin VB, Kovalev AI, Yoshikawa I, Okajima S. 2000. Relationship between the 137cs wholebody counting results and soil and food contamination in farms near chernobyl. Health Physics 78:86–89. doi: 10.1097/00004032-200001000-00014.

Talukder MR, Sarkar A, Rashid MH. 2019. The role of arbuscular mycorrhizal fungi in the bioprotection of ash gourd (*Benincasa hispida*) against damping off disease. Fundamental and Applied Agriculture 4:704–712. doi: 10.5455/faa.6098.

USDA. 2019. Natural Resources Conservation Service: Soil. U.S. Department of Agriculture.

van der Gon HACD, Kropff MJ, van Breemen N, Wassmann R, Lantin RS, Aduna E, Corton TM, van Laar HH. 2002. Optimizing grain yields reduces CH4 emissions from rice paddy fields. Proceedings of the National Academy of Sciences 99:12021–12024. doi: 10.1073/pnas.192276599.

Vega FA, Covelo EF, Andrade ML. 2007. Accidental organochlorine pesticide contamination of soil in porriño, spain. Journal of Environmental Quality 36:272–279. doi: 10.2134/jeq2006.0053.

Vodyanitskii Y. 2016. Standards for the contents of heavy metals in soils of some states. Annals of Agrarian Science 14:257–263. doi: 10.1016/j.aasci.2016.08.011.

Wagner JC. 1980. The pneumoconioses due to mineral dusts. Journal of the Geological Society 137:537–545. doi: 10.1144/gsjgs.137.5.0537.

Waldron HA. 1985. Occupational health and the archaeologist. Occupational and Environmental Medicine 42:793–794. doi: 10.1136/oem.42.12.793.

Welch RM, Graham RD. 2004. Breeding for micronutrients in staple food crops from a human nutrition perspective. Journal of Experimental Botany 55:353–364. doi: 10.1093/jxb/erh064.

White PJ, Broadley MR. 2009. Biofortification of crops with seven mineral elements often lacking in human diets - iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytologist 182:49–84. doi: 10.1111/j.1469-8137.2008.02738.x.

WHO. 1996. Trace Elements in Human Nutrition and Health. World Health Organization, Geneva, Switzerland.

WHO. 2012. The World Health Report. World Health Organization, Geneva, Switzerland.

© 2020 by the author(s). This work is licensed under a Creative Commons. Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License

The Official Journal of the **Farm to Fork Foundation**
ISSN: 2518–2021 (print)
ISSN: 2415–4474 (electronic)
http://www.f2ffoundation.org/faa