Soil and Human Health: Current Status and Future Needs

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Soil and Human Health: Current Status and Future Needs

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ABSTRACT: Soil influences human health in a variety of ways, with human health being linked to the health of the soil. Historically, emphasis has been placed on the negative impacts that soils have on human health, including exposures to toxins and pathogenic organisms or the problems created by growing crops in nutrient-deficient soils. However, there are a number of positive ways that soils enhance human health, from food production and nutrient supply to the supply of medications and enhancement of the immune system. It is increasingly recognized that the soil is an ecosystem with a myriad of interconnected parts, each influencing the other, and when all necessary parts are present and functioning (ie, the soil is healthy), human health also benefits. Despite the advances that have been made, there are still many areas that need additional investigation. We do not have a good understanding of how chemical mixtures in the environment influence human health, and chemical mixtures in soil are the rule, not the exception. We also have sparse information on how most chemicals react within the chemically and biologically active soil ecosystem, and what those reactions mean for human health. There is a need to better integrate soil ecology and agronomic crop production with human health, food/nutrition science, and genetics to enhance bacterial and fungal sequencing capabilities, metagenomics, and the subsequent analysis and interpretation. While considerable work has focused on soil microbiology, the macroorganisms have received much less attention regarding links to human health and need considerable attention. Finally, there is a pressing need to effectively communicate soil and human health connections to our broader society, as people cannot act on information they do not have. Multidisciplinary teams of researchers, including scientists, social scientists, and others, will be essential to move all these issues forward.

KEYWORDS: Soil pollution, persistent organic pollutants, soil organisms, antibiotic resistance, nutrient supply, biofortification, science communication

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Introduction

In 1948, the World Health Organization (WHO)[1] adapted the definition of human health as "a state of complete physical, mental and social wellbeing, and not merely the absence of disease or infirmity." The US Department of Health and Human Services[2] recognizes that achieving this definition of human health is

> "determined in part by access to social and economic opportunities; the resources and supports available in our homes, neighborhoods, and communities; the quality of our schooling; the safety of our workplaces; the cleanliness of our water, food, and air; and the nature of our social interactions and relationships."

Likewise, the WHO[3,4] recognizes that inequities in the distribution of power, wealth, and resources at local, national, and global levels negatively impact the conditions in which people are born, grow, live, work, and age, resulting in significant health inequities around the globe. The importance of addressing these key social determinants of health (SDOH) is reflected by the fact that 1 of the 4 overarching goals of Healthy People 2020, the US federal government's prevention agenda and national health objectives, is to "create social and physical environments that promote good health for all."[2] Furthermore, given that approximately 60% of preventable deaths in the United States are linked to modifiable behaviors and/or community-based exposures,[5] the Centers for Medicare and Medicaid Services (CMS) is exploring direct payment for non-medical interventions that address SDOH.[6] An exemplar is North Carolina's Section 1115 Medicaid Waiver authorizing expenditure of US $650 million in Medicaid funding to address SDOH in up to 2% of Medicaid enrollees in the state.[7]

Healthy People 2020 identifies 5 key SDOH: (1) economic stability, (2) education, (3) social and community context, (4) health and health care, and (5) neighborhood and built environment. Within each of these 5 SDOH arenas are a number of key underlying factors, many of which arguably rely either

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directly or indirectly on soil health, which has been defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans."[8] For example, access to soils and the health of soils impacts employment, food insecurity, and poverty; all factors comprising the arena of economic stability. In the arena of neighborhood and build environment soil health impacts the underlying factors of access to foods that support healthy eating patterns, environmental conditions, and quality of housing as well as impacting air and water quality.[9]

The intersections between soil health and human health are myriad and, from a human health perspective, may best be viewed though a lens of what soils "do *for* us" vs what soils "do *to* us"[10] (Table 1). The most obvious thing that soils do for us is serve as the basis for most food production. However, less apparent to health care practitioners and the public at large are the other critical ecosystem services healthy soils provide for us, including carbon sequestration, detoxification, water and nutrient retention, and maintaining biodiversity.[11] Of particular importance are the ecosystem services that mitigate global climate (carbon sequestration, water retention). This is because global climate change poses a number of significant health challenges. These include more frequent, severe, and prolonged heat events, forest fires, erosion of outdoor air quality, flooding from rising sea level and worsening precipitation events, expansion of vector-borne diseases, and increases in food- and weather-related infections.[12] In fact, the WHO states that climate change is the greatest threat to global health in the 21st century.

Since antiquity, it has been recognized that certain properties of soils have negative effects on human health.[13,14] Hence, it should not be surprising that, rather than recognizing what soil health does for human health, a majority of health care and public health practitioners only consider what soils do to human health. This includes causing disease through exposures to soil-borne toxins such as arsenic, lead, cadmium, and other heavy metals; asbestos; or infectious agents such as viruses, enteric bacteria, fungi, and parasites. There are also diseases such as hypothyroidism/multinodular goiter, Keshan/Kashin Beck disease, or anemia that are associated with soil deficiencies in iodine, selenium, and iron, respectively.[15,16]

Many aspects of the relationship between soils and human health have been elucidated and well reviewed.[11,14,17-23] More holistic frameworks for both assessing and defining soil health that are rooted in ecological theory are emerging that will allow a more nuanced, complex, and complete understanding of how soils and human health are interconnected. In this article, we discuss why chemical pollution of soil, soil micro- and macroorganisms, and soil nutrient supply should be considered as key determinants of human health. We also identify key gaps in our understanding in these relationships that require future research and discuss strategies for effectively communicating the importance of soils to human health. Our ultimate goal is for soils to be "given their due"[24] as a social determinant of human health.

Soil Pollution and Human Health

Current status

The impacts of soil pollution on human health have been extensively studied, especially heavy metals in urban areas,[25,26] mining areas,[27-29] near industrial areas,[30-32] and areas affected by warfare activities.[33] Such studies have also been conducted in agricultural fields.[34-36]

Traditionally, most of the studies investigating soil chemistry impacts on human health were focused on heavy metals.[20,37] Several indices have been developed to assess the degree of soil contamination and its potential impact on human health such as contamination factor, geoaccumulation index, enrichment factor, contamination degree, sum of pollution index, single pollution index, ecological risk index, integrated pollution index, Nemerow pollution index, pollution load index, hazard index, dermal absorption factor, and aggregated carcinogenic risks. These indices aid in understanding the status of soil contamination and exposure risks for humans. For more details about these indices, please refer to the literature.[30,38-42] Although some metals are essential for plant growth (eg, copper, iron, zinc), their presence in high concentrations can induce toxicity for plants and expose the human population to disease problems. High concentrations of heavy metals in the body can affect several systems including the blood, liver, brain, kidneys, and lungs. Long-term exposure to even low levels of heavy metals can result in neurological and physical degenerative processes (eg, Parkinson disease and Alzheimer disease) and cancer.[43] The impacts of high concentrations of heavy metals on human health are well summarized in recent publications.[37,44-46]

Additional soil chemistry studies that have investigated human health links include the impacts of persistent organic pollutants (POPs) (Table 2) and radionuclides on human health. In the United States, Grindler et al[47] observed a high positive association between the concentration of POPs in urine and early age menopause. High concentrations of polychlorinated biphenyls (PCBs) affect fetal growth and childbirth weight. Other POPs such as dichlorodiphenyltrichloroethane (DDT), dichlorodiphenyldichloroethylene (DDE), and hexachlorobenzene (HCB) affect childbirth weight as well.[48] POPs are also considered endocrine disruptors.[49] POPs can accumulate in soils because they were used as pesticides (see the numerous pesticides listed in Table 2) and deliberately applied to the environment, but non-pesticide POPs have also been added to the environment through both deliberate and accidental means.[50]

Pesticides used in agricultural fields are associated with an increased risk of developing several chronic diseases such as diabetes, cancer, and asthma, as well as a variety of short-term problems (eg, dizziness, nausea, skin and eye irritation, and headaches).[51] It is estimated that 25 million agricultural workers per year are affected by pesticide poisoning.[52] Associated health problems are not limited to pesticides used on animals. Herbicides are also recognized to have negative impacts on

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Table 1. Select properties of soil or soil components that may act directly and/or indirectly as determinants of human health.

	DIRECT EFFECTS	INDIRECT EFFECTS
What soils “Do for us” (positive)	1. Deliberate ingestion of soil (geophagia), particularly clays, is hypothesized to compensate for mineral deficiencies and/or detoxify via absorption of dietary toxins in the gut[14] 2. Provide substrate/structure on which most humans live	1. Provide a myriad of key ecosystem services (ES)[290] A. *Provisioning services* (“products that soil ES make available for human use””) *Food and fiber production*—soils support the production of a majority of the earth’s supply of food and fiber *Building materials*—sand for cement and fill, clay for bricks, wood for building *Biorepository*—source of antibiotic-producing organisms B. *Regulating Services* (mediation/moderation of environment in ways that affect health, safety, comfort) *Climate regulation*—modulation via cycling of key greenhouse gases including carbon dioxide, methane, and nitrous oxide *Water regulation*—storm water mitigation via retention, surface, and ground water purification *Bioremediation*—decontamination of toxic waste and/or pathogens via soil microbiota C. *Cultural Services* (“non-material, and normally non-rival and non-consumptive outputs [*sic*] that affect the physical and mental states of people”) *Aesthetic and recreational*—promotes health and well-being through supporting aesthetically pleasing environments and recreational opportunities
What soils “Do to us” (negative effects) Natural vs Anthropogenic	1. Disease/health effects due to direct exposure to soils or soil components primarily via: A. *Ingestion* *Gastroenteritis*—diarrheal disease caused by ingestion of small quantities of soil contaminated with enteric bacterial pathogens (*Campylobacter, Escherichia coli, Shigella* spp.) or viruses (Norwalk virus) or protozoans (*Cryptosporidium parvum*) *Helminthiasis*—parasitic intestinal infection caused by ingestion of soil containing *Ascaris* or whipworm eggs *Element toxicity*—ingestion of naturally contaminated soils or soils contaminated by anthropogenic activities may cause toxicity most notably due to lead, arsenic, cadmium, and nitrate *Xenobiotic exposure*—xenobiotics are synthetic chemicals, typically carbon based, often characterized by long environmental half-lives, and increasing recognized as having endocrine disrupting effects at very low concentrations. Exposure may cause cancer, obesity/metabolic disease, reproductive, developmental, and cognitive anomalies B. *Inhalation* *Coccidioidomycosis*—pulmonary infection AKA valley fever due to inhalation of dust-borne fungal spores *Mesothelioma*—cancer of lining of the lung caused by inhalation of soil dust containing asbestos *Silicosis*—pulmonary fibrosis caused by inhalation of silica crystals *Lung cancer*—inhalation of radon that naturally occurs in soils and accumulates in basements/underground structures C. *Dermal absorption/penetration* *Podoconiosis*—chronic debilitating non-filarial elephantiasis of lower extremities due to penetration of skin by fine volcanic soils with resultant chronic inflammation. 1 to 2 million people affected *Tetanus*—paralysis caused by wound contamination with soil containing *Clostridium tetani* spores *Helminthiasis*—parasitic intestinal infection caused by penetration of skin by hookworm larvae in soil	1. Disease/health effects due to soil deficiencies A. *Inherent poor soil fertility*—may result in food insecurity with resultant protein-energy malnutrition, growth stunting, immunocompromised ion and death B. *Micronutrient/trace element deficiencies* *Iodine*—deficiency causes congenital anomalies, mental retardation, hypothyroidism, and goiter. Remerging as a problem in Europe. 740 million people currently affected. 2 billion people at risk *Iron*—deficiency results in anemia, fatigue, cognitive impairment, and impaired immunity. 1 to 2 billion people at risk *Selenium*—deficiency associated with low glutathione peroxidase levels, impaired antioxidant and redox status, pseudoalbinism, and Keshan disease. 0.5 to 1.0 billion people at risk *Zinc*—deficiency impairs wound healing and immunity

Source: Table based on Oliver,[299] Oliver and Gregory,[14] Brevik et al,[290] and Steffan et al.[56]

human health, such as glyphosate which is considered carcinogenic for humans and wildlife.[53,54]

Radionuclides can exist in soil naturally or as a consequence of anthropogenic activities (eg, medical and nuclear waste), and they are correlated with diseases such as cancer and leukemia.[55] The Chernobyl (April 26, 1986) and, more recently, Fukushima (March 11, 2011) accidents brought to light the importance of radionuclides’ impacts on human health.[56] With Chernobyl, ^{137}Cs contamination of farm products was related to the concentration of the radionuclide in the

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Table 2. Persistent organic pollutants identified by the Stockholm Convention (SC).

CHEMICAL	YEAR ADDED	SOURCE	ANNEX IN SC	ADDITIONAL NOTES
Aldrin	2001	P	A	
Chlordane	2001	P	A	
Dichlorodiphenyltrichloroethane (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, UP	A & C	
Mirex	2001	P	A	
Toxaphene	2001	P	A	
Polychlorinated biphenyls (PCB)	2001	IC, UP	A & C	Has specific exemptions under Annex A
Polychlorinated dibenzo-p-dioxins (PCDD)	2001	UP	C	
Polychlorinated dibenzofurans (PCDF)	2001	UP	C	
Alpha hexachlorocyclohexane	2009	P	A	No exceptions or acceptable uses
Beta hexachlorocyclohexane	2009	P	A	No exceptions or acceptable uses
Chlordecone	2009	P	A	No exceptions or acceptable uses
Hexabromobiphenyl	2009	IC	A	No exceptions or acceptable uses
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, UP	A & C	No exceptions or acceptable uses
Perfluorooctane sulfonic acid, its salts, and perfluorooctane sulfonyl fluoride	2009	IC	A & B	Acceptable purposes and specific exemptions in accordance with Part III of Annex B, amended 2019
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, UP	A & C	No exceptions or acceptable uses, added to annex C in 2017
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, UP	A & C	Can be used for production of polyfluorinated naphthalenes, including octafluoronaphthalene
Decabromodiphenyl ether	2017	IC	A	Exemptions for certain uses in vehicles, aircraft, textiles, additives in plastic housings, etc, polyurethane foam for building insulation

(Continued)

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Table 2. (Continued)

CHEMICAL	YEAR ADDED	SOURCE	ANNEX IN SC	ADDITIONAL NOTES
Short-chain chlorinated paraffins	2017	IC	A	Allowed as additives in transmission belts, rubber conveyor belts, leather, lubricant additives, tubes for outdoor decoration bulbs, paints, adhesives, metal processing, plasticizers
Dicofol	2019	P	A	No exceptions or acceptable uses

Source: Table based on Stockholm Convention[300,301] (modified from Steffan et al[56]).
Abbreviations: IC, industrial chemicals; P, pesticide; POP, persistent organic pollutants; UP, unintentional production/by-products.
Some POPs can still be used for specific purposes as outlined in the SC.

soil through the consumption of crops and cattle raised on those soils.[57] A recent study carried out by Komissarova and Paramonova[58] in an area affected by the Chernobyl accident found that some areas still exceeded the ^{137}Cs safety standard by 3.5 to 6 times in 2017. Despite this high concentration, the transfer of this radionuclide to crops and forages was limited. After the Fukushima accident, it was estimated that Japanese soils were highly contaminated with ^{137}Cs, which will affect agricultural products and human health for decades.[59]

Chemicals released by warfare activities also increase soil pollution. Apart from heavy metals and radionuclides, other toxic elements are released into the soil such as energetic materials, nitroaromatic explosives, organophosphorus nerve agents, and oil products.[33,60] Energetic materials, nitroaromatic explosive, and organophosphorus nerve agents are among the deadliest warfare-related materials identified in soils.[61,62]

Humans can be exposed to soil chemicals, pathogens, and minerals by respiration, skin absorption or penetration, and ingestion.[56] Several indices have been developed to assess the impact of contaminated soil on cancer through ingestion, inhalation, and dermal contact.[63] The inhalation of soil particles occurs as a consequence of dust transport by wind. Dust transport has been recognized to have an impact on diseases such as pulmonary fibrosis, chronic obstructive pulmonary disease, sarcoidosis, and asthma. This especially affects people with weak or compromised immune systems, such as children, older people, and people already suffering from cardiopulmonary chronic diseases.[64] It has been reported that chemicals are transported with dust particles (eg, arsenic), increasing human health risks.[65,66] Dust events are particularly common in arid and semi-arid areas. However, the expansion of human activities (eg, road development, urban sprawl, agriculture, mining) in other climates is increasing the number of dust events in temperate continental,[67] tropical monsoon,[68] subtropical monsoon,[69] continental monsoon,[70] and temperate oceanic[71] climates. Previous works showed that skin contact with soils with a high level of heavy metals might cause skin diseases[27] such as itching[72] and rashes.[73] Ingestion of contaminated soil particles can increase levels of heavy metals in the blood.[74] Plants can uptake a large number of heavy metals, quickly passing them up the food chain.[75] This problem has been reported in areas irrigated with wastewater,[76] and in farms and gardens located close to cities, industrial, and mining areas. Although the impact of heavy metals on human health through dermal contract is recognized, the risks seem to be higher through inhalation or ingestion.[26,36,77]

Urban agriculture has recently been encouraged as a way to contribute to increasing the quality and quantity of soil-related ecosystem services.[78,79] It is estimated that the global impacts of urban agriculture could provide ecosystem services that are valued at between US $80 and US $160 billion annually.[80] Urban agriculture also has positive impacts on food security,[81] poverty alleviation,[82] community development, and social justice[83]; reduces energy demand and carbon footprint[84]; increases the resilience of urban communities[85]; creates jobs[86]; and increases the local economy and education.[87] All of these can have a positive impact on human health. Urban agriculture has the ability to make an important contribution to sustainable development and the achievement of the United Nations Sustainable development goals (eg, no poverty, zero hunger, sustainable cities and communities, climate action, life on land).[88,89]

There are a large number of works focused on mapping soil heavy metal contamination in urban, industrial,[40,90,91] and agricultural areas,[92,93] as well as at the continental scale.[94] New methods such as proximal and remote sensing techniques have recently been applied to map heavy metals in soils.[95-97] These techniques represent a substantial advance in mapping, mainly because more sample points can be processed in a reduced amount of time than with more conventional methods. The identification of spatial patterns is crucial to understand the sources of pollution, the factors that govern soil pollution distribution, and the population exposed to soil contamination. Therefore, appropriate mapping is critical to mitigate the impacts of soil pollution on human health.[98] Several maps of soil radionuclides in areas affected by the Chernobyl accident and monitoring people's exposure to associated radionuclides have been created.[99-101] A similar effort was carried out in Japan after Fukushima.[102] Some works have combined the mapping of heavy metals and radioactivity.[103]

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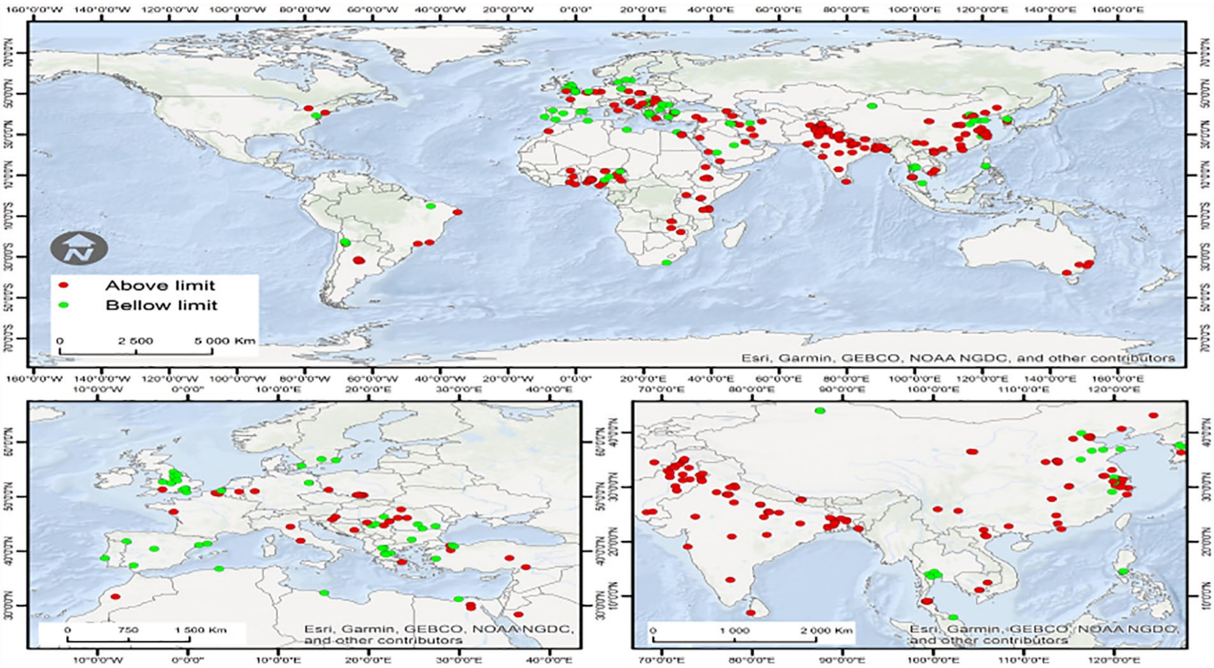

Figure 1. Studies in urban and peri-urban areas that investigated the concentration of heavy metals in fruits and vegetables. Red dots show sites where at least one chemical element had a concentration above the guidelines provided by FAO/WHO, the European Union, or national legislation. Green dots show sites where none of the chemical elements had a concentration above FAO/WHO, European Union, or national legislation levels. The criteria for selection of the studies used to create this map are given in Supplementary Materials 1 and 2. FAO indicates Food and Agriculture Organization of the United Nations; WHO, World Health Organization.

Future needs in soil pollution and human health

The relationship between soil pollution through various chemicals and human health is well established, as highlighted in the previous section. This includes exposure to heavy metals, radionuclides, and organic chemicals. Knowing that these issues represent a problem in our modern world, it is important to look to the future and anticipate ways these problems may change, including potential intensification.

Dust transports pollutants over long distances. Dust storms are expected to increase as a consequence of climate and land-use change (eg, urbanization, agriculture intensification, and desertification). Therefore, it is very likely that related problems will also increase.[64,104] Some work has been conducted to identify sources and the type of material being transported and link this to human health.[105-107] However, more research is needed to forecast these events and find ways to minimize their impacts on human health, such as the use of nature-based solutions. Most of the works carried out have been focused on heavy metals pollution, but research into plastics, pesticides, and related organic chemicals increased exponentially in recent years and the number of chemical elements in soil that are known to be harmful to human health has increased.[108-110] It is vital to understand the spatial distribution of soil microplastics, pesticides, etc, to identify areas where soil conditions threaten human health. In addition, it is crucial to identify critical thresholds of these elements in the soil that can be considered harmful for human health.[111] Most of the work that has been conducted to date focuses on individual pollutants, but these pollutants interact with both other chemicals and the broader complex soil environment. It is critical that we find ways to determine the threat posed by chemical mixtures and by the interactions these mixtures undergo in soil.[50]

Despite the importance of urban agriculture, several works have highlighted that the food produced in urban areas might have high heavy metal content.[112] This is a pivotal issue that needs to be addressed to ensure the health of those who consume food produced in the urban environment.[113] The use of brownfields for gardening and wastewater for irrigation can pose serious problems related to contamination of the vegetables produced in these areas.[114,115] Some urban areas studies have shown the levels of pollutant accumulation in vegetables did not threaten human health, such as Barcelona, Spain[113,116]; Sevilla, Spain[117]; Lisbon, Portugal[118]; Madrid, Spain[119]; Sheffield, UK[120]; and Braganca, Portugal.[121] However, in other cities, the pollutant levels identified were high and threatened human health, including Rio de Janeiro, Brazil[122]; Daejeon, South Korea[123]; Rome, Italy[124]; Melbourne, Australia[125]; Dera Ismail Khan, Pakistan[126]; and Ghaziabad, India.[127] Figure 1 shows study sites where the heavy metal content in fruits and vegetables were analyzed in peri-urban and urban areas. In 74% of the cases, at least one of the metals studied was above the acceptable limits defined by FAO/WHO,[128] European Union,[129] or national legislation. The most pressing concerns regarding heavy metal contamination of fruits and vegetables were observed in India, Pakistan, and China. According to the studies screened in Supplementary Material 1, this was attributed to soil contamination through the use of untreated

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wastewater or the location of the farms near pollutant sources (eg, roads, power plants). Also, the usage of wastewater for irrigation is increasing the accumulation of emergent pollutants (eg, pharmaceuticals) in soils and plants.[130,131] Therefore, it is important that future research in urban food production include robust analysis of both the positive and potential negative human health impacts of such production.

Soil maps can be important tools in understanding the links between soils and human health.[132] The quality of our maps depends on the sampling design used to gather information, methods used, the models used to project point data across a 2- or 3-dimensional mapping product, and the skill and training of those who create the maps.[98,133-135] Therefore, additional research is needed to investigate best soil mapping practices including data collection, analysis, manipulation, and display.[136]

Soil Microorganisms and Human Health

Current status

Human pathogens in soil. Soil serves as a reservoir for a large number of human pathogens and their associated vectors.[24] Soil-borne pathogens can be classified into 4 distinct but not mutually exclusive groups: (1) permanent, those organisms which can complete their entire life cycle in the soil; (2) periodic, those organisms that complete part of their life cycle in the soil or occur naturally in the soil; (3) transient, those organisms that are found naturally in the soil, but don't require the soil for their life cycle; and (4) incidental, those organisms that are not naturally found in the soil, but can survive when introduced into the soil.[137] Pathogens are often introduced into soil via contact with contaminated water, animal or human excrement,[138] or municipal and clinical wastes.[139] Moreover, soil and climatic conditions play a large role in the accumulation and abundance of pathogens in the soil, which affects the infectivity potential. These environmental conditions have been reviewed recently[24,140] and are not further covered in this review; however, Table 3 contains examples of human diseases and associated pathogen(s) found in soil.

Antibiotic resistance and antibiotic products. Since the discovery of penicillin in 1928, the use of antibiotics to treat animal and human bacterial diseases has saved millions of lives.[141] However, it has also led to the emergence of antibiotic-resistant pathogens which have reduced or eliminated the effectiveness of many antibiotics.[142] A rapid increase in the prevalence of antibiotic-resistant bacteria (ARB) in various environments has been documented.[143,144] Resistance to an antibiotic develops via several mechanisms including (but not limited to) the activation of antibiotic transporters (efflux pumps), the production of enzymes to inactivate antibiotics, and modification of the target (active) site of the antibiotic.[145] These mechanisms occur via either spontaneous mutations, through the acquisition of antibiotic resistance genes (ARGs) from other bacteria through horizontal gene transfer (HGT),[146] or through infection via bacteriophages.[147] Often the pathogens acquire multi-drug resistance which complicates treatment and leads to poor patient prognosis.[148]

In terms of antibiotic production, soil-dwelling organisms, namely bacteria, fungi, and actinomycetes, have sourced most of the naturally occurring antibiotics used in human and veterinary medicine.[149] These organisms naturally produce antibiotics to aid in competition during times of ecological stress. It has been suggested that increased ecological stress may lead to an increase in antibiotic-like compound production in soil bacteria,[150] so perhaps it may be that with increased stress on soils worldwide (due to climate change, population growth, ecological devastation, unsustainable management practices, among others) and with new soil organism isolation methods,[151] new antibiotics will be found at a more rapid rate. Alternatively, increased stress on soils worldwide may eliminate microbial species which harbor undiscovered antibiotics.[152] Either way, the rate of antibiotic discovery will still be much slower than the emergence of antibiotic resistance.[153] This is due to the fact that the soil environment contains a large number of ARB and ARGs.[154] The application of antibiotic-laden wastewater, animal manure, and/or night soil to enhance soil fertility often contributes to the increased abundance of ARGs and ARB in soil.[155,156] Genes conferring resistance to the antibiotics tetracycline, fluoroquinolones, and sulfonamides are common in soil amended with animal manure.[157-160]

Worldwide antibiotic use is expected to increase 67% from 2010 to 2030 due to an increase in global demand for food animal production[161,162]; thus, a concomitant increase in antibiotic-laden water and manure is likely. To help offset this expected increase, the Food and Drug Administration in the United States has implemented increased animal drug regulations (known as the Veterinary Feed Directive) to limit the usage of antibiotics administered in feed and drinking water to animals by requiring a prescription from a licensed veterinarian.[163] These new regulations became effective October 1, 2015, to encourage the appropriate use of and avoid unnecessary administration of antibiotics to decrease the threat of antibiotic resistance development. Moreover, the regulations are thought to ensure the availability of antibiotics when needed to timely treat, control, or prevent animal disease. Moreover, antibiotic exposure risk is of increasing concern worldwide with several mitigation strategies being sought, including but not limited to increased wastewater management and governmental take-back programs.[164]

Antibacterial properties of clays. It is not solely soil microbiota that play a role in providing medicines for humans. A number of clay-rich soils throughout the world have been shown to have antibacterial action independent of their biological component. The healing properties of clay-rich soils have been documented for thousands of years[165,166] and used topically or ingested.[167,168] The scientific basis for some of the antibacterial action has been

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Table 3. Examples of human pathogens found in soil and associated diseases.

PATHOGEN(S)	TYPE OF ORGANISM	MEDICAL CONDITION	TRANSMISSION	SOIL NICHE/CARRIER	KNOWN DISTRIBUTION
Clostridium perfringens	Bacterial	Gas gangrene	Skin trauma	Permanent	Worldwide
Streptomyces spp.	Bacterial	Skin infection	Skin trauma	Permanent	Worldwide
Chlamydophila psittaci; Chlamydophila trachomatis	Bacterial	Ornithosis or psittacosis	Contact inhalation	Bird fecal/nasal discharge; placentas and placental fluid of infected animals	Worldwide
Legionella spp.	Bacterial	Legionnaires' disease	Aerosol droplets	Incidental; soil amoebae	Worldwide
Rhodococcus equi	Bacterial	Pneumonia	Inhalation or wound contamination	Incidental; livestock feces	Worldwide
Escherichia coli O157:H7	Bacterial	Gastroenteritis	Ingestion	Incidental; cattle feces	Worldwide
Salmonella spp., *Salmonella typhi*	Bacterial	Salmonellosis; typhoid fever	Ingestion; zoonotic	Incidental; chicken feces; shed by reptiles	Worldwide
Bacillus cereus	Bacterial	Mild gastroenteritis	Ingestion	Incidental; fresh vegetables	Worldwide
Campylobacter jejuni	Bacterial	Mild enteritis to severe dysentery	Ingestion	Incidental; cattle and poultry manure	Worldwide
Shigella spp.	Bacterial	Shigellosis	Ingestion	Incidental	Worldwide
Yersinia enterocolitica	Bacterial	Yersiniosis	Ingestion	Incidental	Worldwide
Clostridium botulinum	Bacterial	Botulism	Ingestion; skin trauma	Permanent	Worldwide
Clostridium tetani	Bacterial	Tetanus	Ingestion; skin trauma	Permanent	Worldwide
Mycobacterium leprae	Bacterial	Hansen disease (Leprosy)	Unknown; person-to-person	Permanent	Tropics; endemic pockets
Burkholderia pseudomallei	Bacterial	Melioidosis	Ingestion; skin trauma; inhalation	Permanent	Worldwide
Pseudomonas aeruginosa	Bacterial	*Pseudomonas aeruginosa* infection	Skin trauma; opportunistic	Permanent	Worldwide
Bacillus anthracis	Bacterial	Anthrax	Ingestion; skin trauma; inhalation	Periodic	Worldwide
Rickettsia spp.	Bacterial	Rocky Mountain Spotted Fever	Tick vector	Periodic	Worldwide
Leptospira spp.	Bacterial	Leptospirosis	Ingestion; skin trauma	Incidental; urine of infected animals	Worldwide; higher incidence in tropics
Listeria monocytogenes	Bacterial	Listeriosis	Ingestion	Incidental	Worldwide
Coxiella burnetii	Bacterial	Q Fever	Inhalation; contact with infected animals	Incidental	Worldwide; excluding New Zealand
Francisella tularensis	Bacterial	Tularemia	Vector; skin trauma; contact with infected animals	Transient	Northern Hemisphere
Trichophyton, Microsporum, Epidermophyton spp.	Fungal	Ringworm; Tinea corporis	Skin trauma/ contact	Permanent	Worldwide
Sporothrix schenckii	Fungal	Sporotrichosis	Skin contact; inhaled spores	Transient	Americas, Europe, Africa

(Continued)

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Table 3. (Continued)

PATHOGEN(S)	TYPE OF ORGANISM	MEDICAL CONDITION	TRANSMISSION	SOIL NICHE/CARRIER	KNOWN DISTRIBUTION
Nocardia, Streptomyces, Madurella, and *Pseudoallescheria* spp.	Fungal	Subcutaneous swelling leading to skin rupture	Skin trauma	Permanent/transient	Mostly 30°N through 15°S latitude
Histoplasma capsulatum	Fungal	Histoplasmosis	Inhalation	Bat/bird feces	Americas, Africa, India, SE Asia
Coccidioides immitis	Fungal	Coccidioidomycosis	Inhalation; skin trauma	Permanent	Americas, Northern Mexico
Aspergillus fumigatus	Fungal	Aspergillosis	Inhalation	Permanent	Worldwide
Blastomyces dermatitidis	Fungal	Blastomycosis	Inhalation; skin trauma (rare)	Permanent	Americas and Africa
Exserohilum rostratum	Fungal	Fungal meningitis	Inhalation	Permanent	Worldwide; especially tropics
Trematode; Fluke; *Schistosoma* spp.	Parasite	Schistosomiasis	Ingestion	Periodic	Tropics
Cestodes; Taenia saginata; Tapeworm	Parasite	Tapeworm	Ingestion	Transient	Worldwide
Taenia solium; Tapeworm	Parasite	Taeniasis and cysticercosis	Ingestion	Transient	Worldwide
Hookworm	Parasite	Ancylostomiasis	Direct contact (burrow through skin)	Periodic	North Africa, Asia, Southern Europe, Americas, Australia
Roundworm; *Ascaris lumbricoides*	Parasite	*Ascariasis*	Ingestion	Transient	Worldwide
Roundworm; *Strongyloides stercoralis*	Parasite	Strongyloidiasis	Ingestion	Transient	Tropical/temperate regions
Enterobius vermicularis	Parasite	Pinworm; enterobiasis	Ingestion	Incidental	Temperate regions
Trichuris trichiura	Parasite	Whipworm; trichuriasis	Ingestion	Incidental	Worldwide
Toxocara canis	Parasite	Toxocariasis	Ingestion	Transient; dog feces	Worldwide
Entamoeba histolytica	Protozoan	Amebiasis; amoebic dysentery	Ingestion	Incidental	Worldwide
Giardia intestinalis	Protozoan	Giardiasis	Ingestion	Transient	Worldwide
Cryptosporidium parvum	Protozoan	Cryptosporidiosis	Ingestion	Transient	Worldwide
Cyclospora cayetanensis	Protozoan	Cyclosporiasis	Ingestion	Incidental	United States
Acanthamoeba spp.	Protozoan	Keratitis; granulomatous amoebic encephalitis	Skin trauma; eye	Incidental	Worldwide
Naegleria fowleri	Protozoan	Primary amoebic meningoencephalitis	Through nose (swimming)	Transient; warm freshwater and soil	Worldwide
Toxoplasma gondii	Protozoan	Toxoplasmosis	Ingestion	Transient; cat feces	Warm climates

Source: Table modified from: Pereg et al.[140] Additional references: Loynachan,[138] Brevik and Burgess,[302] Brevik,[205] Baumgardner,[18] Abrahams,[17] and Burtis et al.[303]

elucidated (reviewed in Williams[169]). However, most clay-rich soils have some antibacterial properties. It appears that the structure and type of clay and factors during its formation (ie, physical and chemical weathering) play a significant role.[170] Most antibacterial clays develop from hydrothermally altered volcanic material where reduced metals are concentrated in hydrothermal water. For example, French Green clay is a reduced iron-rich clay dominated by illite-smectite clays,

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formed from past volcanic activity in the Massif Central region in France.[171] A second example is a clay, owned and marketed by Oregon Mineral Technologies Inc. (OMT) as a healing clay, located in the Cascade Mountains of Oregon, USA. These OMT clays formed under somewhat similar conditions to the French Green clay. However, it is the presence of particular metals, their solubility, and other chemical characteristics that influence its antibacterial properties.[170,172]

Soil microbes and human immune systems. In addition to antibiotic properties and antimicrobial products found in soil, exposure to soil-borne microorganisms likely plays an important direct role in development and regulation of the human immune system. This is related to the concept of the microbiome-gut-brain axis, which emphasizes the role of gut microbiome composition and microbiome-driven signaling pathways in host immune system function and even human behavior.[173,174] Increased focus in medical research fields further explores the linkages between contact with the natural environment, including soils, and microbially driven immunoregulatory responses in humans that positively influence mental and physical well-being. This has been especially studied as it relates to allergy prevalence and is termed the "biodiversity hypothesis."[175,176] For example, early environmental exposure to allergy-causing microbial products such as endotoxins may promote allergen tolerance in children.[177] Chronic allergen exposure such as encountered in rural traditional farming communities can also provide greater protection against allergic diseases compared with communities with similar genetic backgrounds but more industrialized farming practices.[178] The specific contribution of diverse soil-borne microorganisms in host microbiome composition and immune system regulation is also receiving increased focus and helping to delineate the mechanisms by which soil microorganisms contribute to the effects described above. For example, a recent study using mice demonstrated that gut microbes acquired from soil increased anti-inflammatory capacity to T_H2-type inflammation responses compared with mice who received no soil contact.[179] Studies have also demonstrated that exposure to *Mycobacterium vaccae*, a common soil saprophyte, is involved both in immune system activation and in specific serotonergic pathways that influence emotional and behavioral response to stress using mouse models.[180,181] In humans, administration of a heat-killed *M vaccae* preparation has resulted in improved human response to chemotherapy, suggesting a potential role for soil-borne microbial products in immunotherapy.[182] These studies lend support to the idea that human contact with and exposure to soil microbial communities plays an important role in human health both from a developmental and therapeutic perspective and that the complexity and diversity of human and environmental microbiomes are inherently linked.[183]

Soil microorganisms and food systems, human nutrition. Along with their role in human immune system development and function, soil microorganisms have both direct and indirect effects on sustainability, quality, and security of food systems that subsequently influence human health and nutrition. Ensuring a sustainable, nutritious, and stable food supply for a growing world population depends on the interaction between multiple food system components ranging from production and distribution of food and fiber products to consumer and post-consumer practices. Although substantial gains can and should be made possible through genetic improvement of agronomic plants,[184] in this section we will focus on the contribution and influence of soil microorganisms. Specifically, we suggest that soil microbial communities and their functions are critical to human health outcomes of food systems. This occurs through impacts on plant yield and nutritional quality, increases in soil nutrient cycling and pathogen inhibition, and through their role in enhanced long-term ecosystem stability under future global change conditions.

Multiple studies have demonstrated that direct manipulation of plant root and soil microbial communities may be a promising strategy to increase food crop yield and nutritional quality through targeted deployment of beneficial plant-growth-promoting (PGP) bacterial or fungal inoculum on seeds or in soil.[185] For example, inoculating maize plants with PGP rhizobacteria *Pseudomonas alcaligenes, Bacillus polymyxa*, and *Mycobacterium phlei* significantly increased plant growth and nutrient uptake when soil nutrients were scarce.[186] A recent study by Fiorentino et al[187] found that inoculation of 2 lettuce species (*Lactuca sativa* and *Eruca sativa*) with *Trichoderma virens* or *Trichoderma harzianum* fungi increased yields and nutrient content, particularly N, when grown under low soil nutrient levels. *T harzianum* inoculation has also been shown to improve successful colonization of rapeseed (*Brassica napus*) roots by accompanying arbuscular mycorrhizal fungi (AMF), with additive improvements to the number of seed-pods produced per plant.[188] Co-inoculation of AMF and *Pseudomonas fluorescens* bacterium (PFB) with supplemental phosphorus (P) fertilizer increased micronutrient content and yield of the medicinal herb purple coneflower (*Echinacea purpurea*).[189] As a context-dependent plant mutualist that is most effective under P-limited conditions,[190] much research has focused on the potential beneficial effects of inoculating or encouraging colonization of AMF to improve crop production and nutritional quality.[191] For example, recent studies have demonstrated that inoculation or re-introduction of AMF species can increase yield and quality of crops such as tomato,[192] cucumber,[193] and tea plants.[194]

Non-nutritional benefits of PGP bacteria and fungi, such as influencing pathogen or herbivore interactions, and improving plant-soil properties, such as water relations and aggregate stability, are equally important to ensuring sustainable and high-quality food production. For example, a recent meta-analysis of literature focusing on AMF found that associated improvements to soil aggregation and stability, soil moisture dynamics, and pathogen resistance were as influential to plant fitness as

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nutrient uptake.[195] Targeted management of soil fungal and bacterial composition or inoculation is likely important for alleviating biotic stress (eg, disease or herbivory) or abiotic stress (eg, drought or nutrient scarcity), although literature outcomes are mixed.[196,197] Researchers are therefore still delineating the complex plant-microbe-soil interactions involved in manipulating soil microbial communities to optimize crop production and soil ecosystem functioning across a variety of environments and management systems. Multiple reviews have focused on the importance of soil microbial interactions, both with each other and with plants, and associated ecosystem functions to sustainable and high-quality food production.[198-201] Empirical studies have shown that soil microbial community composition and functioning are important drivers of ecosystem processes that promote plant growth and fitness such as nutrient cycling are critical for long-term sustainable plant production.[202,203] Effectively managing soil microbial communities for increased long-term sustainability and ecosystem resilience will be critical to ensure secure food systems and maintain or improve human health and well-being under future global change conditions.

Future needs in soil microorganisms and human health research

Multiple important intersections exist between soil microorganisms and human health. These range from pathogen presence and transmission, antibiotic products and antibiotic resistance, immunoregulatory compounds and signaling from soil-borne organisms, to soil microbial contributions to sustainable and nutritious agricultural products. Based on our discussion above, future research in soil microbial community and human health research should better integrate soil ecology and agronomic crop production with human health and nutritional sciences. For example, more research is needed to investigate the linkages between soil microbial community structure and function in agricultural and natural soils and human health outcomes such as disease and allergy characteristics alongside nutrition and economic well-being. Moreover, continued enhancements in bacterial and fungal sequencing, metagenomics, and the subsequent analysis (including enhanced reference genome databases) are needed to further our understanding of the intersections outlined above. Finally, a complete understanding of these intersections will require a vast array of interdisciplinary teams of scientists including, but not limited to, soil scientists, agronomist, botanists, biologists, microbiologists, ecologists, geneticists, immunologists, medical doctors, veterinarians, food scientists, and statisticians.

Soil Macroorganisms and Human Health

Current status

Biological diversity of soil ecosystems is fundamentally important for soil and human health. Soil macroorganisms are important in establishing soil health, and soil health has direct ties to human health[19,204]; therefore, soil macroorganisms are important to human health at least to the extent they are important to soil health. However, the complexities and associated quantification of that diversity provide many challenges.[205] The association between macroorganisms and productivity of the soil ecosystem is not well understood, though many studies acknowledge that these organisms are important for soil mixing, micropore formation, indicators of soil disturbances, microbial respiration and biomass, microbial community composition, and agro-economics.[205-208] Currently, most studies seek to examine the role and impact of earthworms, ants, mites, and other arthropods in agroecosystems.[209-213] As stated previously, quantifying the impact of soil macroorganisms has proved challenging and past research has typically circumvented these difficulties by using a bioindicator species, with earthworms fitting that role in many cases.[214-216]

Earthworms play roles in recycling organic material, increasing nutrient availability (by incorporating organic materials into the soil and unlocking nutrients held within dead animals and plant matter), improving soil structure with burrowing behaviors, and influencing the habitat and activities of other organisms. Although this information is treated as common knowledge among the academic soil community, only a fraction of earthworm species have been identified and regional variability in diversity and biomass are only now being investigated.[217] Some species of earthworm are drastically affected by heavy metal pollution. For example, *Aporrectodea caliginosa* are not found in soils with zinc levels more than 2000 ppm and even moderate levels resulted in approximately 50% decline in population size.[206] Other studies have shown that *A caliginosa* and *Lumbricus rubellus* can be used to develop a biota-to-soil accumulation factor as there is a direct relationship between the amount of heavy metal bioaccumulation and that found freely in the soil.[218] Ayuke et al[219] showed that fallowing and application of farm yard manure (FYM) in combination with fertilizer increased earthworm diversity and biomass in the top 15 cm of the soil. Earthworms are also known to bioaccumulate motor oil and heavier contamination levels produce inhibitory physiological responses in earthworms causing them to starve rather than eat contaminated soil.[220] These studies reinforce the logic for using earthworms as bioindicators of soil health.

Many other soil animals are fundamentally important in carbon and nutrient cycling. As a result, their abundance and diversity have been used to provide a key contribution to the overall assessment of soil health.[221] Soil disturbance by animals has long been seen as substantially important for shaping landscape ecology.[222] Soil disturbances by vertebrates have been shown to impact many ecological processes including pedogenesis, seed entrapment, plant germination and establishment, soil nutrient heterogeneity, water infiltration and storage, soil respiration, microbial activity, and litter decomposition.[223] Although these processes are required for ecosystem functioning, many smaller vertebrates are facing extinction. However, soil disturbance by animals also has several negative effects

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such as reducing structural stability, inverting the soil profile, and exposing the soil to higher wind and water erosion. Of course, these natural processes are also essential for the positive effects that were stated previously, such as soil formation and infiltration. In Australia, soil turnover rates caused by burrowing mammals vary between 0.1 and over 87 t/ha and native animals have much higher soil turnover rates than non-native species.[224] Although this finding was not statistically significant at $\alpha = 0.05$ ($P = .07$), it does provide insight into how natural systems have become established through evolutionary ecology and a disturbance to that ecological balance could have far-reaching consequences for soil health.

Small animals are responsible for mixing organic matter into the soil profile. This provides substrate for a wide range of soil biota including bacteria, fungi, actinomycetes, nematodes, algae, protozoa, and viruses.[225] Without these substrates, soil biota are dramatically reduced in abundance and diversity.[226] These processes may be very important in the drier areas of the world where soil crusts can form underneath plant litter. The utilization of these nutrients by mycorrhizal fungi provides the framework for plant ecology and is the driving force behind most terrestrial ecosystems,[225] including succession processes in disturbed or newly established environments. Thus, the metrics associated with soil fertility can be directly linked to the macro (and micro) organisms. Although these organisms obviously provide many direct and indirect impacts to soil health, most research has focused on only a handful or "bioindicator" species to examine these complex relationships. This examination of the literature is in no way exhaustive, but to our knowledge, represents the current state of information regarding the impacts of macroorganisms on soil health. Further research is needed to unravel the complexities of the interactions between macroorganisms and soil health and to identify new potential soil health bioindicators.

Future needs in soil macroorganisms and human health

Many of the studies examining the impact of macroorganisms on soil health do so with the use of a bioindicator species. However, most of the studies are attempting to answer complex and difficult ecological questions, which cannot be adequately represented by a single or even a few species, with an emphasis on agricultural or environmental stability. A major need for information regarding macroorganisms in soil health stems from 2 very important areas: (1) agricultural environments and (2) restoration and reclamation.[227] The answer to both of these problems requires the analysis of the resource to determine the level of degradation; however, in most cases, predegradation information is not available.[227] This includes species of invertebrates and vertebrates present in the system. Most studies examining the impact of soil health on agricultural production take place in small, localized areas.[228] Larger studies examining additional natural and native ecosystems are warranted to fully understand the impacts on the ecological system. These same conditions are true for disturbed natural areas in which restoration or reclamation is taking place. Most emphasis on soil health in the literature is orientated toward soil microorganisms. Future work should seek to examine the interconnectedness between soil micro- and macroorganisms in one of the most complex habitats on Earth, soil, in both predisturbance and post-disturbance instances.[229,230]

Thakur et al[231] documented the integration of soil biodiversity assays in relation to the amount of work done on different organisms in soil ecology (Table 4). This work highlights the emphasis placed on microorganisms and the little effort that has been placed on macroorganisms. Table 4 suggests that macroorganisms are often overlooked in soil ecological analysis and are underrepresented in the current literature. This also shows the relatively small geographic area covered by these studies; future work needs to focus on a more comprehensive understanding of how macroorganisms maintain and establish soil health over broad scales. Soil biodiversity (and bioindicator) research should aim to investigate the feedback mechanisms within the ecological setting. This would allow us to provide an integrated understanding of the complexity of these systems. The movement of soil organisms including dispersal needs to be assessed to understand soil biodiversity patterns.[232,233]

Understanding the life-history characteristics of an organism is fundamental to understanding its role in a natural setting. For many of the macroorganisms inhabiting the soil environment, little information is known about these basic life characteristics.[234] However, even less is known about how macroorganisms that are not typically considered as being part of the soil biosphere influence soil health. For instance, a literature search to examine the relationship between the presence of grazing ungulates (non-cattle) and the impact on soil will yield no results. Yet, we know that organisms such as those in *Cervidae* family interact with other organisms and processes both within and growing from the soil. They also provide nutrients for this environment but most research has focused on this aspect in terms of FYM (cattle deposition). Also, there has been no empirical examination of aerial macroorganisms impact to the soil environment. Recent work (computational) suggests that bat species provide ecological services of approximately US $3.7 billion/year in North America as the primary predators of agricultural pests.[235] This information suggests that bats occupy agricultural environments in high abundances and therefore must deposit guano during nightly flights. However, no research exists as to the impact or contribution of this high-quality fertilizer in agricultural settings. Also, many bird species migrate over the agricultural regions of North America yet no direct connection between those species and soil health exists. Likewise, there is no research on whether or not humans can be exposed to pathogens through these aerial droppings.

Many studies have examined the impact of pesticide use on microorganisms[236,237] yet the only species of macroorganisms

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Table 4. Number of studies providing support (Yes or No) for each of the 5 biodiversity theories. Support is also listed for the 4 categories of body size (microorganisms, microfauna, mesofauna, and macrofauna). The minimum and maximum grain and extent investigated for each theory are shown. The data presented in this table includes all cases (note that there is some overlap of studies between niche and neutral theories). Highlighted area indicates macroorganisms.

THEORY SUPPORT	SPECIES-ENERGY RELATIONSHIPS		ISLAND BIOGEOGRAPHY		METACOMMUNITY THEORY		NICHE		NEUTRAL	
	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
N	5	4	16	7	17	1	16	8	12	13
Microorganisms	4	3	7	0	6	1	8	8	9	7
Microfauna	0	0	1	2	1	0	0	0	1	0
Mesofauna	0	0	7	5	9	0	3	0	2	3
Macrofauna	2	0	1	0	1	0	5	0	0	3
Minimum extent	100 m	1 km	1 km	1 km	10 m	100 km	10 m	10 m	1 m	10 m
Maximum extent	1000 km	1000 km	100 km	100 km	100 km	100 km	Global	Global	Global	Global
Minimum grain	10 cm	10 cm	1 cm	1 cm	1 cm	10 cm	1 cm	10 cm	1 cm	1 cm
Maximum grain	10 m	10 cm	10 cm	10 cm	10 cm	10 cm	10 m	10 m	10 m	10 m

Table based on Thakur et al.[231] See Supplementary Material 1, S1, for a list of the studies included. N is the total number of cases.

to be extensively studied in contaminated soils are earthworms (see above). Contaminated/altered soils should be the focus of much of the future work on soil health. Without background knowledge about soil ecology, insights and interpretations of those findings will be limited in their application. The most relevant concept that comes from a literature review on this subject suggests that the role of macroorganisms might be more critical than previously thought (as judged by the lack of peer-review publications). Certain studies are beginning to shed light on this problem by examining the role burrowing macroorganisms have in establishing microbiota in the soil[225] but have since been abandoned. It is not clear why these efforts have been abandoned. Information gathered by examining the ecological diversity, establishment, stability, and dynamics are essential for a thorough understanding of the soil biosphere and, by extension, soil health.

Finally, there is a need to understand the direct links that exist between soil macroorganisms and human health. Rodents that live in soil burrows can be vectors for hantavirus,[238] and while considered rare, prairie dog-to-human transmission of *Francisella tularensis* (the plague) has been documented.[239] Both of the links noted here need additional study, and other such links undoubtedly exist, but research in this area has not been a priority.

Nutrient Supply From the Soil

Current status

Nutrient inputs to soils are essential for food production. While nutrients already present in the soil may initially be enough to sustain plant growth in fertile soils, constant nutrient removal through harvest of crop or animal products eventually necessitates the replacement of removed nutrients to sustain further production. This becomes even more important in highly weathered tropical soils with inherent low fertility. Although the supply of some nutrients, like nitrogen, seems to be endless (eg, atmospheric nitrogen, N), the finite nature of global resources of other nutrients, such as phosphorus (P), potassium (K), and zinc (Zn) is of concern.[240] Among the many roles of soils, nutrient storage and supply is one of the most important ones, which in turn supports the production of food and fiber. Thus, soils are vital to human health because they support both quantity and quality of food and feed production that is essential for animal and human consumption. During the past decades, intensification of agriculture in many regions has resulted in a decline in the content of organic matter in agricultural soils.[241] This in consequence has led to negative effects on the regulatory services of soil, air, and water quality.[242] Therefore, to sustain biomass production of higher nutritive quality and to avoid negative environmental impacts, fertile soils need to be preserved and to be restored where lost. The soil function "fertility" refers to the ability of soil to support and sustain plant growth by regulating nutrient supply. This is facilitated by (1) the storage of nutrients in soil organic matter, (2) nutrient recycling from organic to plant available forms, and (3) physical-chemical processes that control nutrient sorption, availability, and losses to the atmosphere and water.[241] Overall, the fertility and functioning of soils strongly depend on interaction between the soil mineral matrix, plants, and microbes; these are responsible for the preservation and availability of nutrients in soils.[243]

Intensification of agriculture through advances in agricultural technology and increasing food demand for an ever-growing population have put our soils under pressure, leading to nutrient depletion, physical degradation, and reduction in biodiversity. This jeopardizes their capacity and ability to meet

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the needs of future generations. This has also led to deficiencies of micronutrients in soils worldwide which in turn have adverse effects on animal and human health. Micronutrient deficiencies are currently identified as the main contributors to the global burden of diseases, as nearly half of the world's population suffers the insidious effects of micronutrient malnutrition.[244] More than 2 billion people suffer from one or more micronutrient deficiency diseases.[245] Worldwide more than 800 million people, mostly women and children, do not have access to food that meets their basic energy needs, and nearly one-third of these live in India.[246] As anticipated, deficiencies of micronutrients are highly prevalent in places where cereals with low nutritional quality are the main component of the diet.[247] There is an increasing awareness of the need to pay greater attention to the role of micronutrients in soil, plant, animal, and human nutrition. This would help explain the adverse effects of deficiencies and toxicities and avoid suboptimal concentrations that limit the attainment of optimum economical yield of crops along with productivity and welfare of animal and human well-being. In South Asia, where cereal-cereal rotations are prevalent and cereals are the staple food, incidence of micronutrients malnutrition is the highest and therefore these deficiencies have been noted as the top-priority public health issues that need to be addressed to achieve health security.[248]

Deficiencies of minerals essential for the health of animals and humans exist in many soils around the world, while other soils have accumulated toxic elements (eg, cadmium, Cd, and arsenic, As). The contamination of soil with these elements can result in phytotoxic effects as they enter the food chain[249] and in the deterioration of surface water and groundwater.[250] It is also important to mention that about 50% of the cereal-cultivated soils globally have low amounts of plant available Zn, indicating that there is an urgent need for enhancing concentrations of Zn and other micronutrients in cereal-based foods.[251] According to model studies, enrichment of cereal-based foods with Zn effectively saves the lives of about 50 000 children annually.[252]

Future needs in nutrient supply from the soil

An exponential rise in population between 1961 and 2000 increased the demand for food. The demand was met by a combination of scientific and technological advances, government policy, institutional intervention and business investment, innovation, and delivery. However, increased farm inputs and outputs were partly at the expense of detrimental effects on the environment.[253,254] In 2050, it is estimated there will be 9.7 billion people, and we will require about 70% more food available for human consumption than is consumed today.

Arable land is a finite resource; therefore, to meet the higher food demands of the future, we need intensification of food production. The agricultural areas where soils present numerous physical, chemical, and biological (low organic matter) constraints to plant growth present a big challenge. Meeting future food demands using finite and non-replaceable resources, without further environmental degradation, presents a major challenge. Hence, the best soil and fertilizer management practices will play an essential role in ensuring food security for the next generations.

A good example that comes from the most populous country in the world, China, illustrates this fact. China's population is predicted to peak at around 1.47 billion by the mid-2030s. The growing population together with anticipated economic expansion means the projected grain demand must increase by at least 50%.[255] To attain this goal, China must increase per hectare crop yields because significant expansion of arable land is unlikely.[255] One way to improve grain yield by 50% is to further boost fertilizer use (particularly N) from the current level of ~250 to 375 $\mathrm{kg\,N\,ha^{-1}}$,[256] assuming that a partial factor productivity for nitrogen (PFPN, defined as kg grain increase per kg N applied) of 26 $\mathrm{kg\,kg^{-1}}$ can be attained. This can theoretically be achieved because field experiments ($n = 43$) in China have demonstrated dramatic maize yield increases from 6.8 to 15.2 $\mathrm{Mg\,ha^{-1}}$ with high N input, averaging 747 $\mathrm{kg\,ha^{-1}}$.[257] However, this would exacerbate current problems including China's pollution and ecological degradation. Alternatively, crop yield may be improved through other management options. For example, improving soil quality and productivity by emphasizing organic inputs has resulted in relatively high yields in Chinese studies[258,259] and elsewhere (eg, Rothamsted, UK).[260]

Recent data from 66 on-farm trials across northern China suggested that it is possible to significantly increase yields and reduce our environmental footprint.[257] These experiments, using N rates (~237 $\mathrm{kg\,ha^{-1}}$) that are like current farming methods, produced an average of 13 Mg maize $\mathrm{ha^{-1}}$, compared with 6.8 $\mathrm{Mg\,ha^{-1}}$ in adjacent farmer's fields using current methods. The PFPN levels were 57 $\mathrm{kg\,kg^{-1}}$ in the experimental fields compared with 26 $\mathrm{kg\,kg^{-1}}$ for current farming methods. Management techniques employed in these large-scale projects, termed the integrated soil-crop system management (ISSM) approach, can be summarized into 4 principle aspects: (1) improving soil quality by recycling organic resources, (2) enhancing NUE accounting for various nutrient sources and matching nutrient supply with the dynamics of crop needs, (3) reducing the gap between potential yield and actual yield using superior varieties and improved cultivation, and (4) reducing N loss by cutting N loss pathways (Figure 2).

In addition to producing enough calories through intensification of agriculture as the example from China shows, we also need to enrich our food and feed crops with micronutrients to ensure adequate supply for human and animal health. Two approaches, ie, *genetic* or *agronomic biofortification*, have been proposed to increase the concentration of micronutrients, and especially of Zn, Fe, and Se, in food crops. Zn/Fe fertilization strategies positively influence the accumulation of these micronutrients in plant systems and offer the fastest way to achieve this without yield penalty.

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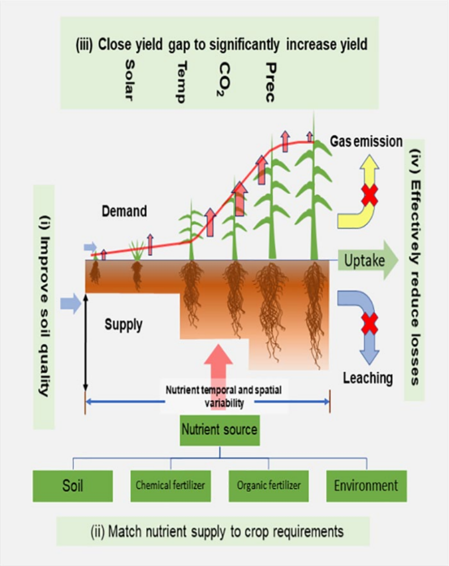

Figure 2. Conceptual frameworks for the integrated soil-crop system management (ISSM) approach. The key points of this strategy are presented in the text above.
Source: Adapted from Cui et al.[304]

Fertilizer application to food crops is essential both to increase food productivity and nutritional quality of food for human consumption. However, non-judicious and excessive fertilization can lead to contamination of soils, resulting in further contamination of surface and groundwaters. The contamination of soil with Cd and As can result in phytotoxic effects as they enter the food chain[249] and in the deterioration of surface water and groundwater.[250] Similarly, the contamination can also be caused by surface runoff and erosion of fertilizer nutrients like nitrogen and phosphorus. Numerous examples of ground water contamination by nitrogen (N) fertilizers are presented in the literature. For example, Lawniczak et al[261] found higher N concentrations in groundwater in the watersheds dominated by arable fields in comparison to forestry catchments and the highest N concentration was noted in the areas with a higher level of fertilizer application.

Genetic modification to produce plants with useful traits such as increased pest resistance, reduced post-harvest losses, increased yield, or enhanced content of desirable constituents is readily apparent.[262] The HarvestPlus, a Global Challenge Program of the Consultative (now Consortium) Group of International Agricultural Research (CGIAR), focuses on breeding for higher levels of Fe, Zn, and beta-carotene in the major staple crops in developing countries. However, genetic biofortification of food crops poses several challenges: (1) integration of the disciplines across their boundaries is difficult, (2) there should be no loss in yield, (3) the new grains need to be acceptable for consumption, and (4) certainty of improved nutrition.[263] Despite these challenges, biofortified food crop cultivation in developing countries in Asia and Africa, where micronutrient problems are widespread, provide a potential solution to solve the malnutrition problem.

Agronomic biofortification mainly refers to adequate fertilization using an appropriate method and time of application. This approach can be used to enrich genetically inefficient cultivars by application of micronutrient fertilizers at different rates, methods, and at different crop growth stages.[264] Agronomic biofortification may also be necessary for Zn, on soils with low Zn availability, which represent nearly half of the cereal growing areas of the world.[251]

Genetic breeding or genetic biofortification is a powerful tool and sustainable strategy, but a long-term process. In the context of nutrient supply, genetic breeding is thought of as a traditional breeding approach and not the genetically modified organisms (GMO) approach. Also, newly developed genotypes should be able to efficiently extract large amounts of nutrients from potentially deficient soils and accumulate nutrients in whole grain at sufficient levels for human consumption. Due to the large genotypic variation in Zn deficiency among crops,[251] there is need for targeted selection and breeding of plants with greater efficiency, both in terms of higher grain yield and grain Zn concentration.

The physiological basis for micronutrient efficiency in crop plants plays a major role in controlling the accumulation of micronutrients in edible portions of seeds. It has also been reported that nipping practice enhanced Fe concentration both in efficient and inefficient cultivars of chickpea and pigeon pea grown in India.[265] The grain Fe concentration increased by 17% and 5% in efficient cultivars after nipping and defoliation, while in inefficient cultivars, the increase was 10% and 12%, respectively.[266]

Communicating the Soil-Human Health Connection

The need for communication with the public

All of our knowledge goes unused if people are not aware of it. As scientists we spend a lot of time communicating with each other, but are not always so effective at communicating outside the scientific sphere.[267] To make informed decisions about a topic, people have to be aware of that topic.[268] Once aware of a problem or an issue, people are more likely to engage with that issue.[269] However, few people seem to recognize the links between soils and human health.[205] This certainly is not because of a lack of communication between scientists; a number of recent papers, books, and book chapters have addressed this issue in the literature of multiple scientific and human health fields,[11,14,23,24,56,270-272] just to list a few. Given the abundance of scientific communication coupled with the relative lack of public recognition, the logical conclusion is that the scientific community is failing to communicate the importance of the soil-human health connection to the broader public.

Before people will connect with a soil message, they need to see soil as something that is important in their lives.[273] At present the public perception of soil is often negative, in fact, the public perception of soil is often “dirt” rather than “soil,” something that is reinforced in sayings such as “soiled,” “dirt poor,”

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"dirt bag," and "mudslinging."[274,275] To change perceptions of soil, it is important that we do 2 things: (1) find a way to make a positive connection between people and soil and (2) find a way to reach people with this message. If the negative image of soil can be changed, and people learn that soil is important to their health, they should then theoretically behave in ways that will improve soil conditions and thus their own health.[276] This section of the article will address ways that this communication disconnect might be rectified and human health associated with soil improved accordingly.

Concepts for a positive connection

Making a positive connection between the general public and soil involves presenting a viewpoint of soil that people who are not intimately vested in soil can connect with. Brevik et al[276] proposed soil health and soil security as 2 concepts that show promise in this regard. There are several advantages to using the soil health concept. One is that the idea of human health is already implicit in widely accepted definitions of soil health,[277] and the connection between soil health and human health is already documented.[19,204] Commonly used soil health definitions also incorporate the concepts of improving air and water quality, and these are goals that already enjoy widespread public support.[278,279] Soil health already has international acceptance by agricultural interests[280-282] and policy makers.[283] Some farmers already recognize that links exist between the health of their soils and the health of those who consume products produced on those soils.[284] Therefore, soil health shows promise as a concept to connect people to soil.

The soil security concept is much more recent than soil health and does not yet have the same recognition.[276] However, soil security seeks to take advantage of the recognition that concepts such as food security, water security, and energy security have gained, particularly among policymakers,[285] and links have been identified between soil security and human health.[286] Soil security also incorporates social aspects into the concept, which makes it appealing as a possible way to connect people to soil. The term "ecosystem services" was introduced in the 1990s and has rapidly gained widespread acceptance in many of the natural sciences.[287] However, including soils in ecosystem services evaluations was not common until the 2000s.[287] Soils have been linked to a wide range of ecosystem services,[288,289] including those that support human health.[11,290] The importance of ecosystem services is now widely accepted within the scientific community,[287] but at present there is some evidence that there is little recognition of ecosystem services by the urban public. Collins et al[291] and Bagstad et al[292] found the public had a limited ability to perceive the importance of ecosystem services provisioning regions. Therefore, while soil security and soil ecosystem services are concepts that have potential to engage the public, each also appears to need more public exposure to do so most effectively.

Ways to communicate

Having a message that will resonate with the public is only one part of the picture. Another major aspect is how that message will be communicated. There are many options for this, including social marketing and social media. Both should be effective ways to communicate soil information to a public audience.

Social marketing applies marketing techniques and principles with the goal of influencing public behavior in a way that benefits society.[293] In traditional marketing, the goal is to convince people to make a purchase; in social marketing, the goal is to illicit a specific behavioral change.[294] Regarding the soil concepts previously discussed (soil health, soil security, and soil ecosystem services), the ultimate goal of a social marketing campaign would be to create behaviors that promote soil health, soil security, and soil ecosystem services. This promotion may not be direct. For example, the willingness of consumers to pay a premium price for products produced in a way that promotes soil security/health/ecosystem services could convince farmers and ranchers to adopt such practices.[295] Some early efforts at social marketing for soil purposes are being attempted,[276] time will tell whether or not they end up being successful.

Social media has become a powerful platform for communication in the modern world, and it comes in many different forms. There are 13 types of social media[296] and its use is expanding rapidly, making popular social media outlets effective platforms for marketing efforts.[297] However, social media views often occur through the recommendations of peers, rather than randomly like on a billboard or television, which creates a strong emotional affiliation with the message. Unlike traditional marketing, where the content of the message is most important, the context of the message (who it comes from) is more important on social media.[297] In other words, when a social media marketing message comes from a source the recipient trusts, the recipient is more likely to accept the content of the message, and vice versa. Informal messaging is more likely to be persuasive in the social media environment than traditional formal marketing. This introduces unique challenges to generating an effective social media marketing campaign, but it also offers the opportunity to reach people on budgets that can be much smaller than those required for traditional marketing outlets.[298]

There are some current attempts to market soil science through social media. Examples include the "Soils Matter" blog (https://soilsmatter.wordpress.com/) run by the Soil Science Society of America (SSSA), the "Soil Systems Sciences" blog (https://blogs.egu.eu/divisions/sss/) of the European Geosciences Union (EGU), the Twitter feeds run by SSSA (@SSSA_soils), the International Union of Soil Sciences (IUSS) (@IUSS_ORG), and the Soil System Sciences division of EGU (@EGU_SSS), and the Facebook pages run by SSSA, IUSS, and the Soil and Water Conservation

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Society (SWCS). There are also a series of YouTube videos developed or supported by SSSA (eg, https://www.youtube.com/watch?v=vDL6F6GkAzI and https://www.youtube.com/watch?v=y0u_D5hmK6I), Soil Science Australia (eg, https://www.youtube.com/watch?v=S7I-yEUZ1j4), the "PED Talks" YouTube video channel (https://www.youtube.com/channel/UC_NOrrVa1_cCNKQmQoLR5ig) developed by SWCS, and the YouTube channel run by the Soil Health Institute (https://www.youtube.com/channel/UCeBuJZT0GiS-iVxaPNfqkww). Several professional soil science societies have LinkedIn accounts, including SSSA, EGU, and IUSS. Some measurements of the effectiveness of these efforts can be made. The SSSA blog now averages more than 35 000 views per month (Susan Fisk, personal communication, November 10, 2019), each YouTube video displays the number of views it has received, Twitter tells how many times something has been retweeted, and LinkedIn accounts display the number of followers that a professional society has. However, much like social marketing efforts, the long-term effectiveness of marketing through social media has yet to be determined. Being able to link things like number of followers, retweets, or views to the taking of individual action regarding the idea being marketed is a major future need in this area.

Concluding Statements

The idea that soils are important to human health is widely accepted in the modern scientific community. Soils are recognized for their contributions in areas such as the supply of adequate quantities of nutritious food products, medications, and for their assistance in developing the human immune system. Negative health impacts also occur when foods are grown in soils that have nutrient deficiencies or when people are exposed to toxic levels of chemicals or pathogenic organisms through contact with soil or soil products. However, there are still many things we do not know about the links between soils and human health. The potential role of soils in the development of ARB needs additional research, as do the methods used to investigate soil microorganisms. Investigation of the links between soil macroorganisms and human health has barely begun, and there is a need for a more holistic understanding of the soil ecosystem and its links to agronomic production and broader human health. As the global population grows, we will need to produce more food that maintains or enhances its nutrient content on essentially the same land area, assuming we can reverse our current losses of arable land to degradational processes. A large amount of work has focused on heavy metals pollution, plastics, pesticides, and related organic chemicals, but this work typically focuses on a given pollutant as a stand-alone issue. In actuality, the soil is a mixture of many chemicals that are in a very chemically and biologically active environment; research into the health effect of chemical mixtures and how those mixtures react and interact in the soil environment is badly needed. Beyond research, there is a need for scientists to effectively communicate their findings to the broader public, who will not be aware of the challenges and opportunities we face if scientists do not get the word out. Closing all these gaps will require multidisciplinary teams that are able to communicate across those disciplines, as, for example, soil scientists are not typically trained in human health issues and human health experts are not typically training in soil science, while neither of these groups are typically trained in effective large-scale public outreach. Therefore, we need agronomists, biologists, chemists, communications experts, medical doctors, public health experts, toxicologists, sociologists, soil scientists, and others working together toward common goals within the soil and human health realm. In some cases, achieving these collaborations will require a paradigm change in how we presently approach human health issues.

Author Contributions

Conceptualization and design, interpretation, drafting of original article, revision and approval of final article – all authors. Coordination of project – ECB.

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Supplemental material

Supplemental material for this article is available online.

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