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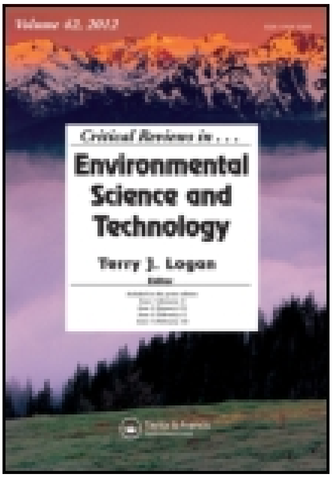

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The Soil Health-Human Health Nexus

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The Soil Health-Human Health Nexus

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Soils can beneficially or adversely affect human health, and likewise human activity can improve or destroy soil health. In the new anthropogenic era, it is worth examining the soil health–human health nexus. To do this, the author evaluates soil from the perspective of what infects us, what heals us, what contaminates us, what nourishes us, and what we breathe. Likewise, the author examines the impact of humans on soil using a similar matrix and suggests strategies to improve human health by maintaining or improving soil health.

KEY WORDS: soil health, soil health-human health

INTRODUCTION

The thin veneer of material that covers much of the earth's surface is known as soil. This fragile skin is frequently less than a meter thick, but is absolutely vital for human life as we know it. Soil is the most complicated biomaterial on the planet other than perhaps humans themselves. Interestingly, the zone of maximum life, activity, and diversity in terrestrial environments is where soils and humans meet at the surface of the earth. Upward or downward movement away from the interface decreases all three parameters. Based on these facts, perhaps it is not surprising that soils affect human health, and that humans affect soil health. Soil health can defined in numerous ways, and can be thought of as analogous to human health. Both soil and humans must be in a state of well-being with respect to their physical, chemical, and biological characteristics. Likewise, neither should be diseased nor compromised, and ideally both should function sustainably at optimum potential. Much is known about how human activity can improve or detrimentally affect soil health, but how soils can beneficially or adversely impact human health is

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less well documented, the exception being the National Research Council publication on Earth Materials and Health.[1] In the new Anthropocene era, the era defined by the influence of human activities on the Earth's ecosystems, it is worth examining the soil health: human health nexus. Herein, I evaluate soil from the perspective of what infects us, what heals us, what contaminates us, what nourishes us, and what we breathe. I examine the impact of humans on soil using a similar matrix. Overall, the influence of soil on human health is immense, and can have positive or negative impacts. By evaluating these impacts, I suggest strategies to improve human health by improving soil health.

SOIL MATRIX AND ARCHITECTURE

The abiotic portion of all soils consists of inorganic particles of different size ranges, notably sands, silts, and clays. Not only are the size ranges different, but the shapes and morphology of these particles also differ. This results in different specific surface areas of the particulates, with the smaller clays having larger surface areas per unit of mass, than the silts and sands. Surface area in turn impacts the surface chemistry of the soil in question, and the rates of chemical reactions and transformations. Under the influence of the soil biota, the different sized inorganic particles combine to form secondary aggregates. Pore spaces within the aggregate structure (intra-aggregate pore space) and between the aggregates (interaggregate pore space) are crucial to the overall soil architecture (Figure 1). The soil architecture in turn is critical for the regulation of water movement and retention, gas exchange, and microsite redox potentials within the soil. Totally enclosed pores (within aggregates) can have much lower redox potentials than open pores between aggregates. The resulting heterogeneity that develops means that both aerobic and anaerobic microorganisms can exist in very close proximity of one another.

Soils also contain biotic components (e.g., plant vegetation, decaying residues, stable soil humus, soil organisms) that add to the soil matrix complexity and architecture. Plant vegetative growth originates in soil, and following the death of plants, senesced vegetation returns to the soil, where it is degraded by heterotrophic soil microorganisms. Nutrients released during degradation are utilized by soil microbes, by new vegetation, and in soil structure development. Inorganic substrates such as ammonium nitrate or sulfate can be subject to autotrophic microbial transformations. Some organic residues are incorporated into the organic backbone of soil known as humus. Degradation of organic substrate also results in microbial gums and slimes, which together with fungal hyphae enhance the process of binding primary inorganic particles into secondary aggregates. Microbial populations

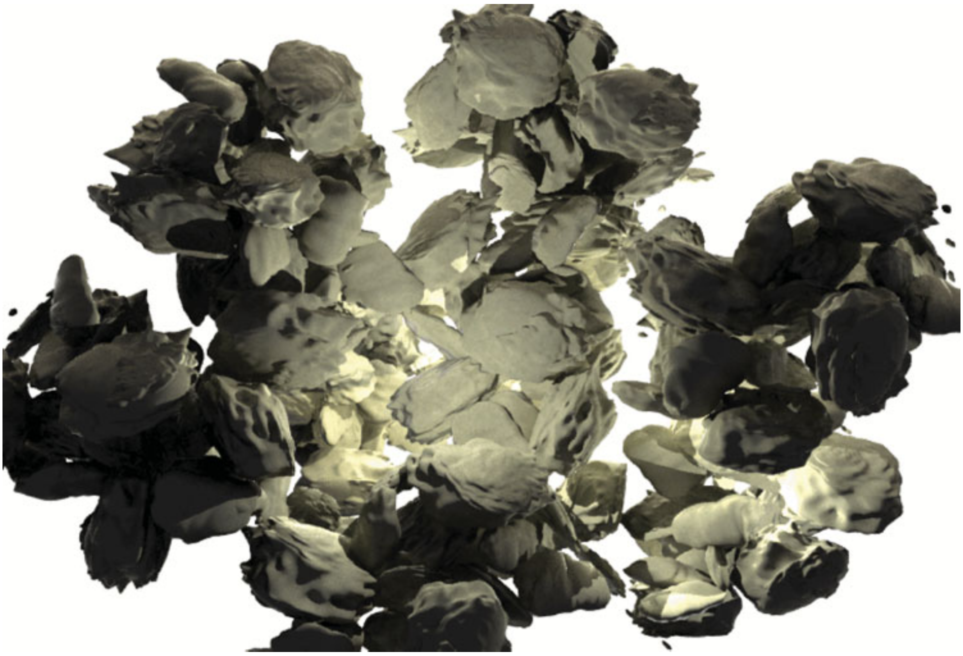

FIGURE 1. Soil architecture resulting from secondary aggregate formation with intra- and interaggregate pore space. Source: I. L. Pepper. (Color figure available online).

proliferate in soil, with billions of bacteria and fungi coexisting in close proximity. Other biological entities include phage and protozoa, which are important for the control of bacterial populations. The diversity of these microbes with respect to substrate utilization (organic vs. inorganic) and redox requirements (aerobic vs. anaerobic) results in diverse microbial communities capable of coexisting in micro-site niches within the heterogenous soil matrix. The microbial populations mediate innumerable biochemical transformations within soils. Despite their very large numbers, microbes occupy less than 1% of the total soil surface area, about the same land area on Earth occupied by humans.[2]

The soil colloidal matrix, micron sized particles including inorganic, organic, and biological entities, dominates soil architecture. Soil architecture, in turn, controls soil chemical and biochemical transformations and soil diversity. The diversity of soil is characterized by physical and temporal heterogeneities across all measured scales from nm to km,[1] and is probably the driving force for the microbial diversity that we see in soil.[2] Diversity estimates of the number of bacterial species on soil range from 2000 to 8.3 million per gram of soil depending on the methodologies utilized.[4] Regardless of the true estimate, the microbial diversity within soil is clearly enormous and this impacts soil health and ultimately human health.

SOILS AND HUMAN HEALTH

What Infects Us

Microbial pathogens are ubiquitous and include prokaryotic bacterial pathogens and eukaryotic fungi and protozoa. In addition, numerous viruses can also infect humans. Pathogens can be indigenous to soils (geo-indigenous), or can be introduced deliberately or accidentally into soils where they normally become inactivated (geo-treatable).

GEO-INDIGENOUS PATHOGENS

Geo-indigenous pathogens are those found in soils that are capable of metabolism growth and reproduction.[5] They are found in all soils and include prokaryotic and eukaryotic organisms (Table 1). *Bacillus anthracis* is a bacterial geo-indigenous pathogen that causes lethal disease in humans via pulmonary, gastrointestinal, or cutaneous modes of infection.[6] The organism is found worldwide and, because it is a spore former, can remain viable in soil for many years.[7] Fortunately, human infections from *Bacillus anthracis* normally occur only following amplification of *Bacillus* numbers in animal carcasses.[8] Anthrax infections from soil alone are less common.

Legionella species are also geo-indigenous, but Legionnaires disease (which can be fatal) is usually associated with inhalation of *L. pneumophila*

TABLE 1. Human geo-indigenous soil pathogens

Type of organism	Affliction	Incidence in soil
Human virus	NA	Never indigenous: no host
Bacteria		
- *Bacillus anthracis*	Anthrax	Routinely found in most soils
- *Legionella* spp.	Legionnaire's disease	Found in soil composts and potting soil
- *Clostridium perfringens*	Minor infections and gas gangrene	Common soil organism
- *Burkholderia pseudomallei*	Meliodiosis	Endemic in southeast Asia
Fungi		
- *Coccidioides immitis*	Valley fever	Highly prevalent in southwestern United States
- *Histoplasma capsulatum*	Respiratory infections	Prevalent in the midwestern and southern United States
Protozoa		
- *Naegleria fowleri*	Brain encephalitis	Found in soil and water
- *Balamuthia mandrillaris*	Brain encephalitis	Found in soil and water

Note. Modified from Pepper et al.[5]

in water droplets as aerosols. However, a less serious form of illness can also be contacted via *L. longbeachae* associated with potting soil.[9]

Many species of *Clostridium* are found in soil including *Clostridium perfringens*, the causative agent of gas gangrene. Typically the organism enters via a wound and multiplies in necrotic tissue. Li et al.[10] isolated *Clostridium perfringens* type A from soil that carried the chromosomal enterotoxin *cpe*, suggesting that soil can be a reservoir for *cpe*-positive isolates that cause non–foodborne gastrointestinal diseases. *Burkholderia pseudomallei* (aka. *Pseudomonas pseudomallei*) is an aerobic rod shaped gram-negative organism that infects humans and animals resulting in the disease melioidoses. The disease is also known as Whitmore's disease, and can be fatal, but is predominantly a disease of tropical climates, particularly Southeast Asia and Northern Australia. It is also found in Latin and South America.[11] Typically the organism is found in soil, but can also be found in contaminated water. Symptoms of the disease can exist in acute or chronic form, and include chest pains, pain in joints, skin infections, or even pneumonia.

Important fungal geo-indigenous pathogens include *Coccidioides immitis* and *Histoplasma capsulatum*. *Coccidioides immitis* is a soil-borne fungus that causes a respiratory illness known as Valley fever. It preferentially grows in the semiarid region of the Southwest United States including California, Arizona, New Mexico, and Texas.[12] Symptoms can be mild to fatal. *Histoplasma capsulatum* also causes respiratory infections. The fungus is found worldwide in soils, but in the United States. it is endemic to southeastern and midwestern states.[13] Histoplasmosis can be asymptomatic or mild, but the infections can be very serious or even fatal for immunocompromised individuals.

Protozoan parasites can also be found in soil or water and result in human infections. For example *Naegleria fowleri* and *Balamuthia mandrillaris* both cause brain encephalitis, which is almost always fatal.[14,15]

Overall, the incidence of geo-indigenous pathogens in most if not all soils is well documented. However, the impact of geo-indigenous pathogens on human health is both variable and complex. Of the geo-indigenous pathogens discussed, spore forming organisms result in the most serious human health effects, likely because they can easily be disseminated as aerosols via airborne transmission. For example, both *C. immitis* and *H. capsulatum* produce spores that can be inhaled and cause respiratory problems. Humans are constantly exposed to soil, and geo-indigenous pathogens usually cause endemic disease, but outbreaks are infrequent.

INTRODUCED PATHOGENS (GEO-TREATABLE)

Human pathogens that are not indigenous to soil can be introduced into soil either deliberately or accidentally via anthropogenic activities. Such introduced pathogens normally rapidly die-off within soil, and can be termed

TABLE 2. Geo-treatable pathogens introduced into soil via animal manures or biosolids

BACTERIA	PROTOZOA
Salmonella sp.	*Cryptosporidium*
Shigella sp.	*Entamoeba histolytica*
Yersinia	*Giardia lamblia*
Vibrio cholerae	*Balantidium coli*
Campylobacter jejuni	*Toxoplasma gondii*
Escherichia coli	
ENTERIC VIRUSES[a]	HELMINTHS
Hepatitis A virus	*Ascaris lumbricoides*
Adenovirus	*Ascaris suum*
Norovirus	*Trichuris trichirua*
Sapporovirus	*Toxocara canis*
Rotavirus	*Taenia saginata*
Enteroviruses	*Taenia solium*
- Polioviruses	*Necator americanus*
- Coxsackieviruses	*Hymenolepsis nana*
- Echoviruses	
- Enteroviruses 68–91	
Reoviruses	
Astroviruses	
Hepatitis E virus	
Picobirnavirus	

[a] Biosolids only.

geo-treatable.[5] Deliberate introduction occurs through land application of animal manures and biosolids in developed countries, and raw human wastes ("night soil") in developing countries. Irrigation with sewage effluent is another potential source of introduced pathogens. Finally, note that pathogens can also be accidentally introduced into soil via animal or bird feces. Animal feces and subsequent transport via surface waters following rainfall events led to several recent foodborne outbreaks in the U.S. including *E. coli* 0157:H7 contamination of spinach and lettuce.[16]

Land application of animal manures and biosolids results in large numbers of diverse pathogens being introduced into soil (Table 2). Bacterial pathogens such as *Campylobacter jejuni*, *Salmonella*, and *Listeria* are found in both biosolids and animal manures. *E. coli* is also found in both residuals, but are more prevalent in animal manures. The protozoa *Cryptosporidium* is also found in both residuals. In contrast human pathogenic viruses are only found in biosolids.[17] Approximately 450,000 animal feeding operations in the United States produce over 100 million dry tons of manure per year.[18] In contrast, approximately 16,000 municipal wastewater treatment plants in the United States produce 5.6 million tons of biosolids annually.[19] Most of the residuals are applied to agricultural land for crop production. The majority of land applied biosolids is Class B biosolids, which contain detectable concentrations of pathogens including human enteric viruses. Regulations dictate site restrictions to allow sufficient time for die-off of the introduced pathogens before for human and animal entry to land application sites.[20] Similar restrictions are imposed on crop production and harvesting on biosolids-amended land. The intent of the site restrictions is to allow for introduced pathogens to be inactivated or geo-treated by soil biotic and abiotic factors. Inactivation of all classes of pathogens in soil is well documented; the death of such organisms normally occurs within several weeks to months, depending on soil type and specific environmental conditions.[17] Animal manures are normally not treated prior to land application, although storage prior to land application can promote some pathogen die-off. Nevertheless, manures are a significant source of introduced or geo-treatable pathogens into soil. A recent study compared the microbial risk of infections to humans resulting from the land application of biosolids versus that from animal manures.[21] The analyses show that if site restrictions for biosolids applications are obeyed, risks are acceptably low. Risks from *Salmonella*, *E. coli* 0157:H7, and *Cryptosporidium* from animal manures were higher than corresponding risks from Class B biosolids due to higher pathogen loads. There are no risks from viruses in animal manures because they contain no human enteric viruses.[21]

Helminths are another significant class of geo-treatable pathogens, and include roundworms, hookworms and nematodes such as *Ascaris lumbricoides* and *Schistosoma* spp.; all can be transmitted from soil to humans.[22] Helminths are geo-treatable, but can survive in soil for several years. The impact of helminths on human health is illustrated by a recent global burden of disease estimate of 39 million disability adjusted life years (DALYs). The value is similar to estimates for tuberculosis (34.7 million DALYs) or malaria (46.5 million DALYs).[23] Current estimates are that more than 1 billion people are infected with at least one species of helminths, with soil being one major route of exposure, the others being food and water.[24]

Fate of Pathogens in Soil

Geo-indigenous pathogens by definition can live in a soil environment. In contrast, geo-treatable pathogens are normally inactivated due to biotic and abiotic stresses.[25] Many studies have demonstrated that soils are very effective in inactivating introduced pathogens through competition, and biotic and abiotic stresses.[25] Geo-indigenous pathogens can normally survive either in environmental niches or in animal or human hosts. In contrast, microbes acquired from animal or human hosts (zoonoses) may have a total dependency on the host for replication and survival.[26] Some pathogenic fungi exist in soil with no requirement for an animal host, and cause human disease. In contrast, viruses are totally dependent on human hosts for replication and survival, and would never be considered, to be indigenous to soil.[5] Emerging pathogens are those recently discovered, and by definition, little is known about their incidence or disease causing potential. Emerging pathogens can arise due to human activities including urbanization and deforestation that change environmental systems and result in exposure to new pathogens. Soils can impact pathogens in ways other than just their survival. For example, soil can influence the pathogenicity and virulence of pathogens. Pathogenicity can be defined as the ability of an organism to produce an infectious disease in humans, whereas virulence is the degree of pathogenicity or intensity of pathogenicity. Pathogenicity and virulence are terms that tend to be used interchangeably, but a loss of virulence can lead to a loss of pathogenicity. The pool of soilborne human pathogenic microbes is dynamic, as is their virulence. Soil health itself can influence the virulence of soil microbes through the interaction of the microbes with the soil environment, including temperature, pH, and hydrolytic enzymes and other organisms including microbial, plant, and animal hosts. Cassadevall[26] compared the emergence of virulence in soil microbes to a deck of cards in which the selected pressures determine which virulence cards will be acquired, maintained or discarded by a particular population. For example, Duriez et al.[27] showed a loss of virulence genes from *E. coli* during manure storage. Virulence maintenance is likely to be particularly important for pathogens introduced into soil via land applied manures or biosolids, or via bird or animal feces.

Geo-treatable pathogens can also interact with neighboring microorganisms in soil resulting in horizontal gene transfer that enables them to become more or less virulent. Such microbe-microbe interactions can lead to genotypic and phenotypic changes that affect not only pathogenicity but also metabolic functions and microorganism survival. For example, Ishii et al.[28] isolated *E. coli* from soil that had apparently adapted to life in soil, but at the cost of losing pathogenicity.

What Heals Us

SOILS AND ANTIBIOTICS

As well as containing pathogenic microbes that can infect us, soils also contain organisms that provide a treasure chest of natural products critical to maintaining or even improving human health. The earliest of these classes of compounds to be discovered were the antibiotics. Antibiotics are compounds produced by soil microorganisms that kill or inhibit other microorganisms, and soils were the source of the first known antibiotics. Penicillin was isolated from the soilborne fungus *Penicillium* by Sir Alexander Fleming in 1929.[29] In 1943, Selman Waksman discovered streptomycin, a feat for which he received the Nobel Prize. This antibiotic was isolated from *Streptomyces griseus*, and, since then, soil actinomycetes have been shown to be a prime source of antibiotics.[30]

Although antibiotics have been fabulously successful in treating bacterial infections, they also pose the potential problem of antibiotic-resistant bacteria. Bacteria are prokaryotic organisms with the ability to metabolize and replicate quickly, and are extremely adaptable genetically. During replication, genetic or mutational changes can occur that confer resistance to specific antibiotics. Thus the more antibiotics are used, the greater the chance that antibiotic-resistant strains will develop. In particular, concern centers on the potential for human pathogenic bacteria to become resistant to widely used antibiotics. Not surprisingly, antibiotic-resistant soil bacteria are widely distributed throughout most soils where they exist as indigenous soilborne organisms.[31,32] Many soil isolates can be resistant to multiple antibiotics, with some resistant to as many as 20 antibiotics.[31] Thus, soils are not only a source of antibiotics, but also antibiotic-resistant bacteria.

Human activities such as land application of municipal biosolids or animal manures have been implicated as potentially increasing the concentrations of antibiotic-resistant bacteria within soil. But, in a recent study, concentrations of antibiotic-resistant bacteria did not increase even after 20 continuous years of land application of biosolids, when compared to neighboring soil that had not received biosolids.[32] In contrast, soils receiving dairy manures have been shown to have enhanced concentrations.[33] Most concern over soilborne antibiotic-resistant bacteria relates to the introduction of animal manures from swine, poultry, or cows fed antibiotics as part of their diet. Pollution-induced community tolerance (PICT) theory predicts that such practices leads to increased tolerances of soil organisms to the specified antibiotics.[34] However, overall, hospital environments are far more likely to be detrimental to human health than the soil environment. In hospitals, large numbers of patients receive antibiotics providing a selective pressure that encourages antibiotic-resistant bacterial pathogens capable of human infection. Of particular concern are the methicillin-resistant strains of *Staphylococcus aureus* (MRSA).

SOILS AND OTHER NATURAL PRODUCTS

Billions of microorganisms can be found in soils. Early estimates of bacterial diversity were based on culturable methodologies, and relatively low numbers were reported. Newer molecular technologies, including 16S rRNA sequence analysis and pyrosequencing that do not utilize culturable assays, have resulted in much higher estimates.[4,35]

In addition to bacteria, fungi are also present in soil with immense diversity and both bacterial and fungal endophytes are a rich source of natural products. Endophytes are bacteria or fungal microbes that colonize plant roots without pathogenic effects. Endophytes produce metabolites that not only protect plant roots, thereby improving plant health, but can also improve human health. Endophytes have been shown to produce novel antibiotics, antimycotics, immunosuppresents, and anticancer agents.[36]

Microtubule-stabilizing agents (MSAs) such as paclitaxel have been isolated from endophytic fungi associated with the yew (Taxus) species. Because paclitaxel acts as a cell poison that arrests cell division, it has become a highly potent anti-cancer agent.[37] Endophytes also have useful applications in agriculture and industry, including enhanced phytoremediation,[38] inhibition of plant pathogens,[39] and enhanced plant biomass.[40]

Very recently, a new technology known as genomic mining has resulted in new discoveries of useful natural products. Genomic mining is the identification of protein-encoding regions of a genome, and the assignment of functions to these genes on the basis of sequence similarity homologies against other genes of known structure. The technology allows the identification of new drug products, resulting from gene clusters, that are not normally expressed under laboratory conditions.[41,42] These new approaches bode well for future sources of new natural products that maintain and even improve human health.

What We Drink

Soils and soil health can dramatically affect human health by influencing what we drink. Soils intrinsically contain many elements that, when solubilized, can adversely impact human health, but also contain elements that can benefit human health. For example, fluoride containing soil minerals can represent natural sources of fluoride in groundwater. At moderate concentrations in water (0.7–1.2 mg/L) fluoride helps prevent dental caries and can improve bone matrix integrity.[3] Excess concentrations (<4 mg/L) can be detrimental resulting in fluorosis, but the general consensus is that moderate levels of fluoride benefit human health.[43] Similarly, calcium and magnesium minerals in soil can also solubilize resulting in positive human health effects. However the most important impact of soils on what we drink is through protection of groundwater from anthropogenic contaminants.[1]

ROLE OF THE CRITICAL ZONE IN PROTECTING GROUNDWATER

In many areas of the world, groundwater is utilized as a potable source of water and is subject to contamination. Regardless of whether the chemical (or microbial) contaminants arise from natural intrinsic soil constituents or from anthropogenic activities, groundwater contamination is of particular concern. Residence times for groundwaters range from several years to over 100 years, and once contaminated, are difficult to remediate. Surface soils and sub-surface vadose zones play critical roles in protecting underground aquifers from potential contamination or enhancing the potential for contamination, depending on their physical, biological, and chemical characteristics. For example, a healthy soil with viable microbial populations can often actively degrade toxic organic contaminants. Soils can also attenuate contaminants through chemical processes. The susceptibility of a specific aquifer to

TABLE 3. Factors affecting groundwater vulnerability to contamination

Factor	Increased vulnerability	Decreased vulnerability
Depth to groundwater	Shallow	Deep
Soil type	Well drained (sandy)	Poorly drained (high clay, organic matter content)
Vadose zone physical properties	Preferential flow channels	Horizontal low-permeability layers
Recharge	High precipitation, high infiltration	Low precipitation, low infiltration
Subsurface attenuation processes	Minimal attenuation	Significant attenuation

Source: Brusseau and Tick.[109]

contamination is referred to as groundwater vulnerability, which depends on multiple factors (Table 3). Overall, chemical (and microbial) contaminants arising from soil or from introduction into soil must travel through the surface soil and vadose zone prior to aquifer contamination. The soils is the material that has developed due to weathering processes over time, whereas the vadose zone is subsurface material that is not subjected to such weathering processes. The two regions function as living filters that can mitigate and limit such transport through chemical, physical, and microbial attenuation processes. Thus, the soil and the vadose zone are part of the critical zone, which ranges from the vegetation top to the aquifer bottom.[44] It is the health of the critical zone that frequently controls the potential for groundwater contamination with natural or introduced waterborne soil constituents.

Health Hazards of Natural Waterborne Soil Constituents

I begin by focusing on chemical contamination of potable source waters from intrinsic soil constituents; anthropogenic contamination of source waters is discussed later. One of the largest health hazards of waterborne soil constituents is arsenic. Long-term chronic arsenic exposure can result in multiple cancers (skin, lung, bladder, and kidney), atherosclerosis and peripheral vascular disease. Worldwide, water contamination is the leading cause of exposure to environmental arsenic and the largest affected populations being Bangladesh and West Bengal in India.[1] Current EPA and WHO maximum contaminant levels for arsenic in drinking water are 10 μg/L.

The tragedy of arsenic poisoning in Bangladesh occurred when tube wells were drilled to allow access to groundwater in the 1970s. Well water use was to preclude the drinking of surface waters that had earlier resulted in dysentery, typhoid and cholera diseases. Sediments above the groundwater contained arsenic complexes such as arseno-pyrite, which is stable under anaerobic conditions. At low redox potentials, sulfate is reduced to sulfide and arsenic is precipitated onto iron sulfide as arseno-pyrite. There are two theories for the mechanism of arsenic contamination of groundwater. The first states that excessive groundwater extraction allowed greater diffusion of oxygen into arsenic containing sediments and oxidation of insoluble arsenopyrite to the soluble hydrated iron arsenate mineral known as pitticite.[45] A second and different theory was proposed by Nickson et al.[46] and is known as the oxyhydroxide reduction theory where arsenic is desorbed from ferric hydroxide under reducing conditions. Soil microorganisms also transform arsenic species found in soil. Specifically, some soil microbes utilize arsenate as a terminal electron acceptor under anaerobic conditions, converting arsenate to arsenite, which is the more toxic and mobile species most likely to contaminate groundwater.[1] Regardless of the mechanism, arsenic contamination of groundwater due to soil arsenic remains the largest mass poisoning in history.[47]

Selenium is another example of an element naturally found in soils that can adversely affect the environment. Ironically, selenium can also provide beneficial health effects to humans, as discussed in the What We Eat section.

Selenium gained infamy in the United States in the 1980s due to selenium toxicity in the Kesterson Reservoir in the San Joaquin Valley in California.[1] Essentially, agricultural irrigation of soils high in selenium resulted in solubilization of the selenium and drainage water collection in the reservoir elevated selenium levels. Birth defects in birds and die-off of water fowl and fish within the reservoir resulted.[48] In June 1986, the reservoir was closed to drainage water inputs to prevent further selenium inputs.[49]

Radioactive material can also originate from soils, rocks, and minerals. In the age of the anthropocene, such materials can be concentrated due to anthropogenic activities such as uranium mining that result in groundwater contamination.[50]

HEALTH HAZARDS OF INTRODUCED WATERBORNE SOIL CONSTITUENTS

Thousands of industrial chemicals are produced via anthropogenic activity that can adversely affect human and soil health. These chemicals can be classified as organic, inorganic or radioactive, and examples of each category are listed in Table 4. Many of these chemicals have the potential to contaminate groundwater. To illustrate this, here I discuss a major inorganic contaminant and an emerging organic contaminant class.

The inorganic contaminant of concern is nitrates. Nitrates are introduced into soils deliberately as inorganic fertilizers, or via land application of animal manures and biosolids. Regardless of whether inorganic or organic forms of nitrate are added, soil microbial processes such as ammonification and nitrification result in nitrate as the major soil constituent. Nitrates are highly soluble and can easily reach groundwater. In humans, nitrate is reduced to nitrite, which in infants combines with fetal hemoglobin inhibiting oxygen transport. The result is blue baby syndrome or methemoglobinemia, which can be fatal. Therefore an international standard of 10 ppm of $NO_3{-}N$ for

TABLE 4. Examples of organic, inorganic, and radioactive chemical contaminants

Organic contaminants
Petroleum hydrocarbons (fuels): benzene, toluene, xylene, polycyclic aromatics
Chlorinated solvents: Trichloroethene, tetrachlorethene, trichloroethane, carbon tetrachloride
Pesticides: DDT (dichloro-diphenyl-trichloro-ethane), 2,4-D (2,4-Dichlorophenoxyacetic acid), atrazine
Polychlorinated biphenyls (PCBs): insulating fluids, plasticizers, pigments
Coal tar/creosote: Polycyclic aromatics
Pharmaceuticals/food additives/cosmetics: drugs, surfactants, dyes
Gaseous compounds: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs)

Inorganic contaminants
Inorganic salts: sodium, calcium, nitrate, sulfate
Heavy/trace metals: lead, zinc, cadmium, mercury, arsenic

Radioactive contaminants
Solid elements: uranium, strontium, cobalt, plutonium
Gaseous elements: radon

Source: Brusseau et al.[110]

groundwater has been set. Nitrates have also been linked to gastric and bladder cancers, but evidence to date is inconclusive.[51]

The emerging organic contaminants of concern are endocrine disruptors (EDCs); chemicals that interfere with endocrine glands, their hormones or the activities of hormones. One source of EDCs is pharmaceuticals and personal care products introduced into soil or surface waters via treated wastewater or biosolids applications. Other endocrine disruptors include polybrominated diphenyl ethers (PBDEs)—utilized as flame retardants—and some pesticides. A particularly infamous pesticide is DDT, the focus of Rachel Carson's book *Silent Spring*, which stimulated the environmental movement in the United States over half a century ago.

Interest in endocrine disruptors peaked following the U.S. Geological Survey (USGS) study in 1999–2000. Yet again, anthropogenic activities are credited with causing 80% of surface waters sampled as containing at least one of the 95 trace contaminants (EDCs) analyzed. However, it is important to note that sampling points were intentionally chosen from those sites most likely to be impacted by anthropogenic activities such as wastewater treatment or concentrated animal feedlot operations. Thus the results are not representative of U.S. surface waters in general. The hormones and hormone mimics found in U.S. surface waters are shown in Table 5, and at first sign the incidence data are highly alarming. However, a reasonable perception of the potential adverse health risks can be obtained by comparing the maximum concentrations found in the surface waters with the medicinal dosage of various pharmaceuticals (Table 6). For example, drinking water that contained the highest concentration of ibuprofen found in the USGS study (1 μg/L) would require 550 years to be equivalent to two Advil tablets (400 mg) assuming consumption of 2 L of water per day. Despite this, bioassays are

TABLE 5. Hormones and hormone mimics observed in U.S. surface waters

Compound	Description	Detection limit (μg L^{-1})	Frequency of detection (%)	Max. (μg L^{-1})	Median (μg L^{-1})
Progesterone	Reproductive hormone	0.005	4.1	0.199	0.11
Testosterone	Reproductive hormone	0.005	4.1	0.214	0.017
17β-Estradiol	Reproductive hormone	0.05	9.5	0.093	0.009
17α-Estradiol	Reproductive hormone	0.005	5.4	0.074	0.030
Estriol	Reproductive hormone	0.005	20.3	0.043	0.019
Estrone	Reproductive hormone	0.005	6.8	0.027	0.112
Mestranol	Ovulation inhibitor	0.005	4.3	0.407	0.017
19-Norethisterone	Ovulation inhibitor	0.005	12.2	0.872	0.048
17α-Ethinyl estradiol	Ovulation inhibitor	0.005	5.7	0.273	0.094
cis-Androsterone	Urinary steroid	0.005	13.5	0.214	0.017
4 Nonylphenol	Detergent metabolite	1.0	51.6	40	0.7
4-Nonylphenol monoethoxylate	Detergent metabolite	1.0	45.1	20	1
4-Nonylphenol diethoxylate	Detergent metabolite	1.1	34.1	9	1
4-Octyphenol monoethyoxylate	Detergent metabolite	0.1	41.8	2	0.15
4-Octophenoldiethoxy late	Detergent	0.2	23.1	1	0.095
Bisphenol A	Plasticizer	0.09	39.6	12	0.13

Adapted from Arnold et al.[111]

now being developed to evaluate the effects of mixtures of EDCs including synergistic effects.[52] To date, adverse human health effects of EDCs have not been documented, but concern centers on environmental effects including developmental abnormalities in fish such as intersex characteristics. In addition, there is a need for long-term low-dose exposure of EDCs to humans to evaluate whether adverse human health effects occur.

EDCs can be introduced into soils via effluent irrigation of crops or land application of animal manures (estrogenic compounds and antibiotics) or biosolids (estrogenic compounds and polybrominated diphenyl ethers [PBDEs]).[53] The fate of estrogenic compounds and PBDEs following introduction into soil is quite different. PBDEs are highly hydrophobic and hence sorb to (especially, organic) colloids, and remain undegraded for decades.[54] Certain

TABLE 6. Representative pharmaceuticals measured in the 1999–2009 USGS reconnaissance of U.S. streams[112]: a comparison of drinking water levels with medicinal doses

Chemical/use	Percentage of samples with compound	Maximum concentration (μg L^{-1})	Medicinal dosage
Caffeine/stimulant	71	6	130 mg[a]
Ibuprofen/anti-inflammatory	9.5	1	400 mg[b]
Cimetidine/antacid	9.5	0.58	800 mg day[c]
17α-Ethinyl estradiol/oral contraceptive	16	0.831	20–35 μg[d]
Testosterone/hormone replacement	2.8	0.214	150–450 mg[e]
Erythromycin/antibacterial	21.5	1.7	1000 mg day[f]
Ciprofloxacin/antibacterial	2.6	0.03	400–800 day[f]

Adapted from Arnold et al.[111]

[a] The mass of caffeine in two Excedrin tablets. There is 135 mg of caffeine in an 8-oz. cup of coffee.

[b] The mass of ibuprofen in two tables of Advil.

[c] The lowest adult daily dose of cimetidine.

[d] Range of 17α-ethinyl estradiol masses in birth control pills.

[e] Range of testosterone masses provided over 3–6 months when used for hormone replacement.

[f] Recommended adult dosages.

Source of medicinal dosages: *Physicians' Desk Reference* (2002).[113]

PBDE congeners (BDE-47, -99) degrade more rapidly relative to others that remain stable (BDE-138–153).[55] However, the hydrophobic nature of PBDEs also results in low solubility and bioavailability negating transport to underground aquifers. In contrast, estrogenic compounds including 4-nonylphenol estradiol and estrone degrade rapidly in soil with a half-life of 16(23 days.[56] Degradation of some estrogens occurs more rapidly under aerobic conditions than anaerobic conditions.[57]

In summary, contamination of groundwater via EDCs introduced into soil is unlikely to adversely impact human health, but could lead to detrimental environmental impacts through runoff into surface waters.

What We Eat

From the perspective of what we eat, soils can impact human health directly through ingestion of earth materials themselves or indirectly through ingestion of food that is grown in soil.

Direct Consumption of Soil

The direct consumption of soil or clay is known as geophagy or pica, and has been documented since historical times.[58] Voluntary ingestion of soil still occurs worldwide, and typical quantities ingested are as 20–50 g per day.[1] Typically geophagia is an acquired habitual response, perhaps as a result of nutritional deficiencies that result from a poor diet. Beneficial health effects of geophagia include exposure to essential trace elements. Adverse health effects of geophagia can include exposure to pathogens such as helminths.[59] There is also the potential for exposure to toxic trace elements such as lead found in polluted urban environments.

Involuntary or accidental ingestion of soil is orders of magnitude less: approximately 50 mg per day for children, and even less for adults. Soil can also inadvertently be consumed by humans through soil particles adhering to improperly washed agricultural vegetables or fruits. In this case, the potential health benefits and hazards are similar to those listed for geophagics, but the exposure is much less.

Soil and Food

Soil is fundamentally important for food production and quality because the vast majority of food for human or animal consumption is grown in soil. Chemicals including inorganic fertilizers and pesticides are frequently used to ensure good yields for commercial farmers, but the soil itself is vital for plant growth and ultimately for human nutrition. The interface between the soil and plant roots is mediated by the rhizosphere, which contains both rhizosphere microorganisms and endophytes. The rhizosphere encompasses the closest millimeters of soil surrounding plant roots, and is characterized by extremely high soil microbial populations, typically orders of magnitude higher than those found in bulk nonrhizosphere soil. Root exudates take part in signaling events between plant roots and the microbes found within the rhizosphere.[60] Beneficial organisms influence nutrient uptake by plants, and in many cases result in biocontrol of pathogens that induce plant disease. Two plant-microbe interactions are particularly important: rhizobia and mycorrhizal fungi. Rhizobia are heterotrophic bacteria that live symbiotically with legumes. Root nodules develop where the rhizobia live, and fix atmospheric nitrogen into ammonia for the plant. In return, the plant provides the rhizobia with metabolites. Global estimates of biological nitrogen fixation have been estimated at 2.95 Tg of fixed N annually for pulses and 18.5 Tg for oilseed legumes.[61] Soybean (*Glycine max*) is the dominant crop legume representing 68% of global crop production.[61]

In contrast, endophytes are those bacteria that can colonize the internal tissue of a plant without negative impacts on their host.[38] Mycorrhizal fungi are endophytes that enhance phosphorus uptake by plant roots. In many cases, a tripartite symbiosis occurs that involves the plant, mycorrhizal fungi and rhizobia.[62] Overall it can be seen that the relationship between plant growth and soil microorganisms is complex and vitally affects vegetative food production.

However, soils also affect food production in other ways such as food quality. Specifically, soil quality determines the nutritional value and safety of the foods grown.[63] Plants can take up heavy metals from contaminated soils and enter the food chain. Soils contaminated with geo-treatable pathogens can also adversely impact human health through adhesion to food produce grown on such soils. Efforts to avoid potential risks from anthropogenic compounds have prompted renewed interest in organic gardening and organic foods. There are many definitions of organic gardening, but essentially it consists of growing crops without inorganic fertilizers or pesticides. Instead, organic sources of nutrients are supplied and pests are controlled using natural organic products or management practices such as planting strategies and use of natural biocontrol agents. Crop production using organic fertilizers is normally very successful because nutrients are released slowly over time, acting as a slow release fertilizer. Crop quality of organic foods is usually excellent, but claims of nutritional and improved health effects over conventionally fertilized crops are more controversial. Dangour et al.[64] recently completed a systematic review of nearly 100,000 studies evaluating nutritionally related health effects of organic foods. The authors concluded that evidence is lacking for positive nutrition-related health effects resulting from the consumption of organically produced foodstuffs. That being said, it is clear that plants grown in soils for human consumption are critical in maintaining human health, regardless of whether they are grown organically or conventionally. Similarly, regardless of whether crops are grown organically or conventionally, it is important that the soil have adequate supplies of both macronutrients such as nitrogen and phosphorus and micronutrients such as iron or zinc. Whereas lack of macronutrients is normally quite obvious and results in poor plant growth, lack of micronutrients can result in human micronutrient malnutrition, also known as hidden hunger.[65,66]

What We Breathe

All humans are aerobic and therefore require oxygen as a terminal electron acceptor. This is acquired by the air that we breathe, which contains approximately 21% oxygen. Soils can adversely impact the quality of the air we breathe either directly or indirectly. Direct effects include suspended particulates and gases originating from earth materials. Indirect effects include the inhalation of microorganisms attached to soil particles—known as bioaerosols. Soils can also impact what we breathe following transport indoors, into our homes.

DIRECT EFFECTS OF SOILS ON WHAT WE BREATHE

Particulates suspended in air are called aerosols and cause adverse human health effects through respiratory intake and deposition in nasal and bronchial airways. In particular, the severity of asthma can be enhanced

TABLE 7. Annual aerosol production from natural sources and human activities

Source	PM_{10} (millions of tons)
Industrial processes	
Chemical industries	0.070
Metals processing	0.220
Petroleum industries	0.041
Other industries	0.530
Solvent utilization	0.006
Storage and transport	0.114
Waste disposal and recycling	0.296
Fuel Combustion	
Electric utilities	0.290
Industrial	0.314
On-road vehicles	0.268
Nonroad sources	0.466
Other	
Agriculture and forestry	4.707
Fire and other combustion	1.015
Unpaved roads	12.305
Paved roads	2.515
Construction	4.022
Wind erosion	5.316

Council on Environmental Quality, 1997.[114]
Source: National Research Council.[1]

by particulate matter inhalation, resulting in airway inflammation.[1] Smaller aerosolized particles travel further into the respiratory system and cause more serious health problems than larger particles. Accordingly, U.S. EPA categorizes airborne particulates as PM_{10} (particles with diameters less than or equal to 10 μm), and $PM_{2.5}$ (particles less than or equal to 2.5 μm). In addition to the greater adverse health effects, $PM_{2.5}$ particulates, once aerosolized, remain in the air longer. The sources of airborne particles are shown in Table 7, and clearly identify soils as major contributors to aerosols through wind erosion, agricultural activities and unpaved roads. Aerosolized soil particles can also serve as a source of airborne heavy metals. Young et al.[67] documented enhanced concentrations of airborne lead adjacent to five industrial facilities and roadsides.

The general adverse health effects caused by inhalation of earth materials on respiratory functions are well documented, but two types of soil particles result in specific adverse health effects: asbestos and silica-containing minerals. Fibrous materials, collectively known as asbestos, occur naturally as soil minerals. Asbestos can result in asbestosis, a noncancerous disease that causes scar tissue to develop within the lungs (fibrosis) with associated decreased pulmonary lung function. Asbestos is also considered a human carcinogen that can result in mesothelioma and lung cancer.[68] Serpentinite, a metamorphic rock commonly found in California (where it is the state rock), contains the mineral chrysotile. The Coalinga Mine in California was one of the best known chrysotile asbestos deposits in the United States,[69] and serpentine soils are common in the area.[1]

Another common soil mineral is quartz (SiO_2), which if inhaled can result in silicosis and nodular lesions in the upper lung. Silicosis is mostly an occupational concern for construction workers who sandblast and use jackhammers. Another source of SiO_2 is diatoms, the source of diatomaceous earth. Finally note that silica particles can be emitted during volcanic eruptions.[1,70]

One other direct impact of soil on what we breathe can be radon, a colorless, tasteless, odorless gas produced by the natural radioactive decay of rocks or soil containing uranium-bearing minerals. Radon can be inhaled directly or via adhesion to dust particles, and subsequently carried into the lungs where it can result in lung cancer.[50]

INDIRECT EFFECTS OF SOILS ON WHAT WE BREATHE

Biological airborne contaminants (bioaerosols) can also be adhered to particulates and subsequently inhaled or ingested. Because air is a harsh environment for vegetative microbial cells, inhalation of spores suspended in air is the major concern. For example, coccidioidomycosis (also known as Valley fever) is a disease caused by inhalation of spores of the fungus (*Coccidioides immitis*). The fungus is particularly prevalent in hot arid regions including the southwestern United States.

Allergens such as endotoxin can also exist as bioaerosols and cause adverse health effects. Endotoxin, also known as lipopolysaccharide, is derived from the cell wall of gram-negative bacteria, and soil can be an important source of aerosolized endotoxin. Farming operations such as driving a tractor across a field result in high levels of aerosolized endotoxin.[32] Finally note that gaseous mycotoxins produced by soil fungal molds including *Aspergillus*, *Altemaria*, *Fusarium*, and *Penicillium* can cause a variety of health problems. Aflatoxin, produced by *Aspergillus flavus*, is a potent carcinogen.[71]

IMPACT OF SOIL TRANSPORTED INTO HOMES VIA TRACK-IN

Inadvertent soil ingestion can expose young children to environmental contaminants. Exterior soil tracked into homes on footwear can be deposited on carpets or other floor surfaces, and subsequently ingested or absorbed by children playing on the floor. Such exterior deposition of soil indoors is known as track-in.[72] The risk associated with dermal absorption of chemicals from contaminated soil is a function of particle size distribution, with smaller particles $<63\ \mu m$ being more likely to adhere to skin.[73] A recent transport model for soil track-in showed that soil imported into homes was assimilated into household dust loadings in constant flux and rarely achieved steady state distributions.[74] Layton and Beamer[75] further showed that track-in soil was an important component of household dust along with organic matter, shed skin cells and organic fibers. Soil track-in and resuspension was the primary source of lead in household dust.

HUMANS AND SOIL HEALTH

Soils develop over hundreds or thousands of years via the five soil forming factors: parent materials, climate, vegetation and organisms (including humans), topography, and time. Undisturbed, soils develop an exquisitely complex architecture based on texture, structure, horizonation, organic matter, and microbial communities. Undisturbed pristine soils also develop pseudoequilibria that adjust to seasonal changes, and control both microbial populations and activities, and the vegetation that becomes established on the surface soil. Ultimately ecosystems become established, and the terrestrial environment can be thought of as a large organelle with an amoeba defense that degrades natural organic residues introduced into it. This concept is a modification of the original Gaia hypothesis in which James Lovelock proposed that the earth behaves as a super organism.[76] In the age of the anthropocene, humans have developed the ability to significantly alter soils and/or ecosystems either directly or indirectly. Direct activities include farming, deforestation urbanization and direct introduction of contaminants. Humans can directly change three of the five soil forming factors within a short time period of days to months, namely parent materials, vegetation, and topography. Although still controversial, over periods of decades it is likely that humans can also indirectly influence climate. Thus, only time is not subject to human influence. Under the assault of human activities the characteristics of previously pristine soils change dramatically and pseudoequilibria are disturbed. The concept of soil health, sometimes referred to as soil quality, has been widely discussed and even debated. Doran[77] defined soil health as the capacity of a living soil to function, within natural or managed ecosystems boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. In this review, I embrace the concept of a living soil, and, as defined in the Introduction, think of soil health as analogous to human health. Both must be in a state of well-being with respect to their physical, chemical, and biological characteristics. Likewise neither should be diseased nor compromised, and ideally, both should function sustainably at optimal potential. Human activities can maintain or even improve soil health, but often such activities are detrimental. The impacts are particularly clear the case of introduced contaminants, which can outsmart the soil amoeba defense. Thus, I now document some of the human activities that impact soil health.

What Infects or Disturbs Soils

Here I use the term *infect* loosely to characterize the introduction of chemical or microbial constituents into soil that have the potential to adversely impact or disturb soil health. I use the term *disturb* to describe actions that physically or chemically alter soils or their microbial inhabitants. Overall soils are remarkably resilient to the introduction of foreign constituents particularly if they are natural and organic. Hence almost all vegetation returned to soil is degraded over time via soil microbial populations. Likewise, foreign microorganisms introduced into a soil via bird droppings, animal feces, animal manures, or municipal biosolids normally cannot complete with the indigenous soil organisms and are rapidly killed off.[25] However, if the foreign constituents introduced into soil are inorganic and/or anthropogenic, soils can become adversely affected or infected. For example, most heavy metals introduced into a soil cannot be degraded microbially, although they may be methylated and volatilized as in the case of selenium and tend to remain within the soil indefinitely.[78] Soil microorganisms are known to develop heavy metal resistance and to be capable of changing the valence state of metals by using them as terminal electron acceptors.[79] Many specific mechanisms of resistance are now being established at the molecular genetic level.[80] Metal toxicity to soils usually occurs at very high metal loading rates, of if the soil pH becomes acidic, which increases the solubility of cationic heavy metals.

Anthropogenic organic compounds are also well documented as being capable of infecting a soil. Anthropogenic organics are frequently not degraded by soil microorganisms for two fundamental reasons. First, the organic structures are often dissimilar to most natural organic compounds, and thus soil microbes are unlikely to possess the enzyme systems necessary to degrade the compound. Second, many anthropogenic compounds are hydrophobic, and sorb to inorganic colloids, where they are protected from degradation.[81] For example, PBDEs used as flame retardants can remain in soil for up to 20 years with no evidence of degradation.[82]

As well as infecting soils, humans are very effective at disturbing soils. For example, a soil that developed over hundreds or even thousands of years can be obliterated in minutes through the use of a bulldozer. Another example of land degradation is commercial mining activities. Common mining practices include stripping off the surface soil and vadose material to expose mineral ones, which are subsequently treated to extract metals such as copper. The treated ore known as mine-tailings is then returned to the site as a viscous sludge to depths of 3–35 m. Such tailings are in essence crushed rock, which results in a perfect inorganic matrix of sand, silt, and clay-sized particles.[83] The tailings would be considered as a soil except that they have negligible organic matter and virtually no microorganisms. The pH of mine tailings can be acidic or alkaline depending on the mining treatment processes, and normally mine tailings support minimal vegetative growth.[83] Vast areas of the United States contain unvegetated mine tailing sites that are barren and susceptible to air pollution during high wind events. Commercial agriculture is another anthropogenic activity that can adversely impact soil if appropriate management practices are not adhered to. Mismanagement can result in water or wind erosion, salinization, and soil nutrient depletion including organic matter.

Overall, due to human activities such as construction, agriculture, and mining to name a few, millions of acres of pristine soil in the United States have at the least been disturbed and in many cases destroyed.

What Heals Soils

Once infected and particularly when disturbed, soils frequently fail to function as a living soil and soil health is destroyed. The best example of such destruction is evidenced by urban sprawl where large areas of soil become covered with concrete or tarmac. However, soils disturbed by agriculture or mining can be healed by proactive human activities including the sequestration of carbon as soil organic matter.[84]

The benefits of soil organic matter on soil quality of health are very well documented in terms of improving soil structure, soil nutrient status, soil water holding capacity, and the general physical, chemical, and microbial properties of soil. Soil organic matter is also critical for good crop yields.[84] Strategies to increase the soil carbon pool were elegantly documented by Lal[84] including no-till farming, use of cover crops, nutrient management, application of manures or sludges, and water conservation and harvesting. Enhanced carbon sequestration not only has the potential to heal soils, but also promote other global benefits such as reduced global warming and improved food security.[84]

Soils created as mine tailings can also be healed through addition of organic matter such as municipal biosolids. Copper mine tailings outside of Tucson Arizona were restored and revegetated through the application of up to 371 dry ton/ha of Class A municipal biosolids.[83] Sites were monitored post-biosolids application for 10 years. Following biosolids amendment, bacterial numbers in the tailings increased from $<10^3$ cfu g^{-1} to 10^7 cfu g^{-1} and remained elevated throughout the 10-year period. Also during this period, successful revegetation occurred and persisted. At the end of the monitoring period, biosolids amended tailings demonstrated typical bacterial community activities such as nitrification, sulfur oxidation, and dehydrogenase activity. In addition, cloning and sequencing analysis of community DNA showed that the biosolids amended tailings eventually acquired microbial diversity levels similar to a neighboring undisturbed desert soil (Figure 2). The study illustrated that amending copper mine tailings with municipal Class A biosolids

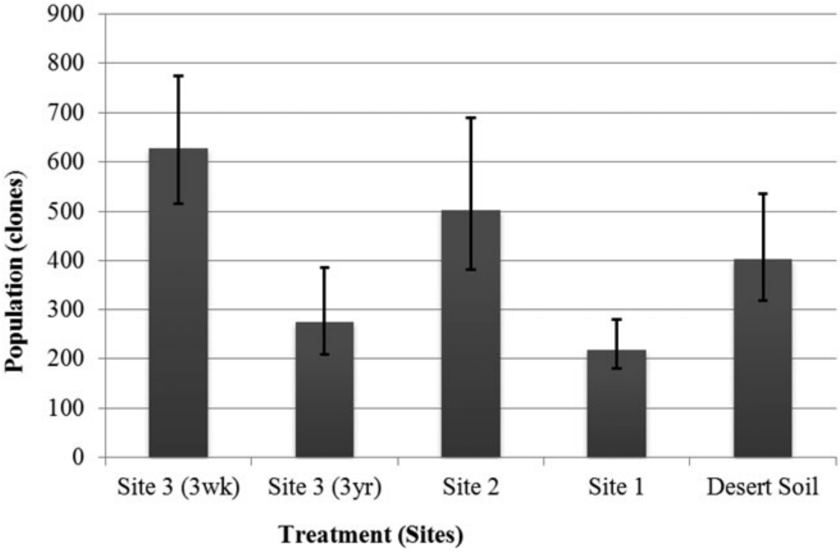

FIGURE 2. Species diversity (Simpson-estimation) as calculated by MOTHUR with 95% confidence intervals represented by error bars at a 0.05 OTU definition level. (Site 3 (3wk) = 3 weeks after application; Site 3 (3yr) = 3 years after application; Site 2 = 9 years after application; Site 1 = 11 years after application, and the unamended desert soil). Source: I. L. Pepper.

was effective in converting barren mine tailings into a functional soil as indicated by healthy soil microbial numbers, activity and diversity, and the establishment of a vegetative cover. Biosolids have also been used successfully to restore other drastically disturbed lands across the nation. Biosolids can also be used to reduce soil erosion and reduce heavy metal bioavailabiity.[85]

Thus, through careful management practices, soils in some cases can be healed and their soil health restored.

What Soils Drink

Humans affect soil health by influencing what and how much soils drink. Water is essential for the formation of all soils, for the maintenance of soil health and, of course, for all biological forms of life. Soil microorganisms can exist for months in soils with very low moisture contents, and even years in some desert areas. However, most soils receive periodic inputs of water as rainfall. Such naturally produced rainfall does not for the most part adversely affect soil health, although acid rain can result in large quantities of calcium and magnesium being lost from soils.[86] Humans however do influence soil health via what soils drink through the application of irrigation

TABLE 8. Characteristics of salt affected soils

Soil	pH	Electrical conductivity (mmhos cm^{-1})	Exchangeable sodium (%)
Saline	<8.5	>4	<15
Saline-sodic	<8.5	>4	>15
Sodic	>8.5	<4	>15

water for crop production in arid regions of the world. As the world population increases, irrigation of crops is likewise expected to increase.[87] In many regions, supplies of good quality water for irrigation are decreasing and there is increased reliance on use of brackish waters. Such waters can ultimately result in the buildup of salts in soil (saline soils) or high pH soils resulting from excess sodium accumulation (sodic soils). The characteristics of such soils are shown in Table 8, and all three categories, saline, saline sodic, or sodic soils result in such poor soil health that they cannot maintain desirable plant growth.

Sodic soils can be healed or restored through soil amendments such as gypsum ($CaSO_4$ $2H_2O$), or application of elemental sulfur to calcareous soils. The sulfur is oxidized by autotrophic soil bacteria such as *Thiobacillus thiooxidans*, which results in the production of sulfuric acid to react with $CaCO_3$ to yield $CaSo_4$. The soluble Ca from gypsum replaces the exchangeable Na ions and soil integrity is restored with a concomitant soil pH decrease. Saline soils were historically recovered through the application of excessive amounts of irrigation water, above and beyond crop consumptive use demands, to leach excess salts through the soil profile and out of the root zone. The amount of excess irrigation water is referred to as the leaching fraction. Traditional understanding of salt removal promoted large leaching fractions and large amounts of irrigation water being essentially wasted as drainage. In addition, application of excess water increases the potential for pollution of groundwater with pesticides and nitrates and production of saline drainage water that degrades down-stream surface water subsequently reuse for irrigation. Smaller leaching fractions minimize surface and groundwater pollution, but risk soil salinization; hence, erring on the side of larger leaching fractions became conventional wisdom. Recently Letey et al.[88] provided a new evaluation of soil salinity leaching requirements based on new transient-state models that allow more accurate predictions of the dynamics of chemical-physical-biological interactions in agricultural systems. The work group concluded that

> present guidelines overestimate the leaching requirements and the negative consequences of irrigating with saline waters. This error is particularly

> large at low leaching fractions. This is a fortuitous finding because irrigation to achieve low leaching fractions provides a more efficient use of limited water supplies. (Letey et al., p. 502)

Finally, note that as urban population centers grow within arid areas, wastewater treatment results in large amounts of reclaimed water that is increasingly used for irrigation purposes.[89] Although the chemical quality of such waters are frequently very acceptable, such waters often contain water-based pathogens such as *Legionella* or *Mycobacterium*.[90] Overall it can be seen that humans play a key role in maintaining soil health through appropriate crop and irrigation strategies involving the use of poor quality irrigation waters. Such strategies are essential to maintain soil health and environmentally sustainable agriculture.

What Soils Eat

Conventional wisdom does not allow for the concept of soils eating, yet most plant nurseries promote the concept that it is beneficial to feed your soil with organic soil amendments. Technically it is the vast populations of soil microorganisms that ingest food or substrate. These diverse populations result in biochemical transformations through two fundamental mechanisms: (a) oxidation of substrate to obtain energy or (b) reduction of terminal electron acceptors utilized in respiration. Less prominent in soils are the phototrophs, which gain energy via photosynthesis, and fermenting microbes that transfer electrons among organic molecules. The most dominant groups of soil microorganisms are the heterotrophs (including bacteria and fungi) that generate energy by oxidation of organics. In contrast, autotrophic bacteria generate energy via oxidation of inorganics. Heterotrophs are vital to soil health because they biodegrade organic materials, ultimately producing carbon dioxide when compounds are completely mineralized. In pristine or healthy soils, the source of organic residues that are degraded include natural plant vegetation such as grasses or tree leaves, and animal feces and bird droppings. These are normally easily degraded by heterotrophic soil populations.[91] During degradation, soil health is improved due to increased numbers of soil microorganisms, and improved soil structure, which improves soil aeration.

Humans influence soil health in terms of what soils eat in two ways. First, animal manures (raw) and municipal biosolids (treatment product of wastewater) are routinely applied to agricultural land.[92] Second, anthropogenic compounds such as pesticides are also routinely applied to agricultural land. In addition, in the past, many waste organic compounds were routinely deposited into soils including trichloroethylene (TCE). Many of these organic wastes and their constituents can be microbially degraded, but others such

TABLE 9. Examples of potential terminal electron acceptors in soil under variable redox conditions

Soil organism	Terminal electron acceptor	Reaction	Product
Aerobe	O_2	Aerobic respiration	CO_2
Facultative Anaerobe	NO_3	Denitrification	N_2, N_2O
Anaerobe	$SO_4{}^{2-}$	Sulfate reduction	S^{2-}
Anaerobe	CO_2	Methanogenesis	CH_4
Anaerobe	Fe^{3+}	Iron respiration	Fe^{2+}

as PBDEs are hydrophobic, and sorb to soil colloids where they are protected from degradation by soil microbes.[82] In most instances, feeding soil with anthropogenic compounds does not adversely affect soil health. In fact, addition of pharmaceuticals such as estradiol has been documented as enhancing soil biomass.[93] However, additions of high concentrations of toxic anthropogenics can eliminate sensitive populations of microbes such as the nitrifiers.[94] In contrast, feeding soil with natural sources of organic residues such as plant residues or composts is well documented as improving soil health and productivity, and is the basis of organic gardening.[95] More importantly, maintenance of soil organic matter through residue addition is critical to overall soil quality.

What Soils Breathe

Breathing can be defined as the act of respiration, which for organisms results in energy generation. For humans, breathing is straightforward and requires oxygen as a terminal electron acceptor, and all humans are aerobic. In soils, respiration by microbes is more diverse and can be undertaken by aerobic, facultative anaerobic, or true anaerobic microorganisms. In the presence of oxygen, aerobic organisms (heterotrophic or autotrophic) utilize oxygen as a terminal electron acceptor. As oxygen levels within soils decrease other compounds are utilized as terminal electron acceptors by facultative anaerobes such as the denitrifiers, which utilize nitrate. In soils saturated with water, the oxygen status of the soil becomes so depleted that true anaerobic activity occurs, where carbon dioxide, or metals such as Fe^{3+} are utilized as terminal electron acceptors.[91] The terminal electron acceptors that can be utilized in soil under variable redox conditions are shown in Table 9. During heterotrophic aerobic respiration, CO_2 is released into the atmosphere. As soil moisture increases, CO_2 released via aerobic respiration decreases.[96] In contrast, under these conditions, methanogens utilize CO_2 as a terminal electron acceptor with the concomitant release of methane. Many of the products of respiration are greenhouse gases including CO_2, CH_4, and N_2O and enhance global warming and climate change potential.[97]

From the soil's perspective, health is retained regardless of whether aerobic or anaerobic conditions prevail. However, from the perspective of the growth of most plants, anaerobic conditions are unhealthy and saturated soils (oxygen-depleted conditions) often result in plant death. In many areas of the world, natural rainfall regulates the amount of moisture within soils, but humans can clearly influence the redox potential of soils by irrigation practices. Excess irrigation can raise water tables, resulting in anaerobic conditions in the root zone and dramatically reduce plant growth. Humans can also influence soil redox potential by destroying soil structure through compaction of the soil.[98] Frequently this can occur by utilization of heavy farm equipment over moist soils. Such operations can result in massive structure where soil porosity (and oxygen) is minimized.[99] Conversely, the promotion of soil structure during microbial degradation of organic soil amendments added to soil by humans, can result in more favorable aerobic conditions.[100] As such, human activity can yet again directly influence soil health.

IMPROVED HUMAN HEALTH THROUGH SOIL HEALTH MAINTENANCE

Direct Influence on Human Health

The obvious and most direct manner in which we can improve human health through soil health maintenance is via the production of large amounts of healthy foods including cereals and grains, pulse crops, vegetables, and fruits. Here soil health maintenance should focus on humans creating an optimum environment for plant growth as described in all parts of the Humans and Soil Health section. It would also require humans to be careful with respect to pollution prevention. As part of this strategy, organic wastes should only be applied to soils at appropriate agronomic rates that allow for the material to be incorporated into the soil following microbial degradation. With respect to inorganic compounds, care must also be taken, and wastes with excessive amounts of heavy metals such as Zn, Cd, or Hg should not be applied to soils. The green revolution of the 20th century resulted in vast increases in crop yields for many decades. However more recently, attention has turned to sustainable practices that protect soil health and degradation including reduced tillage practices.[95,101] The importance of soil health maintenance on improved human health through safe food production cannot be overemphasized.

Indirect Influence on Human Health

A major indirect effect of soil health on human health is the influence of soils on global warming. Currently there is a debate about how soils may influence global warming.[102] Soils can be a source of CO_2 due to microbial

TABLE 10. Strategies and practices that can improve human health through soil health maintenance

Strategy	Impact on human health
A. Influence of soil health on agricultural food production	
Soil pollution prevention	
- Reduce heavy metal soil inputs	Healthy food production
- Reduce pesticide use	
- Reduce antibiotic use for animals	
Sustainable agriculture	
- Reduced tillage	Enhanced food production both now and in the future
- Erosion control	
- Integrated pest management	
- Organic amendments	
B. Influence of soil health on global warming	
Reduction of greenhouse gas emissions	
- Reduced tillage	Reduced global warming
- Enhanced crop production (CO_2 uptake)	
- Enhanced carbon sequestration	
- Set aside land for conservation	
C. Influence of soil health on human health via gardening	
Promotion of gardening	
- Home gardening	Multiple physical and emotional health benefits
- Community gardening	
- Organic gardening	

respiration, or a sink for CO_2 due to enhanced photosynthetic activity and carbon sequestration. Although the debate has yet to be resolved, it is clear that even relatively small changes in soil carbon storage could significantly affect the global carbon balance. Human activities including intensive farm tillage practices enhance soil organic matter degradation releasing CO_2 into the atmosphere.[103] In contrast, setting aside land for conservation, reduced tillage, and enhanced crop productivity (CO_2 uptake) is estimated to enhance soil carbon sequestration to the extent of $\simeq 10^7$ metric tons carbon annually worldwide.[104] Thus human activities could enhance soil health and reduce global warming, both of which could minimize catastrophic impacts on human health via extreme weather events and natural disasters.

A more subtle indirect effect on human health is that of home gardening and community gardens, which promotes a variety of benefits to human health. Nutritional awareness is enhanced by gardening as evidenced by a study of high school students where gardening enhanced the willingness of students to taste vegetables.[105] Similarly, gardening was shown to enhance vegetable consumption in three ethnic groups.[106] Community gardens enhance nutrition and physical activity, promoting public health, and improving quality of life.[107] Van den Berg and Custers[108] recently provided the first experimental evidence that gardening can promote relief from acute stress. Clearly, multiple human health benefits accrue from gardening be it at homes, in schools, or via community gardens, and there has been a resurgence in gardening activities throughout the United States. Besides emotional and social attributes, the grassroots experience of physically interacting with the soil dramatically improves appreciation of soil as a valuable natural resource. Strategies and practices that can improve human health through soil health maintenance are outlined in Table 10.

CONCLUDING REMARKS

In this review article scientific documentation of the soil health–human health nexus has been provided by illustrating the influence of soil health on human health, and conversely, the influence of human activities on soil health. Clearly, soils influence all aspects of our daily lives, and yet the importance of soil with respect to human health is not well recognized by everyday people. The unawareness is, perhaps, surprising given numerous testimonials, including President Franklin D. Roosevelt ("The Nation that destroys its soil destroys itself") and Leonardo da Vinci ("Even the richest soil, if left uncultivated will produce the rankest weeds"). History has taught us that soil is a precious gift, whose health must be maintained, because life on Earth without soil would be impossible.

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