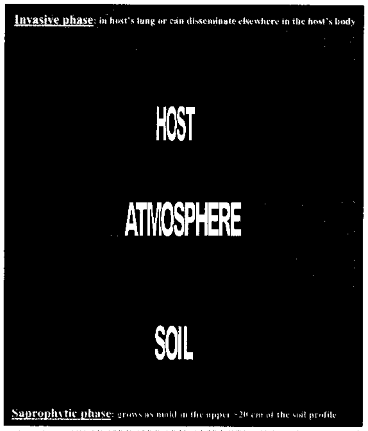

CHAPTER 19

THE ECOLOGY OF SOIL-BORNE HUMAN PATHOGENS

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CONTENTS

I. INTRODUCTION

The surface of the Earth, with the exception of the oceans and polar ice caps, is in large part covered with a marvelously complex layer of material called soil, from which we derive a host of useful products including fiber, fuels, building materials, animal forage, many mineral commodities, natural medicines (including antibiotics), and most of our food supply. Soil is teeming with life and is home for a huge array of living organisms. The vast majority of these living organisms are microbes that are ubiquitous on Earth (Table I). They occur in all soils, salt and fresh water, the harsh climates of the Artic and Antarctic, adjacent to deep-sea hydrothermal vents associated with spreading zones between tectonic plates, throughout the atmosphere, and deep below the surface of the Earth in oil wells where they have been isolated from the surface environment for millions of years (Staley, 2002, p. 13).

Some soil-dwelling microbes are pathogenic for humans, including protozoa, fungi, bacteria, and also viruses and the less well understood prions, both of which require a plant or animal host for their survival.

TABLE I. Typical Numbers of Soil Organisms in Healthy Ecosystems

		Agricultural Soils	*Prairie Soils*	*Forest Soils*
Bacteria	Per teaspoon (one gram dry)	100 million to 1 billion.	100 million to 1 billion.	100 million to 1 billion.
Fungi	Per teaspoon (one gram dry)	Several yards. (Dominated by vesicular-arbuscular mycorrhizal (VAM) fungi).	Tens to hundreds of yards. (Dominated by vesicular-arbuscular mycorrhizal (VAM) fungi).	Several hundred yards in deciduous forests. One to forty miles in coniferous forests (dominated by ectomycorrhizal fungi).
Protozoa	Per teaspoon (one gram dry)	Several thousand flagellates and amoebae, one hundred to several hundred ciliates.	Several thousand flagellates and amoebae, one hundred to several hundred ciliates.	Several hundred thousand amoebae, fewer flagellates.
Nematodes	Per teaspoon (one gram dry)	Ten to twenty bacterial-feeders. A few fungal-feeders. Few predatory nematodes.	Tens to several hundred.	Several hundred bacterial- and fungal-feeders. Many predatory nematodes.
Arthropods	Per cubic foot	Up to one hundred.	Five hundred to two thousand.	Ten to twenty-five thousand. Many more species than in agricultural soils.
Earthworms	Per cubic foot	Five to thirty. More in soils with high organic matter.	Ten to fifty. Arid or semi-arid areas may have none.	Ten to fifty in deciduous woodlands. Very few in coniferous forests.

From NRCS, 1999.

Helminths (which are in the mesofauna size class) are included in this chapter because of their importance as human pathogens and because of the numbers of pathogenic viruses and bacteria associated with them that can be introduced into the soil environment. Over 400 genera of bacteria have been identified with possibly as many as 10,000 species and, with the exception of viruses, they are in most cases more abundant than any other organism in soils. The number of bacteria that can be cultured in the laboratory is probably less than 1%; thus their actual diversity is probably much greater (Paul & Clark, 1996; Coyne, 1999). Fortunately, relatively few of this vast population of microbes are pathogenic for humans. For example, of the approximately 100,000 species of fungi currently recognized (University of Leicester, 1996), only about 300 are known to cause human disease (McGinnis, 1998).

Nonetheless, soil-borne human pathogens have extracted an unbelievable toll in disfigurement, suffering, blindness, death, and medical costs from the human race throughout history, and they will continue to do so for the foreseeable future. Examples are Ascariasis (roundworm) 60,000 deaths in 1993; Schistosomiasis, 200,000 deaths in 1993; and *Clostridium tetani*, killing 450,000 newborns and about 50,000 mothers each year (World Health Organization, 1996). Almost 3 million deaths a year, mostly in developing countries, are attributed to diarrheal diseases, and many are contracted from microbes introduced into the soil via fecal waste and then ingested (NIAID, 2000).

II. SOIL FUNDAMENTALS

Soil may be defined as that part of the regolith that is capable of supporting plant life. The regolith is the portion of unconsolidated rock material that overlies bedrock and forms the surface of most land. The upper boundary of soils is either air or shallow water, and horizontally, soil boundaries are bodies of deep water, rock outcrops, or permanent ice fields. The lower limit of soil layers is the underlying bedrock where biological activity is severely restricted. Microbes are abundant in the upper parts of soil layers, where organic material is more likely to be present, and decrease in numbers with depth. However, some microbes may occur in the deepest soil layers and in places within the fractured underlying bedrock. The physical properties of soils are described in depth by Brian Alloway in Bioavailability of Elements in Soil in this volume. In this chapter only additional material important to the understanding of soil dwelling microbes is presented.

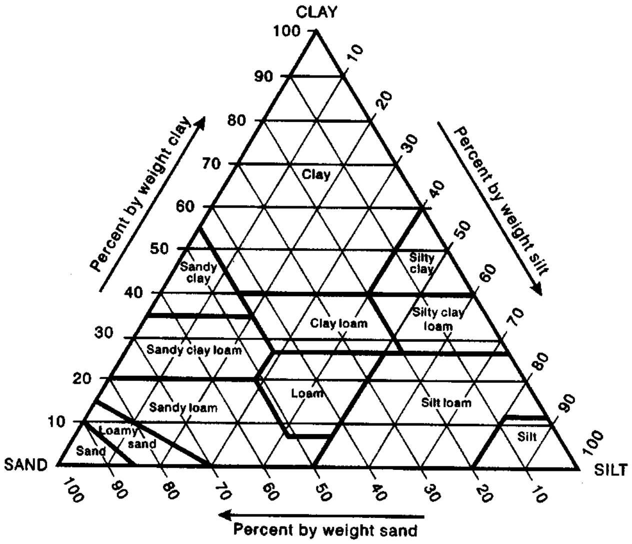

FIGURE 1 U.S. Department of Agriculture soil texture triangle. Sand, silt, and clay are defined by the size of their constituent particles. Sand is composed of particles with sizes ranging from 2.0 to 0.05 mm. Silt is composed of particles from 0.05 to 0.002 mm. Clay is composed of particles less than 0.002 mm in size.

A. Important Physical and Chemical Properties of Soil

Physical properties of soils—texture, porosity, permeability, water-holding capacity, and temperature—are of considerable importance in determining the characteristics and microhabitat utilization of a given soil by microbes. Texture is the term used to describe the relative proportions of sand, silt, and clay-sized particles in a given soil (Figure 1). Texture is important to microbes for several reasons: (1) it is the major factor controlling water holding capacity of a soil, (2) it determines the amount of pore space and the character (size and distribution) of the pore space, (3) it affects the rate of chemical reactions, (4) it is a major control on root penetration by plants, and (5) it controls soil aeration. All of these factors influence the types, distribution, and abundance of different microbes in any given soil profile.

Porosity is the percentage of the volume of a soil not occupied by solids; i.e., the interstices, isolated or interconnected, between individual solid soil particles (either mineral or organic). The availability of water and air are controlled largely by the amount, size, and interconnections between interstices, which are also the habitat for microbes.

Permeability is the ability of a soil to transmit water. Soils that contain a high proportion of sand will have larger continuous pores and will rapidly transmit water and air. In comparison, clay soils, which often have a high porosity because of the small size of individual particles, may have low permeability and transmit water slowly because of poor connectivity between soil interstices and swelling of individual clay particles. Soil water-holding capacity and soil temperature are discussed in the next section.

B. Soil-Forming Factors

Five major factors interact to form soils: parent material, climate, soil organisms, topography, and time.

1. *Parent Material*

Parent material may be residual or transported igneous, metamorphic, or sedimentary bedrock debris. The mineralogy of parent material is very important in determining the type and amount of clay minerals developed in a given soil profile, which in turn has a profound effect on the types and distribution of soil microbes. Texture and the degree of consolidation of the parent material directly control the movement of water and air within the soil, the rooting ability of plants, and consequently the mobility of many microbes.

2. *Climate*

Climate characteristics, temperature and moisture in particular, influence the kinds and amount of soil microorganisms, the rate of decomposition of organic material, weathering rates of mineral matter, rates of formation of secondary minerals, biological activity, and the removal, movement, and deposition of materials between different soil layers.

Soil temperatures vary with latitude, altitude, slope aspect, vegetation cover (shading), soil color, and moisture content. Typically the surface temperature of soils ranges from below freezing to as much as 60°C and displays daily and annual cycles. Soil temperature has an important influence on biological processes such as the germination of seeds, nutrient absorption, root growth, and microbial activity, which generally is enhanced at higher temperatures if adequate moisture is available.

Precipitation may result in water on the land surface, water within the soil horizons, or deeper below the surface in ground water. Water that infiltrates the soil will surround soil particles, fill pore spaces, and may eventually move downward into the water table. A quantitative measure of water availability is the soil water potential, which is defined as the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the soil water (at the point under consideration) (Soil Science Society of America, 1998).

Informally, soil water potential is the amount of energy that must be expended to extract water from soil. It may be expressed mathematically as:

$$\Psi_{soil} = \psi_g + \psi_m + \psi_s$$

where Ψ_{soil} is the soil water potential, (ψ_g) is the gravitational potential, (ψ_m) is the matric potential, and (ψ_s) is the solute (or osmotic) potential. Water potentials are expressed in megapascals (MPa). One megapascal equals 1×10^6 pascals. One atmosphere equals 0.1013 MPa. The matric potential is related to the attraction of water molecules to solid surfaces. In unsaturated soils it is always negative and becomes more negative as the surface area of the soil increases. Solute potential is associated with the solutes in the soil and is always a negative value. It becomes more negative as soil solutes increase and the soils become more saline. The gravitational potential may be positive or negative depending on where in the soil it is measured relative to some arbitrary reference level. The reference level is generally set in the soil profile at some point (e.g., at the water table) below the soil profile considered, thus the gravitational potential is usually positive in reference to microbes. If the reference level is the soil surface then the gravitational potential is negative for any point below the surface. The osmotic and matric potential together determine the amount of energy that must be expended by microbes to extract water from soil.

In general, microbial growth rates are greatest for Ψ_{soil} near −0.01 MPa and decrease as soils become drier and have correspondingly larger, negative water potentials. Microbial activity also decreases as soils become waterlogged or saturated, which results in Ψ_{soil} values at or near zero. At field capacity the matric potential of the soil water will generally be in the range of −0.01 to −0.03 MPa and the wilting point will occur near −1.5 MPa. Soils vary widely in the size and shape of their pore space and this variation precludes a simple relation between the water content of any given soil and the associated water potential. However, when a soil is saturated and all pores are completely filled with water, the matric potential is zero.

Because few soils have solid particles that are uniform in size, shape, or composition, texture and structure have a large influence on the matric potential of unsaturated soils. For example, the amount and type of clay in a given soil is extremely important, as some types of clay will swell as water is added and shrink as they dry. Matric potential is complicated by these changes. As water drains from a saturated soil containing some clay, its removal is mostly influenced by the larger particles (most often sand-sized particles) and the matric potential determination given above is relatively straightforward. As drying progresses the behavior of the clay particles becomes more important. The clay particles carry a variable negative electrical charge and thus tend to repel one another, and work is necessary to bring them closer together. Drying also causes the clay to shrink due to the loss of water between layers in the clay structure. The force of repulsion between the particles thus determines the matric potential of the remaining water. Detailed discussions of water potential and its effects on soil microbes may be found in Griffin (1972), Harris (1981), and Brown (1990).

Many soil microbes obtain nutrients from water by diffusion and rely on water for mobility, either by swimming, movement by Brownian forces, or flow of water. Void spaces smaller than the diameter of a given organism and pores from which water has been removed act as barriers. As soils dry, the water films around solid particles become thinner, which impedes bacterial and protozoal mobility, limits nutrient availability, and slows nutrient diffusion through cell membranes. If films become discontinuous, then microbes may be trapped or have to move in much more tortuous paths in the remaining water films. In general, in wet unsaturated soils, all major groups of microbes are active and in competition. In drying soils with progressively lower matric potentials, unicellular organisms become less active and ultimately microbial activity in relatively dry soils is confined largely to filamentous organisms, such as fungi that can, through growth of hyphae, utilize water unavailable to bacteria.

3. Soil Organisms

Many organisms have long been recognized as having an important role in the genesis of soils. Microbes play an important role in many soil processes. They convert plant and animal residue into humus and produce compounds that help bind soil into aggregates. They create new organic compounds that are nutrients for other microbes. Many microbes have mutually beneficial associations with higher plant forms and may fix the nitrogen that is needed by these organisms. They may also inhibit the growth of disease causing soil-borne organisms and mediate many soil related chemical reactions.

Soil microbial populations are generally more abundant in surface horizons than in deeper horizons but are not uniformly distributed laterally or with depth (Coyne, 1999, p. 152). Typically, populations occur in localized concentrations associated with various favorable and unfavorable microenvironments throughout the soil profile (a vertical section of the soil which includes all the soil horizons). For example, the presence of plant roots is influential in determining the activity of microbes. The soil area influenced by a plant root is called the rhizosphere. This area (a few millimeters from the root) usually has chemical properties quite different from the bulk of the soil because of the uptake by the plant roots of moisture and nutrients and the secretions and exudates of amino and organic acids, sugars, proteins, and other chemical elements from the roots. Microbes may be up to 100 times more concentrated in the rhizosphere than in soil some distance from roots. Plants and microbes may form symbiotic relationships that are mutually beneficial. Examples are bacteria of the genera *Rhizobium* and *Bradyrhizobium* that convert (fix) atmospheric nitrogen into nitrogen compounds that can be utilized by the plant that in turn reciprocates and supplies carbohydrates to the bacteria. Another example are mycorrhizal fungi that attach to and grow on roots thereby acting as an extension of the root system which greatly facilitates the uptake of water and nutrients by the plant. In exchange, the fungus obtains sugars and other nutrients directly from the plant root.

4. *Topography and Time*

On the largest scale, climate and vegetation have great relevance to the distribution and formation of various soil types. On a smaller scale, topography modifies the climate and vegetation factors and has a major role in determining the character and development different soil types. The length of time that a given parent material has been exposed to the forces of climate, development of vegetation, and influence of animal life is believed by many soil scientists to be a strong influence on the nature of soil development. And, in general, the degree of development of differentiation between horizons in a soil is related to the age of a soil.

III. SOIL AS A COMPLEX SYSTEM

The study of complex systems has appeared as a separate scientific discipline only over the last 25 years and debate is ongoing as to its precise definition (Flake, 1998; Cowan et al., 1999). However, there seems to be general agreement about some features that all complex systems exhibit:

1. They are collections of many simple nonlinear units that operate in parallel and interact locally with each other to produce behavior that cannot be directly deduced from the behavior of its component units
2. There are numerous units that operate in layers or at different scales
3. Local interactions within layers sometimes produce a global behavior at another scale or layer, which is called emergent behavior
4. The result of emergent behavior is that simple components combine to form more complexity than the sum of its parts (Flake, 1998).

Soils are the interface between the lithosphere, atmosphere, hydrosphere, and biosphere. They are composed of an enormous number of individual constituents, both organic and inorganic, that are highly diverse in form, composition, and purpose. All the constituents adapt and interact with each other and respond chemically, biologically, and physically to processes specific to any of the abovementioned Earth domains. Rates of reaction to changes in environmental processes are not constant and rarely reach equilibrium. Many processes (perhaps most?) are nonlinear and thermodynamically irreversible. Soils are also open systems that exchange matter, energy, and organisms across numerous boundaries. This incredibly diverse, heterogeneous, dynamic, reactive, and adaptable nature makes the study and description of any aspect of soils a daunting task. Perhaps the overriding rule about soils is that they are constantly changing and adapting to their environment, and that the aggregate behavior of a soil cannot be predicted by summing up the behavior of its individual parts. These changes may be relatively rapid and readily visible or measurable (e.g., microbial growth, movement of soluble components, changes in water potential, seasonal changes in salinity, etc.) or they may be longer term taking place over years, decades, centuries, or millennia (e.g., weathering of silicate minerals and formation of clays, destruction of agricultural lands due to salt accumulation in irrigated areas, vegetation changes due to global warming or cooling, continental erosion, and deposition processes).

Most soil processes and microbial responses are gradational as are many boundaries between soil types, horizons, and chemical and physical properties. This lack of sharply defined volumes bedevils soil mapping and descriptions because spatial gradients in both process and products are at best poorly represented and most often ignored. One way of dealing with diverse data bounded by gradients is through the use of fuzzy logic; a method that allows the grouping of data into continuous sets in which membership can range between 0 and 1. Classes of data may then be expressed on an intermediate scale and spatial variations accounted for. The use of fuzzy logic (by the authors) to describe the habitat of a soil-borne human pathogen (*Coccidioides*) is described in the case study (Section XIII).

IV. PATHOGEN CLASSIFICATION

Classification is necessary to develop and discuss the connections and relationships between geology, soils, and soil-borne human pathogens. Soil fauna have been classified by several criteria including body size, degree of presence in soil, habitat preference, and activity (Wallwork, 1970). Soil-borne human pathogens include many biological entities, most of which contain widely diverse members. Thus, it is useful to organize different pathogenic microbes into groups on the basis of the character of their soil residency. Any type of pathogen that is present in the soil, for any reason or time period, is included in the following classification in which two factors are essential: presence in soil (for any reason), and human pathogenicity. The classification terms of permanent, periodic, and transient from Wallwork (1970) were adopted, but redefined. An additional term, incidental, was added and defined.

Included in our classification are several human pathogens that have been classified as water- or food-borne. Many pathogens classified as water-borne are the result of animal or human fecal, urine, or other wastes introduced first into the soil environment and subsequently washed into surface water or incorporated into groundwater. Infection then follows by contact with, or consumption of, contaminated water. Similar circumstances take place with some food-borne diseases. The pathogen is again introduced into the soil via defecation or through some type of contaminated waste material and then may be consumed on unwashed raw fruit or vegetables.

Many pathogens have complex life cycles that may involve hosts in which they live and reproduce, biological vectors (insects, animals) and physical vectors (wind, water) for transport, and reservoirs to exist in during adverse environmental conditions. Soils provide these features to a wide variety of microbes and thus, the following classification to illustrate the importance of soil attributes and processes in the understanding the pathology of numerous diseases is offered.

In our classification some microbes may be classified as both transient and incidental. An example is *Giardia lamblia*, which can be introduced naturally into the soil through animal feces but can also be introduced anthropogenically via sewage systems, allowing for its dual classification. Four soil-borne pathogen residencies are defined below.

1. Permanent: Pathogenic organisms that are permanent soil inhabitants and can complete their entire life cycle within a soil environment. Examples are the bacteria *Clostridium botulinum*, *C. tetani*, *Burkholderia pseudomallei*, and *Listeria monocytogenes*. Also included are dimorphic organisms if one of their morphologic forms is capable of living and reproducing completely within the soil. Examples of permanent dimorphic soil pathogens are the fungi *Coccidioides* and *Histoplasma capsulatum*.
2. Periodic: Pathogenic organisms that require part of their life cycle to be completed within a soil environment on a regular, recurring basis. Examples are spores of *Bacillus anthracis* and the eggs laid in the soil by tick vectors that contain the bacterium *Rickettsia rickettsii*. Additional examples are eggs of the helminths *Ancylostoma duodenale* and *Necator americanus* (hookworms).
3. Transient: Pathogenic organisms that may naturally occur in soil, but the soil environment is not necessary for the completion of the organism's life cycle. Examples are cysts of a protozoan parasite *G. lamblia* and viruses in the genus *Hantavirus* that are introduced into soil environments worldwide via urine and feces of rodent vectors. Also included are *Leptospira*, a bacterium shed in urine of animals on soil, skin, and water and spores of the bacterium *Coxiella burnetii*.
4. Incidental: Pathogenic organisms introduced into the soil via anthropogenic means such as in sewage

sludge, waste water, septic systems, unsanitary living conditions, biologically toxic spills, dumping of biohazardous waste materials, and release of biological warfare agents. Examples of viruses are enterovirus poliovirus (etiological agent of polio), enterovirus Coxsackie A and -B, and enterovirus hepatitis A. Length of survival time and virulence depend on numerous physical and chemical factors of the soil and the effluent, and it can range from hours to years.

V. GATEWAYS FOR INFECTION

A soil-borne pathogen must come in physical contact with and establish itself in a human to cause disease. There are many ways in which this can be accomplished. First, soil-borne pathogens need to start this process from the soil. From the pathogen residency classification given above, the pathogen may be in the soil on a permanent, periodic, transient, or incidental basis. Permanent and periodic soil-borne organisms occur in the soil through natural pathways. Their presence in the soil is a normal part of the life cycle of a particular organism. Transient soil-borne organisms generally are incorporated into the soil via the excrement of wild or domestic animals. Residency in the soil is not necessary for their survival, but they are deposited there by natural means. Man places incidental organisms in the soil, generally in the form of solid human waste.

Probably the most common method of introducing soil-borne pathogens into the human body is through ingestion. Ingestion of soil-borne microbes is generally accidental, but in some cultures, geophagia is practiced. This subject is covered extensively in Geophagy and the Involuntary Ingestion of Soil, this volume.

In many countries, human waste is a valuable commodity that cannot be wasted. The practice of spreading human waste, or night soil, is found in many cultures and is an efficient means of introducing many human pathogens into the soil. The concentration of viruses in feces can be very high: e.g., enterovirus, 10^6 virus particles per gram; hepatitis A, 10^9 virus particles per gram; and rotavirus, 10^9 virus particles per gram (Sobsey & Shields, 1987). In the United States and other industrialized nations, the application of human waste products in the form of treated sewage sludge is also practiced, but regulated. In the United States 24% of sludge is applied on or just below the land surface as fertilizer (Bertucci et al., 1987). Federal pollution control acts regulate the microbial content of the sludge and access to treated land by people, grazing animals, and use for crops grown for human consumption. In the United States, 90–99% of viruses are removed by primary and secondary sewage treatment (Bertucci et al., 1987). Raw sewage in the United States can contain concentrations as high as 100,000 infectious units per liter (Sobsey & Shields, 1987). A 99% reduction still leaves 1000 infectious units per liter. In countries where no such standard exists, pathogens from human waste have a much easier time entering soil and the environment. Many bacteria are also known to survive the sewage treatment process. If pathogens are ingested that became soil-borne as human waste, the gateway of infection will be referred to as the fecal-soil-oral gateway.

Other oral (ingested) gateways for soil-borne pathogens require an intermediate host. For example, the trematode *Schistosoma mansoni* has a transient soil residency. In soil its eggs hatch into larvae, which can infect an intermediate host. This intermediate host releases infective larvae into its environment, water. Consumption of infected water results in the pathogen moving to the human host. The cestode *Taenia saginata* also has a transient soil residency. Cattle ingest soil infected with this pathogen and develop cysts in their muscles. When humans consume incompletely cooked beef, they can become infected with the pathogen.

A respiratory gateway for soil-borne pathogens occurs when soil-borne pathogens are inhaled as airborne dust. Airborne dust is soil in motion. Human activity or natural forces can cause dust emission for every type of soil given the proper environmental conditions. Each year, several million tons of airborne soil makes its way from Africa to the Americas, Europe, and the Middle East as dust. Asian dust crosses the Pacific Ocean and dust from the southwestern United States can make its way to Canada (Raloff, 2001). Every place on Earth receives dust from both local and distant sources and along with the minerals that make up the inorganic part of the dust ride fungi, bacteria, and viruses. African dust in the Caribbean has been shown to contain the fungus *Aspergillus sedowii*. Between 1973 and 1996 the Queen Elizabeth Hospital in Barbados documented a 17-fold increase in asthma attacks (NASA, 2001). This time frame corresponds to an increased period of dust production in Africa due to drought conditions.

Microbes rarely penetrate the intact skin. It has been speculated that the bacterium *Francisella tularensis*, the etiological agent of tularemia, may be capable of penetrating unbroken skin, but there is little support for this. It may, however, enter through the thinner epithelium of the conjunctiva. The nematode *Strongyloides stercoralis* is capable of burrowing its way through healthy skin. The bacterium *C. tetani* enters the body if contaminated soil makes contact with a break in the skin.

VI. Soil-Borne Human Pathogenic Helminths and Microbes

There are enormous numbers of helminths and microbes in the soil but only a small number of these are pathogenic to humans. Helminths are multicellular parasitic worms with complex reproductive systems and life cycles. Microbes are microscopic or submicroscopic organisms. For our purposes these include protozoa, fungi, bacteria, viruses, and, possibly, the agents (prions) of transmissible spongiform encephalopathies (TSE).

A. The Importance of Soil-Borne Human Pathogenic Helminths and Microbes

Diseases where the responsible pathogen spends some or part of its life in the soil are a major concern. In 1995, the World Health Organization (WHO) estimated that there were 3.7 million deaths worldwide from food-, water-, and soil-borne pathogens. More than 2.4 million of these deaths were children under the age of 5. In that same year, there were over 4 billion (4×10^9) new cases of these diseases (World Health Organization, 1996). A soil-borne bacterium, *C. tetani*, was responsible for almost half a million deaths to newborns and 50,000 mothers each year due to tetanus (World Health Organization, 1996). Billions of infections and over a million deaths occur each year from soil-borne helminths and protozoa (MacLean, 2002).

Some soil-borne human pathogens are called frank pathogens because they are capable of infecting anyone. An example is *C. tetani.* Most soil-inhabiting pathogens are opportunistic pathogens; their main targets of opportunity are individuals with a suppressed immune system. These may include young children, the malnourished, HIV-positive individuals, individuals who have had transplant surgery, and the elderly.

B. The Distribution of Helminths and Microbes in Soils

The distribution of helminths in soils fluctuates greatly with season, climate, and amount of organic matter in the soil. Helminths typically prefer warm, moist soils with plentiful organic material. During favorable conditions, most helminths are found in the upper 10–15 cm of the soil profile. They may move vertically in the soil profile in response to seasonal weather changes.

As discussed in the introduction, microbes are found virtually everywhere on the planet. They cannot move very far on their own, but their small size allows them to be distributed globally by wind, water, animals, and humans.

On a small scale, the type of microbes in the soil are determined by the types of soils and the local climate. *Penicillium* is a fungus that is found in both warm and cold soils, whereas *Aspergillus* (a fungus) grows better in warm soils. *Fusarium*, a fungus that causes banana wilt, does not thrive in soils with the clay mineral smectite (Paul & Clark, 1996). *Coccidioides*, a soil-borne fungus and the etiological agent of coccidioidomycosis, is found in dry, alkaline soils with a soil texture that includes large percentages of silt and very fine sand.

Within a given soil, the distribution of microbes on soil surfaces is uneven or irregular. Microbes are found clustered where conditions are favorable for growth and there may be a relatively large distance between the clusters. The determining factors for the locations of these clumps include the size and distribution of pore spaces in the soil, the soil water potential, the types of gases present in the soil pore spaces, the distribution of organic debris, and the local mineralogy of the soil. The influence of water potential on microbes has been discussed previously. Soil gases tend to be enriched in carbon dioxide and depleted in oxygen due to biological activity. Also, even in well-aerated soils, water may be blocking many pore spaces limiting the diffusion of oxygen in and carbon dioxide out. Some carbon dioxide is dissolved in soil water and produces carbonic acid, which helps to dissolve soil minerals (Coyne, 1999). Many microbes have an affinity for clay minerals within soils. Clays have large surface areas, are chemically reactive, and have a net negative charge. They are a source of inorganic nutrients, such as potassium and ammonia, and modify the chemical and physical habitat immediately around them. Also, clays adsorb water making it less available for microbes.

Most soil-dwelling microbes are found in the upper 8 cm of the soil profile, and their numbers decrease significantly below 25 cm depth (Coyne, 1999). The main reason is that the soil organic content, including root density, tends to decline with soil depth. Also, in alluvial soils the microbial populations fluctuate with textural changes in the soil profile. Microbes are more numerous in clay layers than in sand or coarser size materials. There is an increase in the numbers of microbes in the unsaturated zone directly above water table (Coyne, 1999).

The population of soil-dwelling microbes is also affected by human activities. Global warming (anthropogenic and natural) is changing the characteristics of soils worldwide. Acid rain has changed the pH and mineralogy of soils and has affected the microbial populations of these soils. Clear-cutting can increase microbial populations in soils due to an increased supply of dead organic material (Paul & Clark, 1996). Microbial populations are lower in tilled soils and compacted soils. Tilled soils are less moist than non-tilled and compacted soils have reduced pore space and aeration (Coyne, 1999).

VII. SOIL-BORNE HUMAN PATHOGENIC HELMINTHS

Human pathogenic helminths are all parasites and have man as their definitive host. Most inhabit the human intestines at some point in their life cycle; however, some are systemic in the lymph system or in other tissue.

The exact taxonomy of the helminths is under continuing discussion and will not be addressed here. They can be grouped into the nematodes (including hookworms, roundworms, whipworms, and pinworms), the trematodes (flukes), and the cestodes (tapeworms). Human diseases caused by cestodes and trematodes are saprozoonoses. These are zoonotic diseases where the transmission of the disease requires a non-animal development site or reservoir. In many cases this site is the soil. Table II presents a summary of the soil-borne human pathogenic helminths discussed here.

TABLE II. Selected Soil-Borne Human Pathogenic Helminths

Nematodes
Ancylostoma duodenale and *Necator americanus* (hookworm)
Ascaris lumbricoides (roundworm)
Enterobius vermicularis (pinworm)
Strongyloides stercoralis (roundworm)
Toxocara canis (roundworm)
Trichuris trichiura (whipworm)
Trematodes
Schistosoma spp. (fluke)
Cestodes
Taenia saginata (tapeworm)
Taenia solium (tapeworm)

A. Selected Soil-Borne Human Pathogenic Nematodes

Most human pathogenic helminths are nematodes. There are approximately 10,000 species of nematodes and approximately 1000 of these are found in soils. Most of the soil-dwelling nematodes are found in the upper 10 cm of the soil profile. Desert soils have the lowest population density of nematodes (about $400{,}000/m^2$) with the highest densities occurring in permanent pastures (up to $10{,}000{,}000/m^2$). Although there are large numbers of soil-dwelling nematodes, they do not contribute to a large percentage of the biomass (Coyne, 1999).

Nematodes are generally microscopic and transparent or translucent, ranging in length from about 0.05–2 mm. They have cylindrical unsegmented bodies with a bilateral symmetry. The body is covered with a tough cuticle. Nematodes have internal organs including a digestive, excretory, nervous, and muscular systems. They develop and grow by molting (shedding the cuticle). In almost all cases individual nematode species have sexual organs and separate sexes. Their life cycle begins with the development of an egg (most lay eggs in soil), followed by egg fertilization, embryonic growth in the egg, hatching and development of larvae, and molting and growth into an adult. Nematodes can produce five to six generations a year.

Nematodes are generally associated with water films in soils. These films partially fill the interstitial spaces between soil particles with water and are held in place by adhesion and cohesion. If soil becomes dry, many nematodes can form cysts or enter a dormant period allowing them to survive. They do well in warm organic-rich soils with a neutral pH, but can tolerate many soils. Most nematodes are predators or saprophytes. In this role they regulate microbial populations in soil by consuming up to 5000 bacteria per minute (Coyne, 1999).

The toll from nematode-caused human disease is staggering. Billions of people, rich and poor, are infected throughout the world each year, which causes much discomfort and suffering. There are over 130,000 deaths worldwide from nematode infections annually (MacLean, 2002). Many infections are the result of a lack of appropriate personal hygiene or from poor sanitation. Most nematodes infect a human host by being ingested and some infect by entering through the skin. Almost all soil-borne human pathogenic nematodes inhabit the intestines. One exception is the nematode that causes trichinosis. In this case the mature nematodes live in the small intestines but, after a short period of time, they release larvae that migrate to striated muscle tissue and form cysts. Nematodes are the etiological agent of numerous human diseases and have complex life cycles involving soil, water, and animals as illustrated in the following discussion.

1. *Ancylostoma duodenale* and *Necator americanus*

Two species of hookworms are capable of causing human intestinal infection, generally called ancylostomiasis. These are *Ancylostoma duodenale* and *Necator americanus*. *A. duodenale* is found in parts of southern Europe, North Africa, northern Asia, and parts of western South America. *N. americanus* is found in Central and South America, southern Asia, Australia, and the Pacific Islands. Worldwide, there are approximately 1.2 billion cases annually of human hookworm infections (Cambridge University Schistosomiasis Research Group, 2002). About 100 million of these involve a serious infection that creates a continuous loss of blood leading to chronic anemia. Less severe cases usually include mild diarrhea and cramps. Serious hookworm infection can create major health problems for newborns, children, pregnant women, and the malnourished.

Ancylostomiasis is a disease usually associated with unsanitary conditions. Hookworm eggs pass from the feces of infected humans to the soil. The eggs must be in the terrestrial environment to hatch and the soil residency of *A. duodenale* and *N. americanus* is periodic. Individuals with a major infection can excrete 2000 eggs per gram of feces (National Institutes of Health, 2001). Once exposed to air the eggs will develop rapidly in the upper few centimeters of moist warm soil. They hatch into larvae after a few days and feed on bacteria and organic matter. After about five days they molt and form the infectious form of the larvae. During cool damp periods, the larvae may come to the surface and extend their bodies into the air searching for a host. If they come into contact with human skin they attach and burrow in. The larvae are then transported in the blood to the lungs where they burrow into the airspace then migrate or are coughed up in the bronchi and trachea and are swallowed into the gut. Once in the intestine, they attach themselves to the wall of the small intestine and mature to adulthood which causes damage by blood ingestion. Thus, infection in conjunction with poor nutritional status can induce chronic anemia. Female *N. americanus* hookworms can produce 10,000 eggs daily and female *A. duodenale* can produce 20,000 eggs daily (Cambridge University Schistosomiasis Research Group, 2002).

2. *Ascaris lumbricoides*

Ascaris lumbricoides is a large roundworm that causes ascariasis, an infection of the small intestines. There are over 1.5 billion new cases of ascariasis annually; about 210 million of them are symptomatic (Cambridge University Schistosomiasis Research Group, 2002). Ascariasis is the most common helminthic infection and is distributed worldwide. The highest prevalence is in tropical and subtropical regions and in areas with inadequate sanitation.

A. lumbricoides is the largest nematode (roundworm) parasitizing the human intestine. Adult females can be 20–35 cm long and adult males can be 15–30 cm long (CDC, 2002). Although infections may cause stunted growth, acute symptoms are usually not caused by adult worms. High worm burdens may cause abdominal pain and intestinal obstruction. Migrating adult worms may cause symptomatic occlusion of the biliary tract or oral expulsion. During the lung phase of larval migration, pulmonary symptoms can occur (cough, dyspnea, hemoptysis, eosinophilic pneumonitis).

The female parasite may produce 240,000 eggs per day (CDC, 2002) which are passed in the feces. Fertile eggs may remain viable in the soil for many years if conditions are optimal. In warm, moist, shaded soil they begin to develop and can become infective after about 18 days. The soil residency of *A. lumbricoides* is classified as periodic. Infection occurs when the infective eggs are swallowed through the ingestion of contaminated raw food, such as fruit or vegetables, or through the incidental ingestion of soil. The eggs then hatch in the small intestine and the resulting larvae migrate to the lungs. In the lungs they molt twice and then migrate up through the air passages of the lungs to the trachea. They then enter the throat and are swallowed, finally ending up in the small intestine where they mature and mate, to complete their life cycle. Usually the roundworms only feed on the semi-digested contents of the gut. There is some evidence that they may also feed on blood and tissue taken from the intestinal mucous membrane. The worms can live for up to two years in the intestine (CDC, 2002).

3. *Enterobius vermicularis*

Enterobius vermicularis is a pinworm that causes enterobiasis, often referred to as human pinworm infection. *E. vermicularis* females grow up to 13 mm in length and males grow up to 5 mm. Enterobiasis is a common infection in children worldwide. It is the most common nematode parasite in temperate climates and in areas with modern sanitation. Symptoms are generally mild and vague. Most often anal itching is the only problem. It is estimated that over 200 million people are infected annually (Cambridge University Schistosomiasis Research Group, 2002). Enterobiasis is most common in soils associated with poor sanitation where human feces are distributed in yards or fields, generally, as fertilizer.

Adult pinworms live in the human colon. Eggs are deposited by the female in the perianal region and can enter the environment with the feces. Given the proper conditions, the eggs become infective about 4 hours after being laid. The eggs are resistant to drying and can remain infective in dust for several days (National Institutes of Health, 2001). The soil residency of *E. vermicularis* is classified as incidental. Person-to-person transmission can also occur through handling items contaminated by an infected person. Following ingestion of infective eggs, the larvae hatch in the small intestine and the adults establish themselves in the colon.

4. *Strongyloides stercoralis*

Strongyloides stercoralis is a small roundworm, 2 mm in length, which causes strongyloidiasis. It is parasitic in the mucosa of small intestines. Strongyloidiasis is generally found in tropical and subtropical areas with poor sanitation. However, it does occur in temperate areas, including the southern United States (CDC, 2002). In this area, it is often found in rural areas and in lower socioeconomic groups. Strongyloidiasis is often asymptomatic but sometimes causes chronic disease. In individuals who are immunosuppressed, it can be life-threatening.

The life cycle of *S. stercoralis* is complex. Unlike other helminths, its eggs can hatch in and re-infect the host. It is also capable of completing its life cycle and reproducing in the soil and thus is classified as a permanent soil resident. *S. stercoralis* eggs can hatch in the small intestines and produce rhabditiform larvae that can be passed in the feces of an infected host and may enter the soil. If they molt twice, they become a form (filariform) that is infectious to humans. If the rhabditiform larvae molt four times, they become free-living males and females that can mate and produce rhabditiform larvae in the soil (CDC, 2002).

The parasitic cycle begins when filariform larvae penetrate human skin where they are then transported in the blood to the lungs and penetrate the airway. They are then swallowed and reach the small intestines where they molt twice and become adult, egg-laying females. The eggs hatch into rhabditiform larvae in the host. These larvae can either be passed in the feces or penetrate the intestinal mucosa which creates an internal autoinfection (CDC, 2002).

5. *Toxocara canis*

Toxocara canis is the most common cause of visceral larva migrans. The disease is found worldwide and most often afflicts children aged 1–4 (Pitetti, 2001). The definitive host for *T. canis* is the dog. Humans are called paratenic hosts, because the life cycle of *T. canis* cannot be completed in humans.

A heavily infected dog can pass millions of eggs each day in their feces (Pitetti, 2001). Humans contract *Toxocara* infections as accidental hosts by ingesting embryonated eggs in contaminated soil (CDC, 2002). The soil residency of *T. canis* is transient. The eggs hatch in the small intestine and the resulting larvae invade the mucosa and enter the bloodstream. The larvae can then disseminate to any organ in the body, provoke a granulomatous reaction, and die. Symptoms depend upon the degree of tissue damage and the associated immune system response. In the United States, 2–10% of children test positive for *Toxocara*, and international incidence is probably similar or slightly higher (Pitetti, 2001).

6. *Trichuris trichiura*

Trichuris trichiura is the whipworm responsible for trichuriasis (often called whipworm disease). Trichuriasis is an infection of large intestine and is caused by the accidental ingestion of *T. trichiura* eggs. Most infections are associated with tropical areas with poor sanitation and occur in children. The disease occurs worldwide and there are an estimated 800 million people infected (CDC, 2002). The soil residency of *T. trichiura* is classified as incidental.

Adult *T. trichiura* worms are approximately 4 cm in length. Female worms can shed 3000–20,000 eggs per day in the feces. In the preferred environment of warm, moist, shaded soil the eggs embryonate and become infective in 15–30 days. They are often ingested through soil-contaminated food or hands causing the eggs to hatch in the small intestines. This releases larvae that mature to adults and establish themselves in the large intestine. There, the larvae fix themselves into the mucosa to feed. They have a life span of about one year (CDC, 2002).

B. Selected Soil-Borne Human Pathogenic Trematodes

Trematodes are soft-bodied invertebrate animals with bilateral symmetry that are also called flukes. They can cause parasitic infections in humans. Trematodes have complex life cycles that always involve an intermediate host that is a mollusk. Trematodes and cestodes are members of a group of animals (the phylum Platyhelminths) that are commonly called flatworms, because most species are flattened dorsoventrally. This shape is due to the fact that they must respire by diffusion and no cell can be too far from the surface. Trematodes and cestodes have only one opening to the gut, which must both take in food and expel waste. The gut is often extensive and branched in order to provide nourishment to the entire animal.

As adults, trematodes are usually found in vertebrate animals including fish, amphibians, reptiles, birds, and mammals. These animals serve as the definitive hosts (a host where the adult parasite is able to reproduce sexually), but other intermediate hosts are usually involved in the trematode life cycle. Trematodes may cause highly severe infections of the lungs, bladder, blood, liver, and most often, the gastrointestinal tract. Several *Schistosoma* species are important human pathogens.

1. *Schistosoma mansoni*, *Schistosoma japonicum*, and *Schistosoma haematobium*

Schistosomiasis is a trematode infection that affects over 200 million people in 74 tropical countries. Up to 600 million people worldwide are at risk for this disease, which is spread by bathing or wading in infected rivers, lakes, and irrigation systems (World Health Organization, 1996). People who are repeatedly infected can face liver, intestinal, lung, and bladder damage.

Schistosoma mansoni, *S. japonicum*, and *S. haematobium* are the three species that cause the most prevalent form of the disease. Each species occupies a different geographic region and there are slight differences in the clinical presentation of the disease itself. *S. mansoni* is found in parts of South America, the Caribbean, Africa, and the Middle East; *S. haematobium* in Africa and the Middle East; and *S. japonicum* in the Far East. These trematodes are unusual in that they reproduce sexually (one mated pair of *S. japonicum* can produce about 3000 eggs per day) and that they live in the mesenteric veins that lie outside of the liver. The life expectancy of an adult is from 10 to 25 years. Some of these eggs can pass through the membranes of the bowels and are excreted in feces. The soil-residency of *Schistosoma* spp. is periodic. When fully wetted, the eggs hatch into free-swimming larvae call miracidia. These larvae infect amphibious snails that live in mud on the edges of bodies of water. These larvae are not infectious to humans at this stage of their development.

Once a snail is infected, the larvae reproduce asexually into another free-swimming larval stage and are called cercaria. The fork-tailed cercaria completes development in the snail, migrates to the surface of the snail's soft tissue, and enters the environment (water). If the cercaria comes into contact with the skin of a human host it releases enzymes that soften the skin and allow it to enter the host. Once in the host the cercaria sheds its tail and becomes a schistosomula and finds its way to the mesenteric veins where it matures into an adult worm capable of mating. Diseases caused by *Schistosoma* spp. are saprozoonoses. The disease is a zoonosis, but the eggs require an environmental residence to develop (CDC, 2002; MacLean, 2002; University of California, 2002b).

C. Selected Soil-Borne Human Pathogenic Cestodes

Cestodes are often referred to as tapeworms because of the shape of their long ribbon-like body. They resemble a colony of animals in that their bodies are divided into a series of segments each with its own set of internal organs. Adults of the species can reach 100 m in length.

There are several parasitic tapeworm infections where man is the definitive host. Two examples of soil-borne tapeworms discussed below are *Taenia saginata* and *T. solium*; and both have a periodic soil residency. Adult parasitic human pathogenic cestodes live in the intestines. The bodies of cestodes can be divided into three regions: the scolex or head, the neck, and the strobila. The strobila is composed of a series of segments called proglottids and each proglottid has its own complete set of internal reproductive organs. As the organism grows proglottids are added, and the result may be thousands in a mature animal. This pattern of growth forms a long, ribbon-like body referred to as a tapeworm. Mature proglottids containing eggs are shed from the rear of the animal. The eggs, or proglottids, exit the body in feces and enter the environment.

1. *Taenia saginata* (the beef tapeworm)

Humans are the only definitive host for *T. saginata*, which causes about 50 million cases of tapeworm infection annually at locations spanning the globe. Infections are generally asymptomatic, but in some cases vitamin deficiency may be the result of excessive absorption of nutrients by the parasite. Occasionally mild symptoms like abdominal pain, digestive disturbances, excessive appetite, or loss of appetite, weakness, and loss of weight may accompany the infection.

Adult tapeworms live in the small intestines. They are generally 5 m or less long, but may reach lengths up to 25 m. Mature worms have over 1000 proglottids and mature proglottids contain 80,000–100,000 eggs each. Once mature, the proglottids separate from the tapeworm and can be passed in the feces and may enter the soil. The soil residency is classified as transient. The eggs can survive for months to years in the environment. Cattle become infected by ingesting vegetation contaminated with eggs (or proglottids). The eggs develop in the intestines and release onchospheres that evaginate and invade the intestinal wall. They then migrate to the striated muscles and develop into a cysticercus, which is capable of surviving for several years. Ingesting undercooked meat containing cysticercus infects humans. In the human intestine the cysticercus develops into an adult tapeworm that is capable of surviving for over 30 years (CDC, 2002; MacLean, 2002).

2. *Taenia solium* (the pork tapeworm)

Taenia solium, the pork tapeworm, can cause both taeniasis and cysticercosis in humans. As with beef tapeworm infections, the disease occurs worldwide with about 50 million annual cases. *T. solium* and *T. saginata* have very similar life cycles, but *T. solium* larvae can infect humans as well as swine. Humans are the definitive host for *T. solium* adults, which can live up to 25 years in the intestine. *T. solium* have less than 1000 proglottids and are 2–7 m in length. Their proglottids are less active than in *T. saginata* and each contain about 50,000 eggs. When the proglottids mature, eggs or proglottids are shed in the feces and into the soil. The soil residency is classified as transient. If swine ingest them, they mature to onchospheres that move to the muscles and grow into the larval form of *T. solium*, *Cysticercus cellulosae*. Undercooked pork from infected swine is then infective for taeniasis in humans.

If humans swallow the eggs or proglottids, they can also develop *C. cellulosae* infection which results in cysticercosis, a disease that can be quite severe. It can also develop in humans infected with adult *T. solium* due to autoinfection from proglottids carried to the stomach by reverse peristalsis. In humans, *C. cellulosae* can develop in the striated muscles, the brain, the liver, and in other tissues. When infecting the central nervous system, the pressure produced by growing larvae can cause severe pain, paralysis, optical and/or psychic disturbances, and epileptic convulsions. Mortality due to cysticercosis is estimated at about 50,000 worldwide (CDC, 2002; Duckworth et al., 2002; MacLean, 2002).

VIII. SELECTED SOIL-BORNE HUMAN PATHOGENIC PROTOZOA

Protozoa are single cell eukaryotic organisms that are phagotrophic, which means that they feed by engulfing and ingesting their prey inside a cell membrane. There are over 30,000 species of which only a small number are parasites of man. Most protozoa range in size from 0.01 to 0.1 mm. In soils, they feed on bacteria and algae. The protozoan life cycle ranges from binary fission in a single host to many morphological transformations in a series of hosts. There are no eggs, larva, or adults. There are about 10,000–100,000 protozoa per gram of upper soil surface (Coyne, 1999). Archeozoa are similar to protozoa except that they lack mitochondria.

A. *Cryptosporidium parvum*

Cryptosporidium parvum is a protozoan that causes a self-limiting diarrheal illness called cryptosporidiosis. It can be more serious in infants and in the immunosuppressed. The first documented human case occurred in 1976 and cryptosporidiosis is now considered a worldwide disease. It is especially common in developing countries. No effective specific treatment is known. The incidence of cryptosporidiosis is not known, but an outbreak in Milwaukee in 1993 infected over 400,000 people (Coyne, 1999).

Many animal species, including man, act as a reservoir for *C. parvum*. Infected hosts excrete sporulated oocysts in the feces. In this fashion, oocysts may enter the soil as animal or human waste products. Infection begins when oocysts are ingested, most often through contaminated water and food or by direct fecal-oral transmission. After ingestion, the oocysts mature to sporozoites and parasitize the epithelial cells of the gastrointestinal tract. These parasites then undergo asexual and then sexual reproduction. The soil residency of *C. parvum* is transient-incidental. Generally cryptosporidiosis is a water-borne disease, but *C. parvum* only reaches the environment through human and animal waste. The organism must survive in and travel through soils to become water-borne in many cases. Studies have indicated that *C. parvum* can survive in surface water for six months and in liquid manure tanks for many months (Cambridge University Schistosomiasis Research Group, 2002; CDC, 2002; Duckworth 2002; and Health Canada, 2002).

B. *Cyclospora cayetanensis*

Cyclospora cayetanensis causes cyclosporiasis, a diarrheal disease found worldwide. It is most commonly found in tropical and subtropical regions. This disease has a life cycle similar to *C. parvum* with the exception that when passed in the feces, the oocyst is not infective. This means that no direct fecal-oral transmission can occur. Freshly passed oocysts sporulate after spending days or weeks in the environment at temperatures of between 22 and 32°C and become infective. Soil residency is incidental. Little is known about possible animal reservoirs or environmental survival time for *C. cayetanensis*. The oocysts are thought to be able to survive for long periods of time in the environment if kept moist (CDC, 2002; Garcia, 2002).

C. *Entamoeba histolytica*

Entamoeba histolytica causes amebiasis, a disease characterized by diarrhea, with severe cases including dysentery or a serious invasive liver abscess. Amebiasis is a worldwide disease with an estimated 40,000,000 people infected annually. Around 40,000 die from the disease each year (University of Leicester, 2001). Man is the definitive host. As with *G. lamblia*, *E. histolytica* exists in two forms: the active parasite (trophozoite) and the dormant parasite (cyst). The trophozoites live in the intestine and feed on bacteria or on the wall of the intestine. Trophozoites are expelled in feces and die rapidly. However, cysts expelled in the feces are very hardy and can survive days to weeks in the external environment. In areas where sanitation is poor, indirect transmission of the cysts is more common. The soil residency of *E. histolytica* is incidental (University of Leicester, 2001).

D. *Balantidium coli*

Balantidium coli is the largest protozoan found in humans. It causes balantidiasis, a disease with a worldwide distribution. It is capable of causing acute hemorrhagic diarrhea and ulceration of the colon. Pigs, large primates, humans, and dogs are the definitive hosts. The life cycle and methods of transmission of the parasite are similar to *E. histolytica*. The soil residency is transient-incidental. Under favorable temperature and humidity conditions, the cysts can survive in soil or water for weeks to months (CDC, 2002).

E. *Giardia lamblia*

Giardiasis is a disease that is especially common among children and in places where sanitation is poor worldwide. About 200 million people in Asia, Africa, and Latin America display symptoms and there are about 500,000 new cases annually (World Health Organization, 1996). It is also one of the most common parasitic diseases in developed nations. It is caused by *G. lamblia*, an archeozoan. Clinically, giardiasis presents as noninflammatory diarrhea and associated abdominal cramps, bloating, fatigue, and weight loss. Infections can be asymptomatic or chronic.

G. lamblia trophozoites (the active stage of organism) live in the large intestine of infected humans or animals. At times they form cysts and millions of these cysts (and trophozoites) are released in the feces and may enter the soil. The soil residency of *G. lamblia* is transient-incidental. The cysts can persist for some time (up to many months) in the environment, which includes soil, food, water, or surfaces that have been contaminated. Infection results from ingestion of the cyst, usually in contaminated water or food (University of Leicester, 2001; CDC, 2002).

F. *Isospora belli*

Isospora belli is a protozoan that causes isosporiasis, an infection of the small intestine. Isosporiasis is found worldwide, but is most common in tropical and subtropical areas. It can cause chronic diarrhea, abdominal pain, and weight loss and is especially important in immunosuppressed individuals.

Large and football-shaped *I. belli* oocysts are passed in the feces. The soil residency of *I. belli* is transient-incidental. The oocysts contain a sporoblast (rarely two) that splits and develops cyst walls, thereby becoming sporocysts. Infection occurs by ingestion of sporocysts. *I. belli* has a complex asexual and sexually reproductive cycle within its host, both human and animal, which results in the production of oocysts that are then excreted in feces (University of Leicester, 2001; CDC, 2002).

G. *Toxoplasma gondii*

Toxoplasma gondii causes toxoplasmosis. *T. gondii* infection can produce flu-like symptoms in healthy people and severe disseminated disease in immunosuppressed individuals. It can also cause birth defects in infants when women are exposed during pregnancy. Toxoplasmosis occurs worldwide and is more common in warm climates and at low altitudes. Under some conditions, toxoplasmosis can cause serious pathology, including hepatitis, pneumonia, blindness, and severe neurological disorders.

Cats are the definitive host for *T. gondii*. They generally acquire the infection though consumption of infected rodents. After a cat consumes the tissue containing cysts or oocysts, viable tachyzoites invade the small intestine. These eventually form oocysts that are excreted. The soil residency of *T. gondii* is transient. The oocysts can remain infective in water or soil for about one year. Tachyzoites can also form cysts in tissue. Humans can become infected in several ways including the ingestion of cysts through contaminated food or soil or ingestion of undercooked meat (e.g., lamb, pork, or beef) infected with cysts.

Its life cycle includes two phases called the intestinal (or enteroepithelial) and extraintestinal phases. The intestinal phase occurs in cats only (wild as well as domesticated cats) and produces oocysts. The extraintestinal phase occurs in all infected animals (including cats) and produces tachyzoites and, eventually, bradyzoites or zoitocysts. The disease toxoplasmosis can be transmitted by ingestion of oocysts in cat feces or bradyzoites in raw or undercooked meat (University of Leicester, 2001; CDC, 2002; Health Canada, 2002).

H. *Dientamoeba fragilis*

Dientamoeba fragilis is a protozoan responsible for *D. fragilis* infection. Symptoms occur in only 15–25% of infected individuals and may result in mild, chronic gastrointestinal problems (abdominal pain, gas, diarrhea, etc.). The disease is found worldwide but has a higher prevalence in developing countries with poor sanitation.

D. fragilis trophozoites are one of the smallest human parasites and survive in the human gastrointestinal tract. No cyst stage has been reported, so a fecal-soil-oral infectious gateway is unlikely. The soil residency of *D. fragilis* is unknown. There is evidence that this organism is transmitted among humans in the eggs of human pinworms (*E. vermicularis*). Infection by *D. fragilis* may require infection by *E. vermicularis* (Mack, 2001; CDC, 2002).

IX. SELECTED SOIL-BORNE HUMAN PATHOGENIC FUNGI

There are over 100,000 species of fungi of which about 300 are known to be pathogenic (University of Leicester, 1996; McGinnis, 1998). Fungi are non-motile eukaryotic organisms with chitin-based cell walls that can be grouped into molds and yeasts. Molds are composed of branching filaments called hyphae that grow by elongation at their tips. Hyphae can be composed of one cell with continuous cytoplasm, called coenocytic hyphae, or are composed of cells separated by walls (septa) in which case they are called septate hyphae. The mass of hyphae of an individual organism is referred to as mycelium. Reproduction is through sexual or asexual spores and fragmentation of hyphae. Single cell non-filamentous fungi are called yeasts. They are generally spherical or ovoid in shape and reproduce by budding. Some fungi are dimorphic in that they can switch between filamentous or yeast growth.

Most fungi are saprophytes and must absorb nutrients from the environment. In this way they help decompose dead plants and animals. Fungi do not contain chlorophyll and are therefore not capable of photosynthesis. Most molds are aerobic and cannot survive in saturated soils. They need to be able to extend hyphae into air spaces that contain oxygen. Many yeasts are facultative anaerobes and some yeasts are capable of surviving in anaerobic environments. In moist soils, the largest fraction of the microbial biomass is made up of fungi. Soil-borne fungi are more tolerant of acidic soils,

TABLE III. Selected Soil-Borne Human Pathogenic Fungi and Their Properties

Pathogen(s) and disease	*Distribution and residency*	*Gateway(s) and incidence*[a]	*Comments and soil survival time*
Coccidioides Disease: coccidioidomycosis	Southwestern U.S., Mexico, microfoci in Central and South America Residency: permanent	Respiratory, rarely trauma Incidence: 15/100,000 in Arizona in 1995	Please see the case study in Section XIII for complete information
Histoplasma capsulatum Disease: histoplasmosis	Locally in eastern and central U.S., microfoci in Central and South America, Africa, India, and southeast Asia Residency: permanent	Respiratory Incidence: About 80% of people living in endemic area have a positive skin test; mortality rate is about 10% in HIV-infected persons with disseminated disease	Found in soils contaminated with bird or bat feces
Blastomyces dermatitidis Disease: blastomycosis	South-central, southeastern and mid-western U.S., microfoci in Central and South America and Africa Residency: permanent	Respiratory Incidence: 1 to 2/100,000 in endemic areas	Found in soils enriched with decomposing organic debris
Aspergillus fumigatus; A. flavus; less commonly *A. terreus, A. nidulans, A. niger* Disease: aspergillosis	Worldwide; ubiquitous; found in soil, dust, plants, food, and water Residency: permanent	Respiratory, occasionally via contaminated biomedical devices Incidence: 1 to 2/100,000 is suggested	Found in soils, decomposing plant material, household dust, food, water, and plants
Sporothrix schenckii Disease: sporotrichosis	New World, Africa, and Europe Residency: permanent	Trauma to skin Incidence: disease is uncommon and sporadic	Most common in sphagnum moss, plants, baled hay

[a]Incidence is the annual rate of confirmed infection. An incidence of 15:100,000 means that there were 15 confirmed cases per 100,000 population. From CDC, 2002; DoctorFungus, 2002; Duckworth et al., 2002; Health Canada, 2002.

grow best between 6 and 50°C, and are usually found in the top 15 cm of the soil (Coyne, 1999).

The life cycles of the various fungi are generally not as complex or varied as helminths and protozoa. Table III illustrates selected soil-borne human pathogenic fungi and the diseases they cause. It also contains information on the geographic distribution, soil residency, gateway of infection, and disease incidence for each of the fungi.

X. SELECTED SOIL-BORNE HUMAN PATHOGENIC BACTERIA

Coyne (1999), presents an excellent introduction to bacteria in the soil that is summarized below. Bacteria are single-cell prokaryotic organisms that have existed on Earth for over 3 billion years. They are small, generally less than 50 μm in length and 4 μm in width. One bacterium weighs about 10^{-12} grams. Their small size affords them a high surface area to volume ratio, which allows them to maximize nutrient uptake through diffusion. They also possess a very high metabolism and the ability to reproduce through binary fission. Bacteria occur in a wide variety of shapes. Aerobic bacteria require oxygen for existence, whereas anaerobic bacteria do not tolerate gaseous oxygen. Some bacteria, called facultative anaerobes, prefer oxygen, but can grow without it. Heterotrophic bacteria use organic compounds in the environment for energy and for synthesis of cellular constituents. Autotrophs make use of energy from light or of reactions of inorganic chemicals to fix carbon dioxide and synthesize organic cellular components (University of California, 2002a).

There are up to one billion bacteria in one gram of soil (Table I). In general, they prefer warm, moist soils. Soil bacteria can be classified as autochthonous or allocthonous. Autochthonous organisms inhabit the bulk of the soil and are specialists at getting the most out of the available nutrients. Allocthonous microbes are more opportunistic. They are generally saprophytic or pathogenic and tend to be found in areas that are rich with nutrients, even if only for a limited time period. Allocthonous microbes maximize growth when conditions are right. They often are found in the rhizosphere and many of them are plant pathogens. Allocthonous microbes can cover 5–10% of root surfaces and there is a steep decrease in microbial populations just 5 mm from the plant root.

There are a large number of soil-borne human pathogenic bacteria that generally have similar life cycles. They grow and reproduce through binary fission in the proper conditions. When the conditions are unfavorable, they may die off or form a spore that can grow and reproduce again when conditions improve. Examples of several soil-borne human pathogenic bacteria are presented in Table IV.

Actinomycetes are prokaryotic bacterial organisms that display filamentous growth. They make up 10–50% of the total microbial population in soils (Coyne, 1999). Most actinomycetes are aerobic and prefer warm, dry soils. They tend to be spore formers and are adept at surviving droughts. Most are saprophytic. Due to their filamentous growth, they resemble fungi. The filaments of actinomycetes are much smaller than fungal hyphae, 0.5–1.0 μm as opposed to 3–8 μm for fungi. Although actinomycetes are an important component of the soil microbial population, there are few known to be important soil-borne human pathogens. Four pathogenic genera are included in Table IV. Many actinomycetes make antibacterial molecules. About 75% of the 5000 known antibacterial drugs are derived from actinomycetes (Coyne, 1999).

XI. SELECTED SOIL-BORNE HUMAN PATHOGENIC VIRUSES

There are over 140 types of pathogenic enteric viruses transmitted from humans to the environment in human feces. For some (like the Norwalk virus and rotavirus), immunity is short-term; there is no life-long protection after recovering from an infection (Schwartzbrod, 1995). Viruses are the smallest pathogens, most having maximum dimension of less than 30 nm (Coyne, 1999). They are acellular organisms, have no cell membrane, and occur in many shapes including cubic, helical, and icosahedral. Most viruses have two basic structural components: a protein coating that can help the virus survive in the environment and a nucleic acid core. Viruses are so small that their genetic material (the nucleic acid core) contains only 10–200 genes (Coyne, 1999). There are viruses that infect animals, plants, fungi, protozoans, algae, and bacteria. They are always host specific.

Viruses are parasites that must use the chemical machinery and metabolism of a host cell to reproduce. In a host, viruses attach to a cell, use enzymes to break through the cell wall, and inject their nucleic acid core into the cell. Once in the cell, the genetic material from the virus begins making three types of proteins. It replicates its own genetic material, builds protein coating, and assembles proteins that will help it get out of the cell. These parts come together by chance to form and release a single or many new copies of the original virus. Outside of the host, viruses are inert. They do not grow or reproduce. Human pathogenic viruses with protective coatings can remain infectious in the environment for up to 6 months.

A. Viruses in Soils

Soil is not a natural reservoir for viruses. Viruses can only persist in soil in a dormant state but may retain their infectivity in this state. Plant viruses rarely survive in soils for long periods; however, some insect viruses remain infective for years (Coyne, 1999). Viruses are also known to infect many soil helminths and microbes.

There are a number of factors that influence the ability of a virus to survive and to move in unsaturated soils. Because viruses are added to soil as anthropogenic waste, the objective is to keep the viruses from the water table where generally cool water temperatures can keep the virus alive for long periods of time. Factors that affect survival include: temperature, soil moisture, soil microbial activity, soil type, virus type, soil organic matter, and adsorption of the virus, generally to clay minerals (Sobsey & Shields, 1987). Viruses generally survive longer in cooler, wetter, pH neutral soils with low microbial activity. Humic and fulvic organic material may cause reversible loss of infectivity, but, some other organic materials may complex with the virus and protect it from inactivation by preventing adsorption to

TABLE IV. Selected Soil-Borne Human Pathogenic Bacteria and Their Properties

Pathogen(s) and disease	*Distribution and residency*	*Gateway(s) and information on incidence, morbidity and/or mortality (IMM) if available*	*Comments and soil survival time if available*
Actinomadura Spp. Disease: maduramycosis, actinomycetoma	Tropical regions, especially Africa, India, South and Central America Residency: permanent?	Skin trauma. IMM: Africa may have highest incidence; in the Sudan, 300–400 patients per year are seen; causes disfigurement, rarely fatal	An aerobic actinomycete that is a soil saprophyte
Bacillus anthracis Disease: anthrax	South and Central America, southern and eastern Europe, Asia, Africa, the Caribbean, and the Middle East Residency: periodic(?)	Respiration, skin trauma, ingested (gastrointestinal); often infected by above methods while handling contaminated animal products IMM: unknown to rare.	A spore-forming aerobic bacterium; spores can survive in soil environment for many years, possibly for decades; biological warfare agent.
Burkholderia (Pseudomonas) pseudomallei Disease: melioidosis	Worldwide, primarily in tropical and subtropical regions, especially in Southeast Asia and northern Australia, also in South Pacific Africa, India, and Middle East; isolated cases in Central and South America, Hawaii, and Georgia Residency: permanent	Direct contact with contaminated soil and water, inhalation of dust, ingestion of contaminated water, skin trauma, and contact with mucous membranes IMM: very important cause of morbidity and mortality in Thailand	Possible biological warfare agent; soil saprophyte
Campylobacter jejuni Disease: diarrhea, gastroenteritis, Guillain-Barre syndrome	Worldwide Residency: incidental	Fecal-soil-oral; contaminated water, raw milk, and raw or undercooked meat, poultry, or shellfish IMM: *C. jejuni* along with rotaviruses and enterotoxigenic *Escherichia coli*, is a major cause of diarrhea worldwide	No information on survival in soil; known to survive in 4°C stream water for over four months
Clostridium tetani Disease: tetanus	Worldwide, most frequently in densely populated regions in hot damp climates in soils rich in organic material especially manure Residency: permanent? (in proper setting it can complete life cycle in soil)	Fecal-soil-oral, humans and many animals; tetanus spores introduced into the body through a wound contaminated with soil, street dust, feces, or injected street drugs; also through lacerations, burns, and trivial wounds IMM: annual deaths: newborn = 450,000; maternal = 50,000.	Anaerobic (all *Clostridium* spp.) but can form spores that are very resistant to heat, many antiseptics, and chemical agents
Clostridium botulinum Disease: botulism	Worldwide Residency: permanent? (in proper setting can complete life cycle in soil)	Fecal-soil-oral, humans and many animals; ingestion of contaminated food containing toxin IMM: generally rare, associated with confined outbreaks	Obligate anaerobic bacterium that can live in oxygen-free pockets in soil as vegetative cells or spore; present in the soil and water; spores can be found on food that comes into contact with infected soil or water

continued

Continued

Pathogen(s) and disease	*Distribution and residency*	*Gateway(s) and information on incidence, morbidity and/or mortality (IMM) if available*	*Comments and soil survival time if available*
Clostridium spp. (other than two listed above) Disease: gas gangrene	Worldwide Residency: permanent? (in proper setting can complete life cycle in soil)	Fecal-soil-oral, humans and many animals; skin trauma (major or minor), burns, deep puncture wounds, ear infections, animal bites; spores introduced into the body through a wound contaminated with soil, street dust, feces, or injected street drugs; also through lacerations, burns, and trivial wounds IMM: fairly common before general use of antibiotics to treat injuries; can still pose threat to those immunosuppressed	Before antibiotic treatments, about 5% of battlefield injuries were complicated by this bacterium
Coxiella burnetti Disease: *Q fever*	Worldwide with the exception of New Zealand and Antarctica; Residency: transient	Inhalation of infected aerosol, often produced from animal products and especially during parturition; also shed in urine and feces IMM: morbidity from 5% in urban to 30% in rural areas worldwide	Highly infective, but unable to grow outside of host (commonly goats, sheep, and cattle); has a spore-like form that is very resistant to heat and desiccation and can last for months outside of host in soils
Escherichia coli several pathogenic strains Disease: diarrhea	Worldwide Residency: incidental	Fecal-soil-oral, ingestion of contaminated food IMM: major cause of traveler's diarrhea of which there are some 5 million cases per year worldwide	Can survive for months in cool, dark, nutrient-rich soils
Francisella tularensis Disease: tularemia	Many areas of U.S. with most cases in Arkansas, Oklahoma, and Missouri; increasing numbers of cases in the Scandinavian countries, eastern Europe, and Siberia; also in the Middle East and Japan; rare in the UK, Africa, and Central and South America Residency: transient	Enters soil through tick feces and possibly other sources; humans acquire through contact of infected soil with broken skin (might be able to penetrate unbroken skin) and with mucous membranes; also tick and insect bites, inhalation, and ingestion IMM: worldwide incidence not known; in the U.S. there are now less than 200 cases per year	A zoonosis; one of the most infectious agents known; highly infectious in both skin and aerosol routes; often found in rural areas; possible biological warfare agent; known to survive in water and moist soil for weeks
Leptospira spp. Disease: leptospirosis	Worldwide, but more common in temperate or tropical climates Residency: transient	Ingestion and skin contact, especially mucosal surfaces; contact with water, food, or soil contaminated with urine from infected animals M: about 200 cases annually in U.S.; considered to be the most widespread zoonotic disease in the world	Outbreaks associated with heavy rainfall and flooding; known to survive many weeks in contaminated soil
Listeria monocytogenes Disease: listeriosis	Worldwide? Residency: permanent	Ingestion of food (often uncooked) contaminated by infected soil and water IMM: 2500 serious cases per year in U.S. of which 500 are fatal	Found in soil, water, and fecal material of domestic animals; can grow at temperatures found in refrigerators

continued

Continued

Pathogen(s) and disease	Distribution and residency	Gateway(s) and information on incidence, morbidity and/or mortality (IMM) if available	Comments and soil survival time if available
Nocardia spp., *Rhodococcus* spp. Disease: Nocardiosis	Worldwide, some species more likely in tropics Residency: permanent?	Cutaneous disease from skin trauma contaminated with soil, pulmonary and disseminated infections from inhalation IMM: in the U.S., there are an estimated 500–1000 new cases of Nocardia infection annually	Aerobic actinomycete found in soil and water; *Nocardia asteroides* is tolerant of 40–50°C
Rickettsia rickettsii and other *Rickettsia* spp. Disease: Rocky Mountain spotted fever, other fevers (African tick bite fever, Queensland tick typhus) and spotted fevers (Mediterranean, Japanese)	Worldwide, individual species are geographically contained by their mammalian reservoir Residency: periodic	Zoonosis-spread by bite of tick or by contamination of the skin with tick blood or feces; rodents are the main mammalian reservoir IMM: 3–5% of individuals who become ill with Rocky Mountain spotted fever still die from the infection; U.S. has 250–1200 cases of Rocky Mountain spotted fever annually	Vector in North America is the wood tick, American dog tick, or Lone Star tick; female ticks transfer the bacterium to their eggs that are infective as they mature and hatch in the soil (unlike many other tick vector diseases, i.e., Lyme disease); feces of infected ticks quickly lose their infectivity on drying
Salmonella spp. Disease: primarily salmonellosis (diarrhea), typhoid fever and paratyphoid fever	Worldwide, primarily a food-borne disease Residency: incidental	Fecal-soil-oral, ingestion of contaminated (often uncooked) food contaminated by infected soil and water; shed in human and animal feces IMM: 2–4 million cases in U.S. annually	Can survive in sludges and soils for many months given proper conditions; in sludge applied to arid soils survival may be 6–7 weeks.
Shigella spp. Disease: diarrhea, dysentery	Worldwide Residency: incidental	Fecal-soil-oral, ingestion of contaminated (often uncooked) food contaminated by infected soil and water; shed in human feces IMM: 300,000 cases annually in U.S.	May survive a few weeks in water below 10°C; soil survival unknown
Streptomyces spp. Disease: skin infection	Africa, India, Latin America Residency: permanent?	Skin trauma contaminated with soil IMM: invasive infection is extremely rare	An aerobic actinomycete and soil saprophyte
Thermoactinomyces spp.	Probably worldwide Residency: permanent?	Inhalation IMM: Farmer's lung can occur in 2–10% of farm workers but is regionally variable	Actinomycete found in soil, contaminated compost piles, silos; tolerant of 45–60°C heat.
Yersinia spp. Disease: diarrhea	Worldwide Residency: incidental	Fecal-soil-oral, ingestion of food (often uncooked) contaminated by infected soil and water; ashed in human and animal feces	Disease most often occurs in infants and small children; *Y. enterocolitica* is known to survive in soil for 540 days.

From World Health Organization, 1996; Canadian Centre for Occupational Health and Safety, 1999; Rusin et al., 2000; Carey et al., 2001; Pennsylvania Environmental Network, 2001; Ania and Asenjo, 2002; CDC, 2002; Duckworth et al., 2002; Health Canada, 2002.

soil particles (Sobsey & Shields, 1987). Specific species of viruses have different survivability. Also, viruses tend to survive longer when clustered together.

Soil texture is also very important to virus survival in unsaturated soils. Clay minerals, which are found in fine-grained soils, prolong the virus's ability to survive through adsorption of the virus to these minerals. Adsorption by clay minerals can prolong virus survival because adsorption affords protection against inactivation (Gerba, 1987). They are essentially removed from the water film and physically protected by the clay minerals, but, they can desorb back into water with heavy rain and then be moved passively in the soil. Matson et al. (1987) showed that viruses have been recovered at distances from septic tanks of over 90 m horizontally and up to 67 m vertically in the soil. Schwartzbrod (1995), summarized the survival of viruses in soils. These results indicated that viruses have been shown to survive from 11 to 180 days in soils, and the length of survival depended on the type of soil, humidity, the soil moisture, and the soil temperature.

Sim and Chrysikopoulos (2000) presented an excellent review of virus sorption in an unsaturated soil. The ability of a soil to adsorb viruses is strongly correlated with the degree of soil moisture. Decreasing the moisture content enhances virus sorption onto the solid matrix by forcing viruses to move into a thin film of water surrounding soil particles. Virus adsorption at the liquid-solid interface is mainly from electrostatic double-layer interaction and van der Waals forces. Also, there is enhanced removal of viruses at low soil moisture because viruses are sorbed on the air-water interface as well as the water-mineral (solid) interface. The sorbtion at the air-liquid interface may be greater than the air-solid interface. Sorption at the air-liquid interface is primarily controlled by virus surface hydrophobicity, solution ionic strength, and particle charge. Even though viruses sorbed at the liquid-solid interface can remain infective, viruses sorbed at the air-liquid are deformed by interfacial tension to the degree that the protein coat of the virus is disrupted and the virus is inactivated.

Although the adsorption of viruses to clay minerals and water films in soils can prevent their movement and even kill them, the potential desorption of the viruses from clay minerals means that viruses can reach the ground and surface waters that may be used by man. This, in addition to viruses that may be directly ingested from contaminated soils, indicates that soil-borne viruses are important human pathogens. Table V lists the names of some viruses as well as the diseases they cause.

XII. TRANSMISSIBLE SPONGIFORM ENCEPHALOPATHIES

Transmissible spongiform encephalopathies (TSE) are fatal, degenerative diseases of animals and humans characterized by abnormal limb movements, progressive dementia, and the development of sponge-like holes in brain tissues. The accumulation of an abnormal protease-resistant protein in the brain is associated with all TSE. The nature of the causative agent of TSE is still being debated. One theory is that the agent is a biologically active, self-replicating, infectious protein called a prion, which accumulates in and destroys brain tissue. A second theory is that the agent resembles a virus in that it exists as different strains and causes infective, transmissible diseases and possesses nucleic acids, which carry genetic information (Council for Agricultural Science and Technology, 2000; Rabenau et al., 2001). TSE induced diseases of humans include: Creutzfeldt-Jakob disease, fatal familial insomnia, Gerstmann-Straussler-Scheinker disease, new variant Creutzfeldt-Jakob disease, and Kuru. Major examples in animals include scrapie in sheep, chronic wasting disease in deer and elk, bovine spongiform encephalopathy in cattle (mad cow disease), and TSE in cats, monkeys, and mink. Transmission of TSE is believed to be mostly by ingestion of infected animal parts or transplanted by use of contaminated medical instruments.

The relationship of TSE to the soil environment is unknown. However, some questions require consideration. First, can TSE agents, specifically bovine spongiform encephalopathy (BSE), be introduced into the soil by the natural death of an infected animal or possibly by anthropogenic activities? How long could the TSE agents exist in the soil? Concern has been raised in the UK by scientific advisors that of the nearly 500,000 cattle that were culled, killed, and buried as a result of foot-and-mouth disease, some were likely to be also infected with bovine spongiform encephalopathy and could spread the agent via soil and groundwater (Reuters Health Information, 2001). If this were the case then BSE would be classified as an incidental soil pathogen. TSE agents are found in brain and nervous tissue connected to the brain, and also in bone marrow (National Cattleman's Beef Association and Cattleman's Beef Board, 2001). This fact may be relevant to the possible natural transmission of the disease among cattle. Bone chewing is a relatively common trait of cattle worldwide and is believed to be related to dietary

TABLE V. Selected Soil-Borne Human Pathogenic Viruses and Their Properties

Pathogen(s) and disease	Distribution and residency	Gateway(s) and information on incidence, morbidity, and/or mortality (IMM) if available	Comments and soil survival time if available
Adenovirus spp. Disease: respiratory illness, conjunctivitis, diarrhea	Worldwide, specific viral species are found in specific locations Residency: incidental	Fecal-soil-oral IMM: Almost everyone is infected at some point; diarrheal disease blamed for at least 6 million deaths per year worldwide	Soil association with solid human waste; most infections are mild; serious infection possible in immunosuppressed
Arenavirus spp.: Lassa Fever virus, *A. junin, A. machupo, A. sabia, A. guanarito,* and others Disease: hemorrhagic fever (general), Lassa fever, Argentine, Bolivian, Brazilian, and Venezuelan hemorrhagic fevers	Worldwide, each species of virus has a different associated rodent(s) governing its geographic location Residency: transient	Respiratory and others IMM: The number of Lassa virus infections per year in West Africa is estimated at 100,000–300,000, with approximately 5000 deaths; may also have a nematode vector	Human zoonosis with the definitive reservoir being rodents; virus can enter soil from rodent urine, feces, and saliva; disturbance of feces, infected soil, or nesting materials can aerosolize; also spread by contact with contaminated surface
Astrovirus spp. Disease: diarrhea and gastroenteritis, mostly in children and immunosuppressed individuals	Worldwide Residency: incidental	Fecal-soil-oral IMM: diarrheal disease blamed for at least 6 million deaths per year worldwide	Soil association with solid human waste; most infections are mild; serious infection possible in immunosuppressed individuals
Caliciviruses spp. Including Hepatitis E virus Disease: diarrhea	Worldwide Residency: incidental	Fecal-soil-oral IMM: diarrheal disease blamed for at least 6 million deaths per year worldwide	Childhood diarrhea; most adults may be immune; Hepatitis E is very dangerous in developing countries and has a 20% mortality rate for pregnant women
Hantavirus spp. Including Sin Nombre, Puumala, Thailand, Prospect Hill, Khabarovsk, Thottapalayam, Tula, New York, Black Creek Canal, El Moro Canyon, Bayou, and others Disease: HPS-hantavirus pulmonary syndrome	Worldwide, specific virus species inhabit specific hosts in specific locations Residency: transient	Respiratory and others IMM: probably thousands of cases annually worldwide but quite variable	Human zoonosis with the definitive reservoir being rodents; each species has a different associated rodent(s); virus can enter soil from rodent urine, feces, and saliva; disturbance of feces, infected soil, or nesting materials can aerosolize; HPS has a 40–60% fatality rate

continued

Continued

Pathogen(s) anddisease	*Distribution and residency*	*Gateway(s) and information on incidence, morbidity and/or mortality (IMM) if available*	*Comments and soil survival time if available*
Enterovirus poliovirus Disease: polio	Worldwide Residency: incidental	Fecal-soil-oral, respiratory IMM: disease eliminated in many parts of the world	Soil association with solid human waste; known to survive 91 days in unsaturated sand and humid conditions; known to survive 180 days in saturated sand and compost
Enterovirus Hepatitis A Disease: hepatitis	Worldwide Residency: incidental	Fecal-soil-oral IMM: in countries with poor sanitation, most children infected by age 9	Soil association with solid human waste; known to survive 91 days in sand and humid conditions
Enterovirus Coxsackievirus A Disease: diarrhea, hand-foot-and-mouth disease, respiratory infection	Worldwide Residency: incidental	Fecal-soil-oral IMM: diarrheal disease blamed for at least 6 million deaths per year worldwide	Soil association with solid human waste; known to survive 180 days in saturated sand and compost
Enterovirus Coxsackievirus B Disease: pleurodynia, aseptic meningitis, pericarditis myocarditis	Worldwide Residency: incidental	Fecal-soil-oral	Soil association with solid human waste; known to survive 180 days in saturated sand and compost
Enterovirus echovirus Disease: diarrhea, aseptic meningitis	Worldwide Residency: incidental	Fecal-soil-oral IMM: diarrheal disease blamed for at least 6 million deaths per year worldwide	Soil association with solid human waste; can survive 3–33 weeks depending on soil environment
Norwalk virus Disease: acute viral gastroenteritis, diarrhea	Worldwide Residency: incidental	Fecal-soil-oral IMM: diarrheal disease blamed for at least 6 million deaths per year worldwide	Soil association with solid human waste; very little is known about this virus
Orthopoxvirus variola Disease: smallpox	Worldwide Residency: incidental?	Mostly direct human-to-human transmission, but some respiratory environmental transmission known; humans are the only known reservoir IMM: last case acquired outside of a laboratory was in Somalia in 1977	Variola virus is unlikely to survive for more than 48 hours in environment; virus recovered in scabs on infected corpses after 13 years.
Rotavirus spp. Disease: diarrhea, gastroenteritis	Worldwide Residency: incidental	Fecal-soil-oral, respiratory(?) IMM: Kills 600,000 children worldwide annually; causes 2.7 million cases of gastroenteritis in children under 5 each year in U.S.	Soil association with solid human waste; major cause of death in the third world

From World Health Organization, 1996; Rusin et al., 2000; Toranzos & Marcos, 2000; CDC, 2002; Duckworth et al., 2002; Health Canada, 2002; Public Health Laboratory Service, 2002.

FIGURE 2 Areas endemic for *Coccidioides*. (After Valley Fever Center for Excellence, 2002.)

phosphorus deficiency, which is often associated with soils deficient in phosphorus. Decaying carcasses and bones are part of the surficial soil horizons and host a large array of microbes. If BSE can be transmitted among cattle by ingestion of contaminated bone material then it would also be classified as a transient soil pathogen.

XIII. *COCCIDIOIDES* CASE STUDY

A. Habitat of *Coccidioides*

Coccidioides is a dimorphic soil-inhabiting fungus, an important human pathogen, and the etiological agent of coccidioidomycosis (Valley Fever).

Coccidioides grows in the upper (5–20 cm) horizons of soils in endemic areas (Figure 2). This saprophytic phase of the fungus is characterized by branching, segmented hyphae that form a network of mycelium. As the fungus matures, arthroconidia, 2–5 μm in size, are formed as barrel-shaped, rectangular segments of the hyphae that can be easily separated by soil disturbance (natural or anthropogenic) and consequently be dispersed by the wind. Arthroconidia are also very buoyant and may be readily moved by sheet-wash water during rainstorms only to be concentrated in fine sedimentary material some distance from the initial growth site. Under suitable environmental conditions the arthroconidia can germinate to form new hyphae and mycelium, which can repeat the cycle. If the airborne arthroconidia are inhaled by an appropriate host (humans, animals, even reptiles), then the parasitic phase of *Coccidioides* is initiated (Figure 3). In tissue the arthroconidia transform into spherules 10–80 μm in diameter that, when mature, are internally divided into endospores that are about 3–5 μm in diameter. The mature spherules then rupture and the

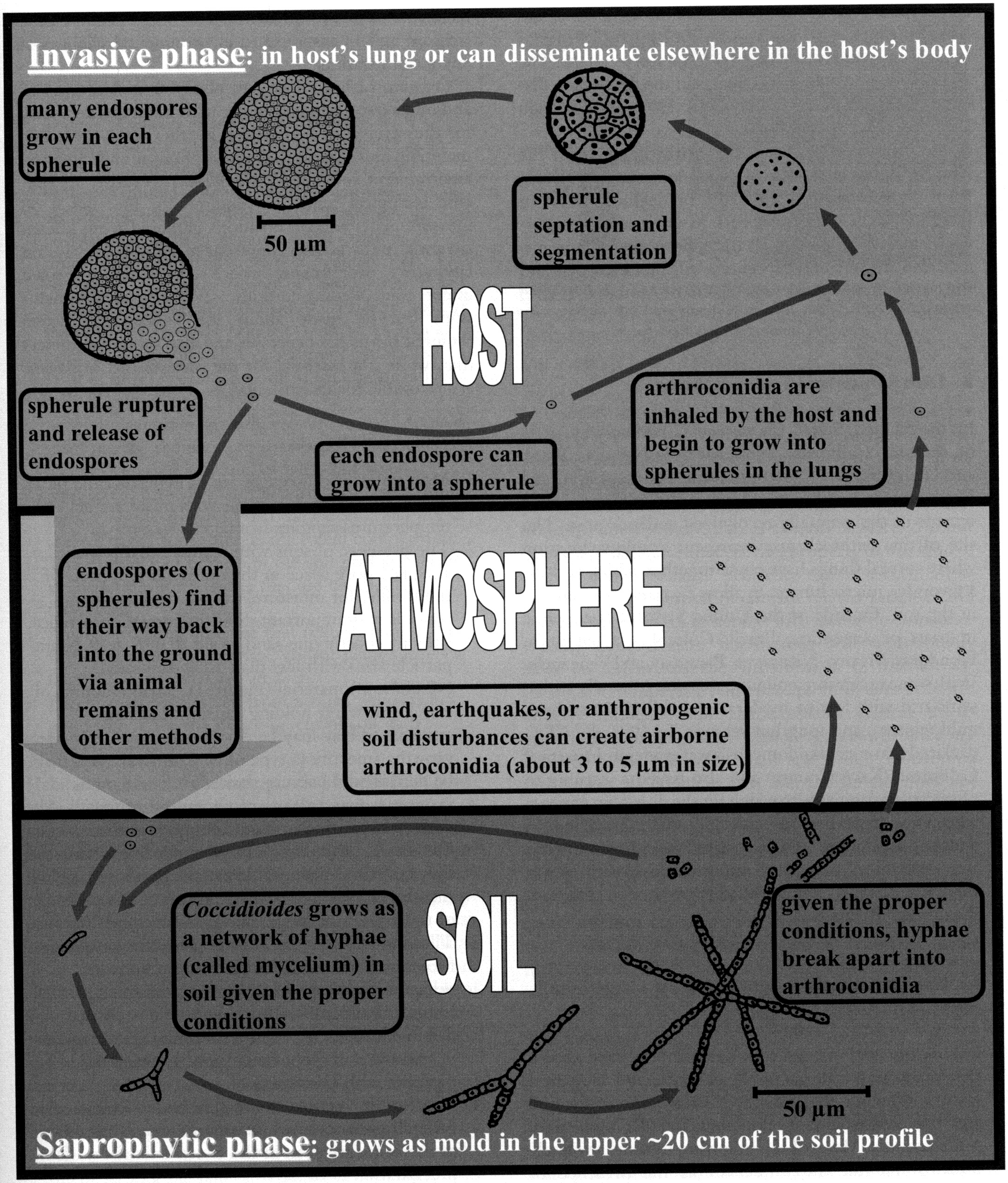

FIGURE 3 The life cycle of *Coccidioides*.

endospores are released into the surrounding tissue and spread the infection locally, or at times, into other organs by disseminating outside of the respiratory system. The epidemiology and human impacts of the disease are discussed in Pappagianis (1980, 1988, 1999) and Galgiani (1993, 1999).

The parasitic phase may end with the death of the host or by the expulsion of spherules outside of living tissue by sputum, pus, exudates, or degradation of an infected carcass. If this occurs in an acceptable environment then the spherules (or endospores) will germinate and hyphae and mycelium will be developed and the saprophytic phase will again be initiated (Fiese, 1958).

B. Distribution and Endemic Areas

In the United States *Coccidioides* is endemic in parts of Arizona, California, New Mexico, Nevada, Texas, and Utah (Figure 2). An outbreak at Dinosaur National Monument in northeastern Utah in 2001 (Figure 2) lies outside of the generally recognized endemic area. The site of this outbreak may represent a unique location where several things have come together, which include a favorable microclimate, to allow *Coccidioides* to survive in the soil. Outside of the United States it is endemic in parts of Argentina, Brazil, Colombia, Guatemala, Honduras, Mexico, Nicaragua, Paraguay, and Venezuela. With some exceptions endemic areas are generally arid to semi-arid with low to moderate rainfall (5–20 inches), mild winters, and long hot seasons. In 1993 the CDC declared that coccidioidomycosis was epidemic in parts of California (Kern County) and also issued a warning to physicians nationwide to watch for the disease in patients who may have become infected while traveling in endemic areas. The CDC also listed coccidioidomycosis as an example of one of the important disease threats to the United States and has called for expanded studies of the disease (Bryan et al., 1994).

C. Habitat Criteria Essential for the Growth and Survival of *Coccidioides*

Laboratory and site-specific field studies have shown that many physical, chemical, climatic, and biological factors influence the growth of *Coccidioides* in the soil and the consequent development and deployment of arthroconidia. Many of the following factors are closely interwoven, and the influence on the presence or growth of *Coccidioides* by any combination of, or single factor, is an intricate balance that varies both in time (season) and in response to environmental changes at any given location.

Oxygen, carbon, nitrogen, phosphorus, sulfur, iron, and other trace elements along with water are necessary for the survival of *Coccidioides*. Furthermore, these raw materials must be available in a physical and chemical environment suitable for *Coccidioides* to satisfy its specific biological functions required for life. Based on measurements and observations gathered from known sites where *Coccidioides* is present in the soil and also on laboratory experiments where *Coccidioides* is grown under controlled conditions, several general conclusions can be made about the habitat parameters required for its life processes and also those parameters that, while not essential for the survival of *Coccidioides*, are favorable for its existence.

1. Important Criteria

1. Most known occurrences are in hyperthermic or thermic aridisols or entisols with mean annual soil temperatures ranging from 15°C to over 22°C.
2. The presence of soils with textures that provide adequate pore space in the upper (20 cm) parts of the profile, for moisture, oxygen, and growing room is very important. Soils in known occurrence sites are mostly fine sand to silt (0.002- to 0.2-mm particle size) with less than 10% clay-sized (<0.002 mm) material (Figure 1). Small amounts of clay foster water holding capacity, but large amounts of clay may be detrimental for *Coccidioides* growth. Smectite (a type of clay mineral) soils may be detrimental because their shrink and swell properties may provide room and water for bacterial growth that would compete with *Coccidioides*. Also, and perhaps, more important, they contain exchangeable cations that lower pH thereby enhancing bacterial growth at the expense of the growth of fungi.
3. The presence of some organic material is needed for carbon and nitrogen but in most known occurrences it is generally sparse, less than 2%. Large amounts of organic compounds may be detrimental because they would foster the growth of bacteria and other fungal species that would compete with *Coccidioides*.
4. Moisture is essential. Rainfall in endemic areas is generally seasonal with some areas receiving most of their precipitation in the winter months while precipitation in other areas may be split between winter rains and summer monsoons. In all cases,

annual precipitation ranges from less than 250 mm to 410 mm.

2. *Favorable Criteria*

1. Many *Coccidioides* growth sites have soils with elevated salinity. High soluble salts may act as an inhibitor of microbial competitors. Measured values of soluble salts in soils from known occurrence sites are sodium, 8–75% greater in positive soils than in negative soils; calcium, 2–5 times greater in positive than in negative soils; potassium, 2–5 times greater in positive than in negative soils; sulfates, 2–5 times greater in positive than in negative soils; borates, 3–25 times greater in positive than in negative soils; and chlorides, 10–240 times greater in positive than in negative soils (Elconin et al., 1964)
2. Several *Coccidioides* growth sites are in soils derived from marine sedimentary rocks. These rocks often contain elevated amounts of salts, and when weathered, provide material with textures favorable for *Coccidioides* growth. Also the elevated salinity of these derived soils inhibits microbial competition.
3. The presence of borates in the soil profile may act as antiseptics for bacteria that are competitive with *Coccidioides.*
4. Any environmental factor that reduces competition with other fungal, bacterial, and/or plant species is favorable for *Coccidioides* growth.
5. Parent material derived from aeolian deposits is a good source for the development of soil with favorable textures.

Habitat modeling of the saprophytic phase of the *Coccidioides* life cycle is difficult due to the limited number of known growth sites. This confounds the establishment of statistical relationships of the physical, chemical, and biological habitat parameters. Therefore, habitat modeling is accomplished using analysis of the physical properties of known *Coccidioides* sites and a spatial fuzzy system. A spatial fuzzy system is a system of spatial variables where some or all of the spatial variables are described with fuzzy sets. The fuzzy system is capable of translating structured knowledge into a flexible numerical framework and processing it with a series of if-then rules called fuzzy associative memory (FAM) rules.

Fuzzy systems can describe nonlinear numerical processes with linguistic common sense terms and can handle differing precision and accuracy in the data. They produce models that can be repeated and updated easily.

Fuzzy system analysis was applied to each 30 × 30 m spatial cell over the study area, Organ Pipe Cactus National Monument, Arizona. The resulting product is a map (Figure 4) depicting each cell's favorableness for hosting *Coccidioides* based on a scale of 0 to 1, which we define as its fuzzy habitat suitability index (FHSI). The fuzzy system allows modelers to change and update relationships among the variables as more is learned about *Coccidioides* habitat. An important property of this kind of analysis is that "what if" scenarios can be used to allow dynamic representation of climate related variables and may predict changes in habitat with changing climate.

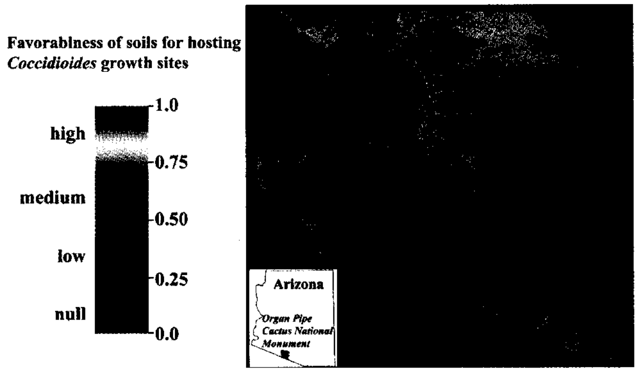

FIGURE 4 The fuzzy habitat suitability index of *Coccidioides* measured as the favorableness of soils for hosting *Coccidioides*, Organ Pipe Cactus National Monument, Arizona.

Long-term climate fluctuations will undoubtedly have an effect on the distribution of *Coccidioides*. Changes in temperature and precipitation over time will directly influence soil characteristics critical to its growth and propagation. *Coccidioides* growth sites are believed to be relatively small and widely distributed throughout its endemic area and the fungus does not readily colonize outside of established growth sites. Laboratory studies show that *Coccidioides* is quite robust with respect to the physical and chemical factors of its habitat, but is very sensitive to competition from other microbes and vegetation. Therefore, climate change models that result in an increase in microbes in the soil profile and in the vegetation of a given area would result in decreased habitat for *Coccidioides* and scenarios that would reduce microbes in the soil profile and the vegetation in a given area may result in an increase in suitable habitat.

XIV. SOILS AND EMERGING DISEASES

Emerging infectious diseases may be defined as those that have newly appeared in a population and those annual precipitation ranges from less than 250 mm to 410 mm.

2. *Favorable Criteria*

1. Many *Coccidioides* growth sites have soils with elevated salinity. High soluble salts may act as an inhibitor of microbial competitors. Measured values of soluble salts in soils from known occurrence sites are sodium, 8–75% greater in positive soils than in negative soils; calcium, 2–5 times greater in positive than in negative soils; potassium, 2–5 times greater in positive than in negative soils; sulfates, 2–5 times greater in positive than in negative soils; borates, 3–25 times greater in positive than in negative soils; and chlorides, 10–240 times greater in positive than in negative soils (Elconin et al., 1964)
2. Several *Coccidioides* growth sites are in soils derived from marine sedimentary rocks. These rocks often contain elevated amounts of salts, and when weathered, provide material with textures favorable for *Coccidioides* growth. Also the elevated salinity of these derived soils inhibits microbial competition.
3. The presence of borates in the soil profile may act as antiseptics for bacteria that are competitive with *Coccidioides.*
4. Any environmental factor that reduces competition with other fungal, bacterial, and/or plant species is favorable for *Coccidioides* growth.
5. Parent material derived from aeolian deposits is a good source for the development of soil with favorable textures.

Habitat modeling of the saprophytic phase of the *Coccidioides* life cycle is difficult due to the limited number of known growth sites. This confounds the establishment of statistical relationships of the physical, chemical, and biological habitat parameters. Therefore, habitat modeling is accomplished using analysis of the physical properties of known *Coccidioides* sites and a spatial fuzzy system. A spatial fuzzy system is a system of spatial variables where some or all of the spatial variables are described with fuzzy sets. The fuzzy system is capable of translating structured knowledge into a flexible numerical framework and processing it with a series of if-then rules called fuzzy associative memory (FAM) rules.

Fuzzy systems can describe nonlinear numerical processes with linguistic common sense terms and can handle differing precision and accuracy in the data. They produce models that can be repeated and updated easily.

Fuzzy system analysis was applied to each 30 × 30 m spatial cell over the study area, Organ Pipe Cactus National Monument, Arizona. The resulting product is a map (Figure 4) depicting each cell's favorableness for hosting *Coccidioides* based on a scale of 0 to 1, which we define as its fuzzy habitat suitability index (FHSI). The fuzzy system allows modelers to change and update relationships among the variables as more is learned about *Coccidioides* habitat. An important property of this kind of analysis is that "what if" scenarios can be used to allow dynamic representation of climate related variables and may predict changes in habitat with changing climate.

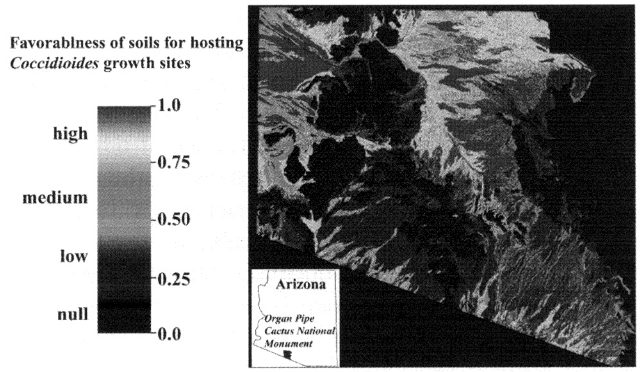

FIGURE 4 The fuzzy habitat suitability index of *Coccidioides* measured as the favorableness of soils for hosting *Coccidioides*, Organ Pipe Cactus National Monument, Arizona.

Long-term climate fluctuations will undoubtedly have an effect on the distribution of *Coccidioides*. Changes in temperature and precipitation over time will directly influence soil characteristics critical to its growth and propagation. *Coccidioides* growth sites are believed to be relatively small and widely distributed throughout its endemic area and the fungus does not readily colonize outside of established growth sites. Laboratory studies show that *Coccidioides* is quite robust with respect to the physical and chemical factors of its habitat, but is very sensitive to competition from other microbes and vegetation. Therefore, climate change models that result in an increase in microbes in the soil profile and in the vegetation of a given area would result in decreased habitat for *Coccidioides* and scenarios that would reduce microbes in the soil profile and the vegetation in a given area may result in an increase in suitable habitat.

XIV. Soils and Emerging Diseases

Emerging infectious diseases may be defined as those that have newly appeared in a population and those whose incidence in humans has increased within the past two decades. A re-emergent disease is the reappearance of a known disease after a decline in incidence (Lederberg et al., 1992, pp. 34, 42). Many soils provide an ideal environment for the emergence of new infectious diseases due to their overall chemical and physical diversity, supply of essential nutrients for microbial growth, and their constantly evolving character in response to various soil forming factors, especially climate.

Disease emergence can be attributed to numerous factors such as the natural evolution and mutation of existing organisms; the spread of known diseases into new populations and/or new geographic areas; increasing human population; ecological changes that increase exposure of people to pathogens carried by insect or animal vectors; environmental changes that increase the exposure of people to contaminated dust, water, and soil; and exposure to as yet unknown pathogens (World Health Organization, 2002). The re-emergence of known soil-borne pathogens may occur in response to the breakdown or overtaxing of existing public health infrastructures as a result of refugee circumstances or other types of major demographic changes.

Examples of recently emerging and re-emerging soil-borne pathogens are *Clostridium* spp. bacteria, which cause a variety of diseases and are probably a permanent soil resident, transmitted by the fecal-oral route and through skin trauma; *Listeria monocytogenes*, a bacterium, which causes listeriosis and is a permanent soil resident transmitted by contact with soil contaminated with infective animal feces and also by inhalation of the organism; Sin Nombre virus, a *Hantavirus*, which causes hemorrhagic fever, is a transient soil resident, and is transmitted by inhalation of dust containing aerosolized rodent urine and feces; *Rotavirus* spp., which causes diarrhea and enteritis, an incidental or less commonly, transient soil resident, transmitted by the fecal-soil-oral route also by the fecal-respiratory route; *Coccidioides*, a fungus, which causes coccidioidomycosis, a permanent soil resident, transmitted by inhalation of *Coccidioides* arthroconidia (Bryan et al., 1994); and variant Creutzfeldt-Jakob disease, a TSE caused by prion infection, outbreaks in the UK in the late 1990s, possibly(?) a transient or incidental soil resident (Lederberg et al., 1992, Table 2.1, p. 36; World Health Organization, 1998).

Antimicrobial resistance, which is a natural consequence of the adaptation of microbes to exposure of drugs designed to kill them, may also cause re-emergence of infectious diseases. Even though resistance to antimicrobial agents is an irreversible, natural, and evolutionary process, it is exacerbated by several human activities including overuse (in developed countries) and under use (in developing countries) of antibiotic drugs; discharges of wastes from pharmaceutical production plants; disposal into landfills and sewage of wastes from common antibacterial household products (soaps, over-the-counter drugs, cosmetics, cleaning supplies, etc.); introduction into the human food chain by agricultural use of antibiotics for disease and pest control on plants and also by use of antibiotics on many types of livestock for therapeutic reasons and as growth enhancers; disposal of waste products from agricultural operations; disposal of sewage sludge in landfills and by application directly onto the land surface; and disposal of all types of household and industrial garbage into landfills (Standing Medical Advisory Committee, 1998, American Academy of Microbiology, 1999). Antibacterial drugs have received the most attention in regards to antimicrobial resistance; however, resistance is also developing to antiviral and antifungal drugs.

The ability of pathogenic microbes to respond and adapt quickly to new environmental conditions is fundamental to the development of antimicrobial resistance. Both the disposal of waste material in landfills and application of sewage sludge to the land surface create chemical and biological modifications of the natural soil environment in any given place and provide new environments that can foster microbial genetic change. In developed countries modern sanitary landfills and municipal sewage plants are closely regulated and designed to limit the escape of chemical and biological toxins. Homes in these countries, not connected to municipal sewage systems, in most cases utilize septic systems with leach fields that rely on the soils for sewage treatment. Nonetheless some sewage sludge and landfill leachates contain a variety of bacterial, parasitic, and viral pathogens derived from food waste, domestic animal feces, disposable diapers, and garden waste.

In developing countries raw sewage and untreated waste of all types are commonly disposed of directly into soils and at times are added directly to soils as fertilizer. Under these circumstances some bacterial pathogens in sludge and sewage may fail to adapt and die out, whereas others will adapt to the new environment and experience new growth.

Also of concern is the presence of residual amounts of antimicrobial agents (pharmaceuticals, heavy metals, toxic chemicals) that may select for the growth of new bacterial forms that are resistant to various antibiotics. Non-biological dispersal of pathogens from landfills are mainly by water (both surface runoff and groundwater in the vadose zone) and wind. Biological dispersal may be due to birds, rodents, insects, and humans.

XV. Interconnections: Geology/Soil/Pathogenic Microbes

The importance of the soil environment for hosting human pathogens was recognized over 2000 years ago by Hippocrates who suggested that a physician, when arriving at an unfamiliar town, should examine the winds, sun aspect, sources of water, and "... the soil too, whether bare and dry or wooded and watered, hollow and hot or high and cold." (Jones, 1923). That wisdom has enormous room for development in the 21st century.

The study of the ecological habitats of soil microbes (both friendly and pathogenic) has been hampered for centuries by the inability to see, measure, count, and weigh organisms too small for the human eye to distinguish, especially *in situ*. It has also been hampered by the inadequate exchange of ideas and approaches among the wide diversity of scientific disciplines studying soils and microbes. Complete scientific descriptions of soil attributes, profiles, and classifications are rarely, if ever, given in the medical and microbiological literature focused on site-specific occurrences of soil-borne human pathogens. This makes it nearly impossible to conduct followup studies or further experiments in the same area or soil type, or to extrapolate results to other locations and studies. Commonly the only mention of the terrestrial environment of pathogenic organisms is described by phrases such as "soil" or "soil contaminated with bird feces," or "moist anaerobic soil," when describing the organism's habitat. This is not meant to fault prior research but instead to underline the need for multidisciplinary efforts. Many scientists are not knowledgeable about soils or soil attributes that affect microbes. Therefore, important geologic-soil-pathogen-process relationships are overlooked in many studies.

Geological features and processes are inherent in many soil attributes, which are, in turn, important controls over microbial activity and existence. For example, the abundance of ferromagnesian minerals and feldspars in a parent rock will determine the abundance and types of clay minerals formed (given the right climatic conditions) in soils by weathering processes. The presence of clay minerals strongly influences soil water potential, soil aggregation and pore size, microbe movement, virus adsorption, and the types of microbes present in any given soil.

Infection by soil-borne pathogens can be prevented or reduced by disrupting their life cycle. However, to do this a complete understanding of the infectious cycle is necessary to determine where interdiction will be most effective. For example, interdiction of the life cycle of soil-borne enteric pathogens is accomplished by the use of proper disposal and sanitation measures of human wastes. Another example is disruption of the hantavirus cycle of infection by controlling rodents in enclosed areas, thereby reducing or preventing exposure to contaminated aerosols from rodent feces and urine. These and similar examples require basic research into all aspects of the life processes and ecology of soil-borne pathogens and their interaction with the physical, chemical, and biological attributes of their habitat. These studies are best accomplished in the field and on-site using, whenever possible, noninvasive methods, some of which are reviewed by Madsen (1996). In the best circumstances, studies of soil-borne human pathogens would include a soil scientist familiar with field measurements and determinations of soil properties and classification. At the minimum, soil pathogen collection sites should be precisely located, soil textures should be determined, sand-silt-clay proportions should be estimated, organic content determined, hydrologic setting described, geomorphologic setting determined, pH and salinity (electrical conductivity) measured, and vegetation type and density described. These observations would go a long way to address Hippocrates' counsel to look at the soils.

Infectious diseases are a major cause of human suffering and mortality and account for an estimated 13 million deaths worldwide each year (World Health Organization, 1999), and that number is expected to grow. As indicated in previous sections, soil-borne human pathogens are important contributors to those numbers. Drug-resistant microbes are increasing at a dramatic rate and large urbanized areas in developing countries with dismal health care and sanitary facilities are magnets for displaced people. Deteriorating natural environments through urbanization, deforestation, and pollution of soils and waters coupled with the ease of human travel ensures breeding places and rapid transportation for many infectious agents. Increased understanding of the life cycles of pathogenic soil-borne microbes, the ecology of their habitats, and the environmental gateways they utilize for infectious transmissions will help break these cycles of infection. These problems are complex in character, global in distribution, and applicable to every human being. Their solutions are contingent on scientists from many disciplines working together to study the attributes and processes of complex soil ecosystems and communicating their results to public health officials.

SEE ALSO THE FOLLOWING CHAPTERS

Chapter 14 (Bioavailability of Elements in Soil) · Chapter 17 (Geophagy and the Involuntary Ingestion of Soil) · Chapter 18 (Natural Aerosolic Mineral Dusts and Human Health) · Chapter 27 (Investigating Vector-Borne and Zoonotic Diseases with Remote Sensing and GIS)

FURTHER READING

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