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Current Opinion in
Environmental Science & Health

Soil pathogens that may potentially cause pandemics, including severe acute respiratory syndrome (SARS) coronaviruses

Joshua J. Steffan[1,2], Jade A. Derby[1] and Eric C. Brevik[1,2]

Abstract

Soil ecosystems contain and support the greatest amount of biodiversity on the planet. A majority of this diversity is made up of microorganisms, most of which are beneficial for humans. However, some of these organisms are considered human pathogens. In light of the current severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) outbreak, one may ponder the origin of the next pandemic and if soil may represent a source of pathogens with pandemic potential. This review focuses on several bacterial, fungal, and viral pathogens that can result in human infection due to direct interaction with the soil. Moreover, the current status of knowledge regarding SARS-CoV-2 survival in and transmission from soil is reviewed.

Addresses

[1] Department of Natural Sciences, Dickinson State University, Dickinson, ND, USA

[2] Department of Agriculture and Technical Studies, Dickinson State University, Dickinson, ND, USA

Corresponding authors: Brevik, Eric C (Eric.Brevik@dickinsonstate.edu); Steffan, Joshua J (Joshua.steffan@dickinsonstate.edu)

Current Opinion in Environmental Science & Health 2020, **17**:35–40

This review comes from a themed issue on **Environmental Health: COVID-19**

Edited by **Avelino Núñez-Delgado**

For a complete overview see the Issue and the Editorial

https://doi.org/10.1016/j.coesh.2020.08.005

Keywords

Soil and human health, Pandemic, Pathogens, Viruses, SARS coronavirus, Zoonosis.

Introduction

Soils provide essential ecosystem services to humans, many of which relate directly to human health [1,2]. The macroorganisms and microorganisms that live in soil are responsible, either directly or indirectly, for providing many of these ecosystem services. The soil ecosystem contains the greatest amount of biodiversity in the world [3]. The inherent complexity of soil systems results in microecosystems for many different pathogenic and nonpathogenic organisms [4]. In most undisturbed ecosystems, pathogens and prey are kept in check by ecological predator—prey relationships [5] and most soil-borne/dwelling pathogens do not pose a risk to human health [6]. However, of the organisms that do cause human disease, many of them or their vectors live in or spend part of their life cycle in soil. This often occurs in disturbed soil ecosystems where pathogens directly or indirectly (i.e., through animals or another vector) enter the human host and cause disease. Therefore, in light of worldwide land use change and degradation, changing climate, weather extremes [7—9], and the current severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) pandemic, one may ponder the origin of the next pandemic and what role, if any, soil may play.

The next viral pandemic will more than likely result from zoonotic infections; therefore, more zoonotic viral pandemics should be expected [10—15]. Less likely, but still meaningful, is the possibility of pandemic reemergence from thawing permafrost soils/burial sites (as discussed in a following section). Recent reviews speculating which pathogen may be next to emerge have recently been published [10—12,16] (Table 1). Numerous government and nonprofit agencies around the world are monitoring these emerging infectious diseases.

For this review, we have focused on: (1) only those pathogens that can cause human disease directly from exposure to soil, (2) exposure to pathogens that are harbored in frozen carcasses buried in the soil, and (3) survival of viruses in the soil. Pathogens found indirectly in the soil such as from the addition of fecal material, wastewater, sewage, manure, etc are not considered further in this review, and due to space limitations not all potential pathogens are discussed. The authors refer the reader to the following in-depth reviews for additional discussion of soil pathogens [17—22].

Direct exposure

Pathogenic bacteria or fungi can directly enter humans through cutaneous wound inoculation, ingestion of contaminated food or direct ingestion of soil (geophagy), or through the respiratory route via aerosols such as windblown endospores or pathogens carried on dust particles. Below we briefly discuss specific pathogens that fall within this broad definition.

Table 1

Soil pathogens that directly cause human infections and their pandemic potential.

Disease	Causative agent	Pandemic potential
Plague (bubonic and pneumonic)	*Yersinia pestis*	High
Melioidosis	*Burkholderia pseudomallei*	Intermediate to High
Anthrax	*Bacillus anthracis*	Low to Intermediate
Tetanus	*Clostridium tetani*	Low
Botulism	*Clostridium botulinum*	Low
Listeriosis (gastrointestinal; meningitis)	*Listeria monocytogenes*	Low
Tularemia	*Francisella tularensis*	Low
Leprosy	*Mycobacterium leprae*	Low
Shigellosis	*Shigella* spp.	Low
Gastrointestinal disease	*Salmonella enterica*	Low
Gastrointestinal disease	*Campylobacter* spp.	Low
Gastrointestinal disease	*Escherichia coli (esp. H0157:H7)*	Low
Legionnaires' Disease	*Legionella* spp.	Low
Coccidioidomycosis	*Coccidioides* spp.	Low
Blastomycosis	*Blastomyces dermatitidis*	Low
Histoplasmosis	*Histoplasma capsulatum*	Low
Sporotrichosis	*Sporothrix schenckii*	Low
Meningitis	*Exserohilum rostratum*	Low
Multiple	*Viruses (unknown; emerging)*	Unknown

Table 1: A summary of the organisms discussed in this review. Pandemic potential is a highly subjective rating based mostly on the ability of the organism to spread person to person via respiratory droplets. A low pandemic rating should not negate continued surveillance as these organisms have and can cause local outbreaks and regional epidemics.

Bacillus anthracis

B. anthracis is a gram-positive bacterium that causes the zoonotic disease anthrax in humans, wildlife, and livestock. Anthrax can clinically present in three different ways depending upon the exposure mechanism (cutaneous, inhalation, or ingestion). *B. anthracis* is found in soils throughout the world as endospores, dormant structures that can last for decades within soils. Extreme weather events such as heavy rains can bring the endospores to the soil surface resulting in exposure and drought/wind can aerosolize anthrax endospores resulting in inhalation anthrax [23]. Escalating soil degradation throughout the world and extreme weather events will likely increase human and animal exposure to *B. anthracis.* However, although a serious disease for those exposed, *B. anthracis* does not readily spread from person to person (is not contagious). Infection occurs only from exposure to endospores, therefore the pandemic potential of anthrax is low, notwithstanding nefarious bioterrorism ambitions (as seen in the United States in 2001) [24].

Clostridium spp.

Tetanus and botulism are two diseases caused by toxins produced by *Clostridium tetani* and *Clostridium botulinum*, respectively. These toxins paralyze muscles and can lead to death [25]. *C. tetani* has a worldwide distribution in soil and feces [21]. Increased prevalence in tropical latitudes is often related to climate and soil pH [25]. *C. botulinum* causes sporadic cases and outbreaks worldwide [21] due to its worldwide distribution in soil and water and can persist in soils for decades [26]. *C. botulinum* endospores often contaminate food that is then ingested resulting in disease. *C. botulinum* endospores resist boiling temperature; therefore, pressure cooking is required to inactivate the endospores. Although a serious disease for those infected, *C. tetani* and *C. botulinum* do not spread readily from person to person (are not contagious) and infection occurs only from exposure to endospores. This exposure results in vegetative cell regeneration and toxin production, therefore the pandemic potential is low.

Listeria monocytogenes

L. monocytogenes causes food-borne gastrointestinal illness and more serious meningitis [21]. It is ubiquitous in soil, water, and vegetation. *L. monocytogenes* does not form endospores, but it can withstand severe environmental stress such as extremes in temperature, pH, salinity, etc. [27]. Again, direct exposure (ingestion of contaminated soil/vegetation or the fecal-oral route) is required to cause disease, and it is therefore not necessarily contagious; therefore, the pandemic potential is low.

Yersinia pestis

Y. pestis, the causative agent of pneumonic and bubonic plague, has greatly affected the course of human history by causing three recorded pandemics [28]. Although *Y. pestis* exists in both rodent populations and their fleas, *Y. pestis* was reportedly isolated from the soil as early as 1894 [29] and later in 1963 [30]. The long-term persistence of *Y. pestis* in soil more than likely plays a role in its epidemiology. *Y. pestis* re-emerges from specific geographical foci after decades of silence, where it has been shown to survive for extended periods of time in soil [31]. Although both pneumonic and bubonic plague are highly fatal bacterial infections, the pneumonic form of plague is exceptionally contagious. Therefore, the pandemic potential of soil-induced/rodent-induced/flea-induced *Y. pestis* infection remains high, not to mention the potential of a bioterrorism-induced pandemic.

Burkholderia pseudomallei

Burkholderia pseudomallei is the causative agent of melioidosis, which is considered a potential emerging infectious disease, especially in tropical, developing countries [32]. The bacterium is mainly found in anthrosol and acrisol soil types that experience high rainfall and temperature [32]. It is not highly contagious, therefore a natural infection—induced pandemic is unlikely; however, the threat of bioterrorism is suspected to be high as an organism that causes a melioidoisis-like disease has been used in the past.

Francisella tularensis

F. tularensis causes tularemia, which infects humans directly through contact with infected wild animals, undercooked wild game meat products, or soil [22]. Found throughout the world in soils (deposited by infected animals), tularemia is a serious disease for those infected. Although highly contagious from environmental sources, it rarely spreads person to person; therefore, the pandemic potential is low.

Other bacteria

A large number of other human bacterial infections have been suggested to occur from exposure to soil. These include *Salmonella enterica*, *Campylobacter* spp., *Escherichia coli* (food-born gastrointestinal disease), *Legionella* spp. (pneumonia; Legionnaires' Disease), *Mycobacterium leprae* (leprosy), *Shigella* spp. (shigellosis), and many others [22]. The bacteria listed above are not highly contagious and therefore the pandemic potential is low.

Fungal infections

Fungi represent one of the most diverse kingdoms on the planet. Most fungi are beneficial, provide essential ecosystem services, and do not cause human disease [33]. In fact, most fungal infections only occur in immunosuppressed persons. However, several pathogenic fungal species are found in soil that can infect immunocompetent individuals [22]. Herein, we briefly mention several of these species. *Coccidioides* spp. are the causative agent of coccidioidomycosis, also known as valley fever, which is acquired through contaminated dust inhalation (although there is debate whether it is a true soil resident) [34]. *Blastomyces dermatitidis*, the causative agent of blastomycosis, is endemic in soils (perhaps not worldwide) and can survive harsh environmental conditions similar to *L. monocytogenes* [35]. *Histoplasma capsulatum* causes histoplasmosis, is found in temperate climate soils throughout the world, and is often an opportunistic pathogen [22,36]. *Sporothrix schenckii* can cause sporotrichosis which is a rare subacute to chronic infection resulting from direct exposure (cutaneous or inhalation) and zoonotic transmission is also know to occur [22]. *Exserohilum rostratum* is commonly found in soils and can cause problems in wounds contaminated with soil or plant material [33]. Although persons infected with these fungal species can have serious, life-threatening diseases, these diseases are not considered to be contagious, therefore the pandemic potential is low.

Exposure to frozen pathogens

Extreme weather events, changing climate, expansion of migratory habitats, population growth, poverty/socio-economic status, refugees and migrants, and warfare/conflict are increasingly causing land use change and degradation [37,38]. Land use change and degradation increases the likelihood of humans being exposed to new or resurrected microbes [39]. New microbes are microorganisms that humans have not previously been exposed to. Exposure can occur during deforestation, refugee migration, and extreme weather events, amongst others. Resurrected microbes, on the other hand, are microbes that are not known to currently circulate in nature but are either found in laboratories or frozen in permafrost (usually in ancient human and animal burial sites). Warming of the northern latitudes melts the permafrost and unthaws the microorganisms found in it. This melting provides extensive new habitat(s) for the emergence of novel pathogens [39]. In fact, deadly infections of the 18th and 19th centuries have been suggested as candidates for potential reemergence. Risk factors include the northern expansion of bird migration (which can also introduce pathogens into the newly unthawed habitat), an increase in insect vector populations, and a large increase in zoonotic infections [40,41].

Two examples will be used to highlight how diseases may migrate from thawed permafrost regions. First, in Russia alone, there are 13,885 known cattle burial grounds, mostly due to anthrax outbreaks. Endospores of Siberian anthrax have been shown to remain viable for about 105 years in permafrost [42] and reports of anthrax transmission to reindeer from these burial sites reinforces this long-term survival rate [41]. Seasonal migration patterns of reindeer could also impact the exposure of humans to *Brucella* spp., the causative agent of brucellosis. Therefore, populations relying on reindeer for food and survival are at high risk. Moreover, future mining, construction, and agricultural development on these thawed soils will only increase the risk for human infection as humans migrate into these areas and disrupt the soil and burial sites [39,43,44]. Secondly, a number of 'new' viruses have been isolated from permafrost. A replication-competent Pithovirus was isolated from 30,000-year-old—thawed permafrost in Siberia [45] and 5000-year-old frozen caribou feces has been shown to contain viable virus particles [46]. If these viruses are human pathogens or mutate, allowing them to infect humans, the current human population is likely to have no prior immunity toward these viruses, so their pandemic potential may be high. However, that is highly speculative; they may also represent no human threat.

Survival of viruses in soil

Compared to soil bacterial and fungal pathogens, the soil virome is drastically understudied in the context of human health [47]. Most articles in the literature fail to adequately distinguish between eukaryotic viruses (viruses that may affect humans) and bacteriophages (viruses that only infect bacteria). Because bacteriophages are not human pathogens, there is potential for confusion in the soil virome literature as many publications describing soil 'viruses' are actually soil bacteriophage studies [47,48]. However, the few studies that have looked at the survival of eukaryotic viruses in soil have shown that viruses are able to adsorb to soil surfaces (i.e. the surface of clays and particulate organic matter) and that soil temperature, moisture content, phosphorus and aluminum levels, and pH all play a role in virus survival [49]. Tierney et al. [50] have shown that poliovirus (a nonenveloped virus) can survive in soil for eleven days in the summer months and ninety-six days in the winter months. Studies comparing the survival of enveloped to nonenveloped viruses have been performed on inanimate surfaces [51,52], but few studies have occurred in the context of soil — a living, complex ecosystem [49]. These types of studies are significant as the viral envelope (a phospholipid bilayer) has been shown to be more prone to desiccation and thereby may be more easily disrupted in the soil environment compared with a 'naked' nonenveloped virus. A study examining the survival of avian influenza (H5N1) in soil demonstrated that this enveloped virus did not survive in sandy topsoil but did survive in purchased construction sand and compost suggesting that different soil characteristics greatly impact virus survival [53]. In summary, factors that affect virus stability in soil include temperature, relative humidity, sunlight/UV radiation, solutes, pH, organic matter, types of clays, nutrient status, type of virus, and the presence/absence of an envelope [51]. Unfortunately, there is not a set of soil indicators or universal assessment(s) that predict viral stability in the soil.

The second major characteristic that affects viral survival in soil is the ability of the virus to aggregate. Gerba and Betancourt [54] have shown that viral aggregates in the environment can support viral survival and resistance to disinfection, which results in underestimation of viral titer in the soil. The studies that use bacteriophages as surrogates for eukaryotic viruses, which we argue is not an adequate comparison, have shown that hot deserts have the lowest bacteriophage abundance, cold deserts and agricultural fields have an intermediate abundance, and the highest abundance is found in forested and wetland soils. However, more studies are required to examine the survival of eukaryotic viruses in soil.

The current SARS-CoV-2 pandemic has led many to ponder if this novel virus survives in soil. A brief discussion by Núñez-Delgado [55] suggests that soil may become contaminated with SARS-CoV-2 from wastewater and sewage sludge, but no research studies have been done to date on SARS-CoV-2 and survival in the soil. Lal et al. [7,8] and Tang et al. [56] have advocated for research into possible pathogen—soil interactions involving SARS-CoV-2. We do know that SARS-CoV (the first SARS pandemic) was spread person to person via inhalation of respiratory droplets, through contact with virus-contaminated surfaces, and via the fecal droplet-respiratory route [57,58], but whether SARS-CoV-2 behaves in a similar fashion is unknown (especially in reference to the fecal droplet route) [59]. RNA viruses such as SARS-CoV-2 are highly prone to mutation; in fact SARS-CoV-2 has already mutated into two types (L and S) [60]. The presence of an envelope suggests that if SARS-CoV-2 survives in the soil, it would be for a relatively shorter period of time (for just a few days [61]) than if it was a nonenveloped virus [51,55]. To date there are no peer-reviewed publications specifically examining the survivability of SARS-CoV-2 in soil. As outlined by Núñez-Delgado [62], more research is needed on SARS-CoV-2 in soils and in potentially contaminated substances added to soils (i.e. wastewater and sewage sludge). Fortunately, the methods used to study viruses in wastewater and sewage sludge may carryover to soils.

Conclusion

The soil is home to many pathogens. Some of these pathogens can directly infect humans, but many more are considered zoonotic diseases, infecting humans via vectors and/or carriers living in or on the soil. As humans continue to interfere with ecological conditions throughout the world, the risk of exposure to these and other novel pathogens will increase [16]. So what can we do to prevent soil-borne diseases? Lal et al. [7,8] and Steffan et al. [63] have provided a blueprint forward placing soils (soil quality and functionality) at the forefront of human health and possibly a path to prevent/reduce the risk of future pandemics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

J.S., J.D., and E.B. were partially supported by the National Science Foundation, Established Program to Stimulate Competitive Research (EPSCoR), under Grant Number IIA-1355466 during the writing of this article. J.S. and J.D. were also supported by an Institutional Development Award (IDeA) from the National Institute of General Medical Sciences of the National Institutes of Health under grant number P20-GM103442.

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