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

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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.

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**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 ssp.**

Tétanos 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
perspective 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/todent-induced/flea-induced *Y. pestis* infection remains high, not to mention the potential of a bioterrorism-induced pandemic.

**Burkholderia pseudomallei**

*B. 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 anthrol 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 melioidosis-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 known 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 unthumbs 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. Endosporas 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 underestimated 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.

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References
1. Brevik EC, Perez L, Pereira P, Steffan JJ, Burgess LC, Gedeon CI: Shelter, clothing, and fuel: often overlooked links between soils, ecosystem services, and human health. Sci Total Environ 2019, 651:134–142.
2. Brevik EC, Perez L, Steffan JJ, Burgess LC: Soil ecosystem services and human health. Current Opinion in Environmental Science & Health 2018, 5:87–92.
3. Wall DH, Nielsen UN, Six J: Soil biodiversity and human health. Nature 2015, 528:69–76.
4. Loyañachan T: Human disease from introduced and resident soilborne pathogens. In Soils and human health. CRC Press; 2013:107–136.
5. Thakur MP, Geisen S: Trophic regulations of the soil microbiome. Trends Microbiol 2019, 27:771–780.
6. Jeffers S, Van der Putten WH: Soil born human diseases. Publications Office; 2011.
7. Lal R: Soil science beyond COVID-19. J Soil Water Conserv 2020, 75:79A–81A.
8. Lal R, Brevik E, Dawson L, Field D, Glaser B, Hartemink A, Hatano R, Monger C, Scholten T, Singh B, et al.: Managing soils for recovering from the COVID-19 pandemic. Soil Systems 2020, 4:46, https://doi.org/10.3390/soilsystems4030046.
9. Gomerio T: Soil degradation, land scarcity and food security: reviewing a complex challenge. Sustainability 2016, 8:281.
10. Khubchandani J, Jordan TR, Yang YT: Ebola, zika, Corona… What is next for our world? Int J Environ Res Publ Health 2020:17.
11. Lloyd-Smith JO: Predictions of virus spillover across species. Nature 2017, 546:603–604.
12. Olival KJ, Hosseini PR, Zambrana-Torrello C, Ross N, Bogich TL, Daszak P: Host and viral traits predict zoonotic spillover from mammals. Nature 2017, 546:646–650.
13. Morse SS, Mazet JA, Woolhouse M, Parrish CR, Carroll D, Karem WB, Zambrana-Torrello C, Lipkin WI, Daszak P: Prediction and prevention of the next pandemic zoonosis. Lancet 2012, 380:1956–1965.
14. Kilpatrick AM, Randolph SE: Drivers, dynamics, and control of emerging vector-borne zoonotic diseases. Lancet 2012, 380:1946–1955.
15. Karem WB, Dobson A, Lloyd-Smith JO, Lubroth J, Dixon MA, Bennett M, Aldrich S, Harrington T, Formenty P, Loh EH, et al.: Ecology of zoonoses: natural and unnatural histories. Lancet 2012, 380:1936–1945.
16. Nii-Trebi N: Emerging and neglected infectious diseases: insights, advances, and challenges. BioMed Res Int 2017, 2017:1–15.
17. Bowers JR, Parise KL, Kelley EJ, Lemmer D, Schupp JM, Driebe EM, Engeltalher DM, Keim P, Barker BM: Direct detection of Coccidioides from Arizona soils using CoccieNV, a highly sensitive and specific real-time PCR assay. Med Mycol 2018, 57:246–255.
18. Schierstaedt J, Grosch R, Schikora A: Agricultural production systems can serve as reservoir for human pathogens. FEMS (Fed Eur Microbiol Soc) Microbiol Lett 2020:366.
19. Brevik EC, Slaughter L, Singh BR, Steffan JJ, Collier D, Barnhart P, Pereira P: Soil and human health: current status and future needs. Air Soil Water Res 2020, 13, 1178622120934441.
20. Dekić S, Hrenovíc J, Durn G, Venter C: Survival of extensively- and pandrug-resistant isolates of Acinetobacter baumannii in soils. Appl Soil Ecol 2020, 147:103396.
21. Perez L, Steffan JJ, Gedeon CI, Thomas P, Brevik E: Medical geology of soil ecology. In Practical applications of medical geology; 2020.
22. Baumgardner DJ: Soil-related bacterial and fungal infections. J Am Board Fam Med 2012, 25:734–744.
23. Dragon DC, Rennie RP: The ecology of anthrax spores: tough but not invincible. Can Vet J 1995, 36:295–301.
24. Zacchia NA, Schmitt K: Medical spending for the 2001 anthrax letter attacks. Disaster Med Public Health Prep 2019, 13:539–546.
25. Espelund M, Klaveness D: Botulism outbreaks in natural environments – an update. Front Microbiol 2014, 5.
26. Long SC, Tauscher T: Watershed issues associated with Clostridium botulinum: a literature review. J Water Health 2006, 4:277–288.
27. Freitag NE, Port GC, Minier MD: Listeria monocytogenes — from saprophyte to intracellular pathogen. Nat Rev Microbiol 2009, 7:623–628.
28. Lynteris C, Soil’ A Suitable: Plague’s urban breeding grounds at the dawn of the third pandemic. Med Hist 2017, 61:343–357.
29. Yersin A: La peste bubonique à Hong Kong. Ann Inst Pasteur 1894, 8:662–667.
30. Mollaret HH: Experimental preservation of plague in soil. Bull Soc Pathol Exot Filières 1963, 56:1168–1182.
31. Ayyadurai S, Houhamdi L, Lepidi H, Nappaz C, Raoult D, Drancourt M: Long-term persistence of virulent Yersinia pestis in soil. Microbiology 2008, 154:2865–2871.
32. Limmathurotsakul D, Golding N, Dance DA, Messina JP, Pigott DM, Moyes CL, Rolim DB, Berthelot E, Day NP, Peacock SJ, et al.: Predicted global distribution of Burkholderia pseudomallei and burden of melioidosis. Nat Microbiol 2016, 1.
33. Brevik EC, Burgess LC: The 2012 fungal meningitis outbreak in the United States: connections between soils and human health. Soil Horiz 2013, 54:1–4.
34. Hasan SE: Medical geology. Reference Module in Earth Systems and Environmental Sciences 2020, https://doi.org/10.1016/B978-0-12-049548-9.12523-0.
35. Baumgardner DJ, Laundre B: Studies on the molecular ecology of Blastomyces dermatitidis. Mycopathologia 2001, 152:51–58.
36. Emmons CW: Isolation of histoplasma capsulatum from soil. Publ Health Rep 1949, 64:892–896.
37. Baude M, Meyer BC, Schindewolf M: Land use change in an agricultural landscape causing degradation of soil based ecosystem services. Sci Total Environ 2019, 659:1526–1536.
38. Froese R, Schilling J: The nexus of climate change, land use, and conflicts. Current Climate Change Reports 2019, 5:24–35.
39. Houwenhuyse S, Macke E, Reyserhove L, Bulteel L, Decaestecker E: Back to the future in a petri dish: origin and impact of resurrected microbes in natural populations. Evol Appl 2017, 11:29–41.
40. Revich BA, Podolnaya MA: Thawing of permafrost may disturb historic cattle burial grounds in East Siberia. Glob Health Action 2011, 4.
41. Revich B, Tokarevich N, Parkinson AJ: Climate change and zoonotic infections in the Russian Arctic. Int J Circumpolar Health 2012, 71:18792.
42. Repin V, Pugachev V, Taranov O, Bronner E: Potential hazard of microorganisms which came from the past. In: Edited by Boeskorov GG, Tichonov AN, Suzuki N, Yukagir mammoth; 2007: 183–190.

43. Teufel B, Sushama L: Abrupt changes across the Arctic permafrost region endanger northern development. Nat Clim Change 2019, 9:858–862.

44. Burkert A, Douglas TA, Waldrop MP, Mackelprang R: Changes in the active, dead, and dormant microbial community structure across a pleistocene permafrost chronosequence. Appl Environ Microbiol 2019, 85, e02646.18.

45. Duchêne S, Holmes EC: Estimating evolutionary rates in giant viruses using ancient genomes. Virus Evolution 2018, 4:vey006.

46. Ng TFF, Chen L-F, Zhou Y, Shapiro B, Stiller M, Heintzman PD, Varsani A, Kondov NO, Wong W, Deng X, et al.: Preservation of viral genomes in 700-y-old caribou feces from a subarctic ice patch. Proc Natl Acad Sci USA 2014, 111:16842–16847.

47. Pratama AA, van Elsas JD: The ’neglected’ soil virome: potential role and impact. Trends Microbiol 2018, 26:649–662.

48. Chattopadhyay S, Puls RW: Forces dictating colloidal interactions between viruses and soil. Chemosphere 2000, 41: 1279–1286.

49. Hurst CJ, Gerba CP, Cech I: Effects of environmental variables and soil characteristics on virus survival in soil. Appl Environ Microbiol 1980, 40:1067–1079.

50. Tierney JT, Sullivan R, Larkin EP: Persistence of poliovirus 1 in soil and on vegetables grown in soil previously flooded with inoculated sewage sludge or effluent. Appl Environ Microbiol 1977, 33:109–113.

51. Vasickova P, Pavlik I, Verani M, Carducci A: Issues concerning survival of viruses on surfaces. Food Environ Virol 2010, 2:24–34.

52. Firquet S, Beaujard S, Lobert P-E, Sané F, Calone D, Izard D, Hober D: Survival of enveloped and non-enveloped viruses on inanimate surfaces. Microb Environ 2015, 30:140–144.

53. Gutiérrez RA, Buchy P: Contaminated soil and transmission of influenza virus (H5N1). Emerg Infect Dis 2012, 18:1530–1532.

54. Gerba CP, Betancourt WQ: Viral aggregation: impact on virus behavior in the environment. Environ Sci Technol 2017, 51: 7318–7325.

55. Núñez-Delgado A: What do we know about the SARS-CoV-2 coronavirus in the environment? Sci Total Environ 2020, 727:138647.

56. Tang C-S, Paleologos EK, Vitone C, Du Y-J, Li J-S, Jiang N-J, Deng Y-F, Chu J, Shen Z, Koda E, et al.: Environmental geotechnics: challenges and opportunities in the post COVID-19 world. Environmental Geotechnics 2020, https://doi.org/10.1680/jenge.20.00054.

57. Casanova L, Rutala WA, Weber DJ, Sobsey MD: Survival of surrogate coronaviruses in water. Water Res 2009, 43: 1893–1898.

58. Chan HLY, Tsui SKW, Sung JJY: Coronavirus in severe acute respiratory syndrome (SARS). Trends Mol Med 2003, 9: 323–325.

59. Sharma VK, Jinadatha C, Lichtfouse E: Environmental chemistry is most relevant to study coronavirus pandemics. Environ Chem Lett 2020, 18:993–996.

60. Yang C-L, Qiu X, Zeng Y-K, Jiang M, Fan H-R, Zhang Z-M: Coronavirus disease 2019: a clinical review. Eur Rev Med Pharmacol Sci 2020, 24:4585–4596.

61. Kampf G, Todt D, Pfaender S, Steinmann E: Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. J Hosp Infect 2020, 104:246–251.

62. Núñez-Delgado A: SARS-CoV-2 in soils. Environ Res 2020, 190:110045.

63. Steffan JJ, Brevik EC, Burgess LC, Cerda A: The effect of soil on human health: an overview. Eur J Soil Sci 2018, 69: 159–171.