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Health and Safety Effects of Airborne Soil Dust in the Americas and Beyond

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Abstract:

The risks associated with airborne soil particles (dust) are often underappreciated, and the gap between the knowledge pool and public awareness can be costly for society. This study reviews the emission, chemical, physical, and biological characteristics of dust and its effects on human and environmental health and safety in the Americas. American dust originates from both local sources and long-range transport from Africa and Asia. Dust properties, trends and interactions with criteria air pollutants are summarized. Human exposure to dust has been associated with adverse health effects, including asthma, fungal infections, and premature death. One of the most striking effects of dust is *Coccidioidomycosis* (Valley fever), an infection caused by inhaling soil-dwelling fungi unique to this region. Dust affects environmental health through providing nutrients to phytoplankton, contaminating water supply and food, spreading crop and marine pathogens, infecting domestic and wild animals, transporting heavy metals and radionuclides, and reducing solar power generation. Dust is also a well-documented safety hazard to road transportation, aviation, and marine navigation, in particular in the southwestern United States where blowing dust is one of the deadliest weather hazards. To mitigate these harmful effects, coordinated regional and international efforts are needed to enhance dust observations and prediction capabilities (especially in South America), implement soil conservation measures, design specific dust mitigation projects for transportation, and conduct surveillance for Valley fever and other diseases. While focusing on the Americas, many of the dust effects found in this region also exist in other parts of the world.

Plain Language Summary

Soil particles suspended in the air, commonly known as dust, impose substantial risks to many sectors of the society, including human health, environmental health, transportation safety and the general economy. This work focuses on the dust effects in the Pan-American region, where the knowledge is rather fragmented, but impacts are costly. Dust in the Americas either comes from local sources or is transported by winds from Asia and Africa. Human exposure to dust can cause adverse health effects, such as asthma, Valley fever, and even death. Dust affects the environment by supplying nutrients to ecosystems, contaminating water and food, spreading pathogens, heavy metals and radionuclides, and reducing solar power generation. Dust is also one of the deadliest weather hazards particularly in the southwestern United States. Finally, the measures to mitigate these harmful effects include coordinated dust prediction and early warning, soil conservation, and public health surveillance.

1. Introduction

Airborne soil particles, commonly referred to as dust, pose myriad risks to human and environmental health and transportation safety around the world. Dust is emitted by mechanical processes such as natural eolian processes (wind), and fugitive processes from human activity (e.g., vehicles, land use practices). It is a form of airborne particulate matter, regulated as an air pollutant in the forms of PM_{10} and $PM_{2.5}$ (particulate matter smaller than 10 and 2.5 µm in diameter) respectively). A classic, thorough description of dust and dust deposits was provided by Pye (1987). Dust deposits nutrients, such as phosphorus (P) and iron (Fe), that can stimulate marine and terrestrial productivity, including in the Amazon Basin (Barkley et al., 2019; Mills, 2004; Prospero et al., 2020; Swap et al., 1994). However, exposure to dust particles has been associated with adverse health effects (World Health Organization, 2021), in particular cardiovascular mortality (Crooks et al., 2016; Tobias et al., 2019) and respiratory diseases (Tobias et al., 2019) including asthma (Kanatani et al., 2010), and other health effects such as Valley fever are under scrutiny (Tong et al., 2017). In the Americas, one of the most well-documented and striking effects of soil dust is the mysterious spread of *Coccidioidomycosis*, commonly known as Valley fever, an infection caused by inhalation of soil-dwelling fungi unique to the Americas. The US Centers for Disease Control and Prevention (CDC) reports that the incidence rate of Valley fever has increased by 800% from 1998 to 2011 (CDC, 2013) in the same regions frequently impacted by dust storms (Tong et al., 2017). Dust storm frequency is more strongly correlated with Valley fever incidences than other known factors in two endemic centers (Maricopa and Pima County, AZ) (Tong et al., 2017). Outside the southwestern US, little is known of Valley fever incidence rates or trends, since regular reporting systems are not in place (Sarafoglou et al., 2020).

The socioeconomic impacts of dust storms extend even beyond the direct disease consequences. Dust storms are well known as safety hazards in transportation, especially motor vehicles travelling on dust-affected highways (Ashley et al., 2015; Lader et al. 2016; Li et al., 2018; Van Pelt et al., 2020b). Although small and short-lived, local-scale dust storms are notoriously difficult to detect and predict and responsible for the majority of fatal dust-related highway accidents (Lader et al., 2016). After extreme heat and flooding, dust storms are the third largest cause of weather fatalities in Arizona, where 157 people were killed and 1324 injured on highways between 1955 and 2011 (Lader et al., 2016). Dust is a safety hazard and growing concern in aviation, both military and civilian (Baddock et al., 2013). Dust storms reduce the recreational values of landscapes (Hand et al., 2016), decrease the performance of solar power plants (Polo and Estalayo, 2015), and spread agricultural (Gonzalez-Martin et al., 2014) and human pathogens (Goudie, 2014), all of which negatively affect local and regional economies. The loss of soil nutrients costs U.S. agriculture 8-10 billion dollars every year (Troeh et al., 2004).

The health and economic burden of dust storms will likely be amplified by climate change as well as changing land and water use practices (Bell et al., 2018). In the 1930s, the United States experienced one of the worst environmental catastrophes in its history, the “Dust Bowl”, a period with numerous large dust storms caused by extended drought, high winds, and poor land management (Lee and Gill, 2015). These dust storms buried farms and forced hundreds of thousands of farmers to abandon their homes to migrate to cities and the West Coast (Worster, 1979). Lessons learned from the Dust Bowl apply today, not only for soil conservation (Sarafoglou et al., 2016) but also for public health. It was as a result of the Dust Bowl that the human health effects of windblown soil dust were first magnified. Brown et al. (1935) carried out the first public health study in the USA of dust storms, in the Dust Bowl of Kansas: they concluded that “dust… was exceedingly irritating to the mucous membranes of the respiratory tract, and in our opinion was a definite contributory factor in the development of untold numbers of acute infections and materially increased the number of deaths from pneumonia and other complications.” The term “dust pneumonia” entered the American vocabulary (Gates, 1938), referring to the dreaded and mysterious respiratory illness that many persons living through the Dust Bowl were exposed to. “Dust bronchitis” entered the medical literature as a related and perhaps more appropriate condition (Toomey and Petersilge, 1944). More recently, “haboob lung syndrome” was introduced as a term by physicians in the zone of the past Dust Bowl (Panikkath et al., 2013) to refer to acute lung disease/pneumonia, sometimes fatal, developed in otherwise healthy people within a few days of unprotected exposure to a modern-day dust storm.

Climate models project drying trends in the late 21st century over the subtropics, including the arid southwest US (Schubert et al., 2004; Seager et al., 2007; Cook et al., 2015; Prein et al., 2016). The predicted drying trend aids speculation of more frequent dust storms and even another “Dust Bowl” in the coming decades (Romm, 2011). Using multi-model output under the Representative Concentration Pathways 8.5 scenario, Pu and Ginoux (2017) projected that dust activity will indeed increase in the southern Great Plains in the coming decades. Due to the projected changes in temperature and precipitation, the area potentially endemic to Valley fever will be more than double by 2100 in the western US (Gorris et al., 2019). Furthermore, water use practices have diverted water away from lakes and rivers, drying out these water bodies and leading to increased dust production from now-dry lake beds (Wang et al 2018; Zucca et al., 2021). An example is the Owens (dry) Lake in California that was desiccated due to water diversion to Los Angeles; this region has long produced substantial levels of particulate matter (PM) that often exceeds air quality guidelines established by the EPA through the National Ambient Air Quality Standards (NAAQS) (Cahill et al 1996). Similar desiccation of the Salton Sea and Great Salt Lake are also being observed along with increases in dust emissions from these drying lake beds (Frie et al 2018; Goodman et al 2019). In addition to increasing PM to unhealthy levels, dust emissions also impact budgets of gaseous criteria air pollutants including ozone (Detener and Crutzen 1993). Besides local sources, the Pan-American region is subject to long-range dust transport from Africa and Asia, a process sensitive to climate change (Prospero et al., 2021).

Despite the high stakes, the risks associated with dust hazards are often underappreciated (Middleton et al., 2018, 2020), particularly so in the Americas. Compared to other major source regions (Africa and Asia), the Americas, and especially South America, typically have received little attention in global dust studies. The body of knowledge of windblown dust in the Americas is rather fragmented and based largely upon anecdotal, regional studies and reports from individual investigators. This lack of coherence and context was recognized when the World Meteorological Organization formed the international Sand and Dust Storm Warning and Advisory System (SDS-WAS) in 2007 at the urging of 40 WMO member countries (WMO, 2015), and again, by request of the UN Secretary General for a Global Assessment of Sand and Dust Storms (UNEP, WMO and UNCCD, 2016). Lack of awareness of windblown dust risks is also illustrated by many key national and inter-governmental public health and climate assessments; dust hazards are neither mentioned nor adequately discussed. The gap between the knowledge pool and public awareness can be costly for affected communities. For instance, while Valley fever is increasingly recognized in the United States, similar diagnostics and reporting systems are limited or non-existent outside the western US, even though the first known case was reported in Argentina in 1892 and coccidioidomycosis has been found from Mexico to Central and South America (Sarafoglou et al., 2020).

The present work aims to compile a comprehensive list of the health and safety effects of dust hazards in the Americas for several purposes. First, current understanding of these effects is reviewed and analyzed; gaps in knowledge are identified for future research and building public health and safety policy for the region. Second, this inventory consolidates scattered information so that researchers and policy makers may better appreciate the global, regional and local context for dust as a health and safety hazard.

2. Dust in Americas

Dust particles in the Americas originate from both local sources (Gillette et al., 1989; Prospero et al., 2002; Yin and Sprigg, 2010; Ginoux et al., 2012) and from long-range dust transport across the Atlantic and Pacific Oceans (Prospero et al., 1981, 2014, 2020, 2021; 2014; Husar et al., 2001; VanCuren et al., 2002; Raga et al., 2021). Sources of windblown dust important to Pan America are depicted in Figure 1. General locations of major dust areas as well those receiving long-range transported dust are discussed here.

2.1 Long-Range Dust Transport

Long-range transport of dust through the atmosphere plays an important role in the evolution of soils downwind on a global scale. The discovery of the African dust transport to the Americas and the Saharan Air Layer has been summarized by Prospero and colleagues (2021). An estimated average of 64 Tg of aerosols composed mainly of desert dust affects North America each year (Yu et al., 2012). African dust emitted from the Saharan desert and Sahel impact the Americas throughout the year, especially the Caribbean region. During the boreal winter, African dust is transported primarily over the Southern Greater Caribbean and Northern South America. The more intensive dust episodes occur during the boreal spring and summer over most of the Caribbean Islands, the Gulf of Mexico, and Southeastern US (Prospero 1981; Prospero and Mayol-Bracero, 2013). Asian dust emitted especially from the Taklamakan and Gobi deserts is present year-round but primarily affects the western US coast and the Hawaiian Islands in the spring (Fischer et al 2009; Parrington et al 1983; Zhao et al 2008). Long-range transport of African dust supplies nutrients (Fe, P) that fertilize the Caribbean, South America including the Amazon Basin, North America and the Hawaiian Islands (Yu et al., 2019). Further, the atmospheric redistribution of soils has developed rich agricultural regions, as in Redland, Florida (Chadwick et al. 1999, Muhs et al. 2007, Prospero et al. 1987, Swap et al. 1992; Swap et al. 1996).

Although the fertilizing effect of this transported dust is considered to be a positive agricultural aspect, negative health impacts also need to be taken into account. Transported African dust frequently elevates PM_{10} levels above the healthy air quality guidelines as recommended by the World Health Organization (WHO; e.g., 50 g/m^3) and increases $PM_{2.5}$ in the Caribbean, parts of North America, including South Florida, and Texas, and South America (Bozlaker et al 2019; Prospero et al 2001; Prospero et al 2008; Prospero et al 2014). African and Asian dust both increase background PM concentrations, which results in exceedances in parts of western North America (Fischer et al 2009; Jaffe et al 203) but can also impact PM on the east coast of the US including parts of New England (DeBell et al 2004). The plume from a large Asian dust event travelled into North America in 1998, leaving a chemical fingerprint of deposited dust inland to the state of Minnesota (Husar et al. 2001). The “Godzilla” dust event during June 13-18, 2020 was arguably the largest and strongest Saharan Air Layer (SAL) in the past 50 years, greatly impacting PM levels and allowing researchers to view the unusually strong environmental signatures associated with this passage (Pu and Jin, 2021; Yu et al., 2021). The dust plume associated with the SAL was easily tracked by geostationary and polar orbiting satellite measurements throughout much of the episode. Typically, SAL profiling reveals an easily identifiable brown haze off the northwestern African coast, where the more significant events show the dust that eventually becomes diluted and barely recognizable as it propagates through the Caribbean Islands. But in the “Godzilla” case, the SAL and its associated African dust plume contained heavy mineral within the dust concentrations, that acted as a tracer and persisted on its westward journey through the Greater Caribbean, Gulf of Mexico, South Central US, then turning eastward toward the Southeast US coast and back into the Atlantic basin; an estimated 10,000 km excursion. Although much of the interest is focused on the aspects downstream off Northwest Africa, the initiation aspects were also covered during the 5 days prior (June 8 - 13) while still over northern Africa.

In addition to PM, long-range transported dust from Asia and Africa can also transport microbes, trace metals, and pollutants (Jaffe et al 2003; Prospero et al 2005; Bozlaker et al 2019; Smith et al 2012). While PM associated with long-range transported dust is on par with concentrations found in urban cities and dust events have been anecdotally associated with increases in hospitalization frequencies, the health impacts associated with chronic exposure to PM exceedances, microbes, trace metals, and pollutants from transported dust remain underexplored and poorly understood.

2.2 Pan-America-Sourced Airborne Dust

Local dust sources in the Americas generally fall into two categories: (1) natural sources from wind erosion over deserts, and (2) anthropogenic sources from soil disturbance by human and animal activities (Gillette and Passi, et al, 1988; Prospero et al., 2002; Ginoux et al., 2012). Satellite remote sensing observations are key to characterizing the major transport paths and to establishing source-receptor relationships (Baddock et al., 2021). Broad-swath imagery, from polar-orbiting instruments such as the NASA Earth Observing System’s MODerate resolution Imaging Spectroradiometers (MODIS) and NOAA’s Visible Infrared Imaging Radiometer Suite (VIIRS) offer the spatial and temporal coverage needed to track major dust plumes across oceans and continents (Kim et al. 2019; Yu et al., 2019). Instruments in geostationary orbits, such as NOAA’s Advanced Baseline Imagers (ABIs), can sample a region multiple times per hour, helping localize dust sources that can otherwise be obscured as a plume expands. With these instruments, dust is usually distinguished from other aerosols based on source location, plume morphology and color, and/or coarse particle size. Multi-angle imaging can be used to identify dust based also on the optical manifestations of particle shape (e.g., *Kalashnikova and*

Kahn, 2006). As dust size distributions are usually dominated by super-micron particles, infrared imagers such as the Atmospheric InfraRed Sounder (AIRS) on NASA's Aqua satellite can also track dust transport, globally (*DeSouza-Machado et al.*, 2006). The spatial distribution of dust storm sources is illustrated in Figure 1, derived from UNCCD Sand and Dust Storms Source Basemap (https://maps.unccd.int/sds/), which represents gridded (geo-referenced) information on the distribution, intensity and variability of SDS sources, developed from soil texture properties, soil moisture, soil temperature, enhanced vegetation index (EVI) and land cover from the Moderate MODIS EVI and MODIS Land Cover from 2014-2018. Figure 1 represents the average intensity of dust sources which can be exposed to wind erosion in all seasons, but not necessarily with the same potential for production of SDS.

In North America, dust sources are distributed predominantly in northern Mexico and western United States, and are generally driven by convective (mesoscale) or non-convective (synoptic scale) windstorms (Novlan et al., 2007; Rivera Rivera et al., 2009). Major sources in Mexico include the Baja California Peninsula (Morales-Acuna et al., 2019) and the Chihuahuan Desert (Rivera Rivera et al., 2010; Baddock et al., 2011, 2016, 2021). In the United States, large areas in the Great Basin, the former "Dust Bowl" region including the panhandles of Texas and Oklahoma, Nebraska, western Kansas, and eastern Colorado, the Red River Valley of North Dakota, and northern Montana are noted for their frequent blowing dust episodes (Ravi et al., 2011). The U.S. portion of the Chihuahuan Desert, from far eastern Arizona across southern New Mexico into west Texas and across the border into Mexico, is one of the most dust-prone regions in the Western Hemisphere (Prospero et al., 2002), from which the U.S. and Mexico trade soil (Figure 2). Large amounts of dust are blown off from dry lake beds (playas) in North America, such as the Lordsburg Playa in western New Mexico (Eibedingil et al., 2021; Van Pelt et al., 2020b), the Great Salt Lake playas (Nicoll et al., 2020) and the Owens Lake bed north of Los Angeles, California, once the single largest dust source in North America (Reheis, 1997), and Paleolake Palomas in Chihuahua, Mexico (Baddock et al., 2021). Satellite remote sensing and local field observations further reveal that dust sources in many of these regions are associated with land use (Lee et al., 2012; Li et al., 2018; Kandakji et al., 2020). The Columbia Plateau in the inland Pacific Northwest of the USA is frequently affected by windblown dust associated with its agricultural lands (Sharratt and Lauer, 2006; Sharratt et al., 2018). Abandoned agricultural fields becoming dust sources (Hyers and Marcus, 1981: Colson et al., 2016; Lopez, 2020) are a growing issue in western North America with economic shocks to the agricultural industry, drought-limited water supply and warming climate. Military training grounds, which are most extensive in the Western USA, can become dust sources (Belnap et al., 2007; Urban et al., 2018). On the Colorado Plateau, Nauman et al. (2018) showed that areas adjacent to highways can generate many times the dust generated from non-traffic areas. In the Tri-State Mining District of Oklahoma, Kansas and Missouri, fine dusts emitted from numerous chat (mining waste, or tailing) piles during extreme weather conditions contribute up to 10% of annual Pb mass flux to a lake 18 km distant from the source (Li and McDonald-Gillespie, 2020).

South America has five particularly large, active dust production areas: (1) The Salar de Uyuni, a large salt flat located in a closed basin in the Bolivian Altiplano, is the main dust source (Gaiero et al, 2013; Ravi et al., 2011); (2) along the west coastal Atacama Desert extending from northern Chile to southern Peru—an occasionally (fewer than 1-3/year) active area with thick dust clouds that bring abundant dust into the equatorial South Pacific Ocean (Reyers et al., 2019); (3) an area known locally as the Arid Diagonal, from west and central Bolivia into Argentina, including the lee-side of the Andes (Mingari et al., 2019; Milana and Kröhling, 2017; Perez-Ramirez et al, 2017); (4) the central and west side of the Las Pampas region, and (5) Argentina's Patagonian Desert, a frequent dust generator (Shao et al., 2013, Cosentino et al, 2019), which has contributed dust to Antarctica (McConnell et al., 2007; Bullard et al., 2016). Some of these sources exhibit a yearly regularity such as the Salar of Uyuni or the dry shores of the rivers Río Piraí, Río Grande, Río Parapetí and Río Pilcomayo in Bolivia (May, 2013). The Mar Chiquita Lake in Argentina exhibits large water level fluctuations at decadal scales (Troin et al, 2010; Carabajal et al., 2021). Seasonality in the Patagonia region is more pronounced. The most active dust source is the dry bed of the lake Colhué Huapi with abundant and thick dust clouds reported several times per year [Gassó and Torres, 2019]. In general, abundant rains in winter and spring result in accumulation of sediment and wind-erodible soil availability for entrainment by the summer. These sources include many others, such as river beds that become active at the end of the austral winter or tidal lakes [Gassó and Stein, 2007; Gassó et al., 2010]. Strong katabatic winds and occasional polar fronts reach the lee-side of the Andes. These are important contributors to local airborne dust. As in North America, grazing on semiarid lands appears to have increased dust deposition rates in the 20th century from rates of the 19th century (Field et al., 2010).

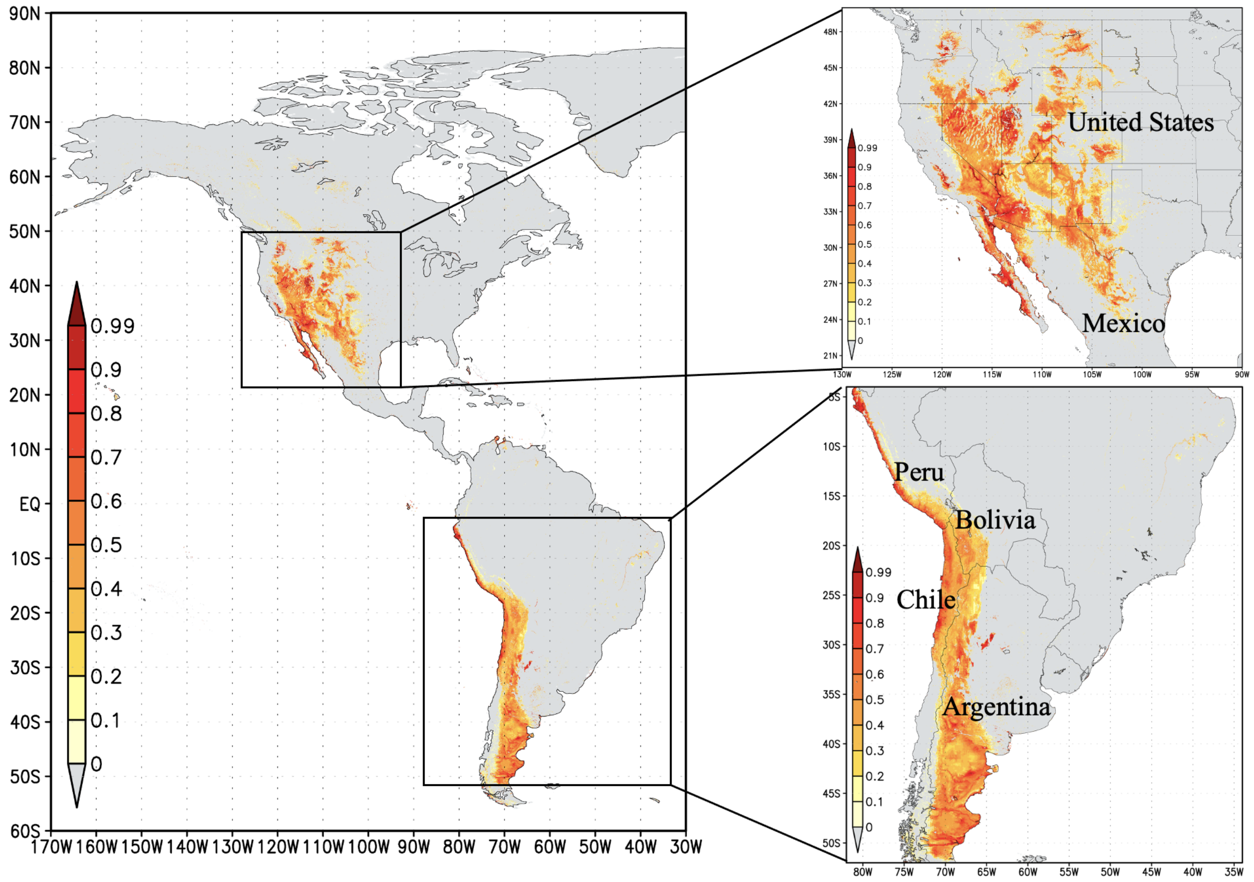

Figure 1. Present-day sand and dust storm sources in the Pan-American region (source: United Nations Convention to Combat Desertification).

2.3 Chemical and physical characteristics of American Dust

Soil is a complex matrix of mineral particles with chemical coatings, gases, water with dissolved chemical species in equilibrium with the particulate coatings, and many forms of organic matter. The exact characteristics of a given soil are controlled by mineral parent material, climate, time, and associated life forms (Weil and Brady, 2016). Mineral particles that make up soil are grouped into three diameter classes: sand (coarsest of the particles, 54 to 2000 µm in diameter), silt (2 to 53 µm in diameter), and clay (less than 2 µm in diameter). Although most dust is silt and clay in weathered soils, in some circumstances such as dry lake beds (playas), dust particles may be composed of the tests of aquatic metazoans and plankton (Bristow and Moller, 2018). The physical characteristics of individual dust particles are used to identify the location of their source (Wang et al., 2017).

Individual dust particles also carry a chemical signature of mineralogy, weathering products, and adsorbed surficial coatings formed during soil genesis. These natural chemical signatures can be used to identify dust source regions (Frie et al., 2019; Wang et al., 2017; Wang et al., 2019; White et al., 2015). Metals are also introduced into the soil surface from deposition of cosmic dust (Benna et al., 2015). In general, concentrations of crustal elements such as Ba, Fe, Mg, and Mn are greater in dust than in the parent soil, due to greater surface area to mass ratios of the smaller particles and the calculated enrichment ratios (Beamer et al., 2012; Trapp et al., 2010; Van Pelt et al., 2020a). In addition to the natural coatings on particles, anthropogenic heavy metals from many sources may cause greater enrichment ratios of, for example, As, Cd, Cu, Cr, Ni, Pb, and Zn in the dust, relative to the soils of provenance, and are a concern for human and environmental health (Rasmussen et al., 2013; Balabanova et al., 2017; Beamer et al., 2012; Trapp et al., 2010; Nicoll et al, 2020; Li and McDonald-Gillespie, 2020; Van Pelt et al., 2020a). As expected, anthropogenic metals in dust are more prominent in urban and industrial areas than in rural areas (Eleftheriadis and Colbeck, 2001).

Mining and smelting are a primary source of anthropogenic metals in dust. These contaminants may arise from actual mining activities to create dust (Csavina et al., 2012; Entwistle et al., 2019), but dust from unprotected tailings on the surface present the specter of legacy contamination that far outlasts the actual mining activities (Dong and Taylor, 2017; Garcia-Vargas et al., 2014; Li and McDonald-Gillespie, 2020; Ono et al., 2016). Mine waste and debris can be carried by water or gravity into a wind-erodible landform, such as the surface of a playa, where the associated metals become part of the emitted windblown dust (Gill et al., 2002). Ore crushing, smokestack emissions, smelting and erosion of slags associated with mining contaminate and increase metallic loads in airborne dust. Chen et al. (2016) modelled the impacts on atmospheric metals from a copper smelter, and others (Garcia-Vargas et al., 2014; Van Pelt et al., 2020a) have documented the spread of smelter-associated soil dust, its spatial patterns by the distance, wind flow, and topographic influences. Other sources of atmospheric metallic contamination are petrochemical industries (Rodriguez-Espinosa et al., 2017), wear of vehicle components associated with transportation (Councell et al., 2004), and erosion or suspension of agricultural soils to which fertilizer materials have been added (Azzi et al., 2017; Dharma-Wardana, 2018; Gong et al., 2019; Wang et al., 2020).

Agricultural operations in semi-arid and arid environments are a potent dust source (Katra, 2020) and management of these systems affects the chemical properties of the dust. In addition to the fertilizer materials just noted, many different forms of organic carbon are emitted from agricultural soils (Padilla et al., 2014) that are natural components of the soil matrix. Biochar added to soils may result in the elemental carbon emission with fugitive dust (Ravi et al., 2016). Pesticides and pesticide daughter products are also present along with natural organic and elemental carbon in fugitive dust, especially in cultivated soils (Yao et al., 2008; Gunier et al., 2011; Bennet et al., 2019; Smith et al., 2013). Persistence of many of these pesticides in atmospheric particulates is of increasing concern, as many operate on a hormonal level and may affect human and environmental health (Socorro et al., 2016). Pesticide persistence research has identified the herbicides glyphosate and atrazine in the soils and rainfall of the Argentine Pampas (Alonso et al., 2018) along with glyphosate and its metabolic daughter product aminomethylphosphonic acid in the soils, surface waters, and dust (Aparicio et al., 2013; Aparicio et al., 2017; Mendez et al., 2017) as well as other areas (Bento et al., 2017). Pesticides used in urban environments in home gardens and lawn management are also deposited as dust near residences (Richards et al., 2016).

2.4 Microbes in Dust

Soils are a living, breathing matrix with a variety of lifeforms performing numerous ecosystem services including nutrient cycling. Microbes found in dust include algae (Tesson et al., 2016), arachaeans (Wehking et al., 2018), bacteria, viruses (Gonzalez-Martin et al. 2013), and fungi (Frohlicdh-Nowoisky et al., 2012). Direct count analyses of topsoils from various desert environments have shown that bacterial and viral populations range from ~10^3 to 10^7 per gram (Gonzalez-Martin et al. 2013). Fungal populations typically occur at ~10^6 per gram (Tate 2000). Bacteria are present in wind eroded sediments in which the overall composition is determined by soil type and management, as well as dust particle size (Gardner et al., 2012). Microbes attached to dust particles have been documented to travel across and between continents (Favet et al., 2013; Katra et al., 2014; Rosselli et al., 2015). Cyanobacteria, ubiquitous in surface crusts of desert soils and playa sediments, produce cyanotoxins hazardous to humans and animals. Fungi multiply by spores that can be transported on winds to new environments, their survival dependent on the time of day when they are released (Oneto et al., 2020). Fungal spores can be aerosolized and remain viable in biomass burning and be transported thousands of kilometers in smoke (Mims and Mims, 2004), and are viable within plumes of windblown dust (Papagianis et al., 1978; Hector, et al., 2011). Aerosolized fungi are important pathogens in the environment (herein, see Section 3.4). Some fungi are potent plant pathogens (Al-Bader et al, 2016; Kim et al., 2019) that hitchhike long distances on intercontinental dust (Toepfer et al., 2011).

Finally, soil-dwelling, multi-cellular organisms and their propagules are transported on and with dust. Studies in wind tunnels reveal that aquatic metazoans may be eroded from dry sediments and remain viable in the transported dust (Pinceel et al., 2015; Rivas et al., 2018). In the natural environment, wind events are credited with the transport of the *Artemia franciscana* cysts (Parekh et al., 2014), several species of Rotifers (Langley et al., 2001) and crustacean zooplankton communities (Lopes et a., 2016). Nematodes, soil-borne plant parasites, have been documented to spread on wind-borne sediments in natural and agricultural ecosystems (Vanstone et al., 2008; de Rooij-van der Goes et al., 2014). Insects as large as locusts have been observed to be transported across the Atlantic to the Caribbean and South America in African dust clouds

(Rosenberg and Burt, 1999).

Although the intense UV radiation at altitudes often encountered in transcontinental transport results in high rates of mortality for many organisms, resistant cyst and spore forms allow some species to thrive in microbial populations in many areas of the world (Hara et al., 2015; Allen et al., 2015) and in human pathogen transport (Eveleth, 2013). A study in the Atacama Desert in northern Chile, one of the driest and most UV irradiated places on Earth, found that a number of bacteria and fungi were able to remain viable after traversing using wind-transported dust (Azua-Bustos et al., 2019). Microbes are observed to survive in the smoke plumes from wildland fires (Kobziar et al., 2018). They can even serve as ice nucleation agents in clouds (Goncalves et al., 2012; Amato et al., 2015; O'Sullivan et al., 2016). Jenkins and Underwood (1988), on the other hand, have found transport of zooplankton by anemochory (wind dispersal of organisms) limited and unlikely over one year at two sites near Springfield, Illinois, USA. Further research is needed to understand the environmental factors controlling the dispersal of dustborne organisms.

2.5 Interactions with air pollution

Dust affects multiple criteria air pollutants regulated by the U.S. EPA such as particulate matter (PM) and its fine ($PM_{2.5}$) and coarse (PM_{10}) components, as well as gaseous pollutants such as sulfur dioxide (SO_2), ozone (O_3), and nitrogen oxides (NO_x NO + NO_2) (Cahill et al., 1996; Cwiertny et al., 2008; Dentener et al., 1996; Usher et al., 2003). Dust can react with criteria air pollutants via gas-particle reactions, also known as heterogeneous reactions (Abbatt et al., 2012). The efficiency of these reactions depends on several factors including the reacting gas, dust mineralogy, and meteorological conditions, most notably, relative humidity (Cwiertny et al., 2008; Mitroo et al., 2019; Tang et al., 2016; Usher et al., 2003). In some cases, these reactions can reduce levels of gaseous pollutants while simultaneously increasing the hygroscopicity of dust particles, which can decrease dust lifetime in the atmosphere (Andreae & Rosenfeld, 2008).

In addition to direct impact on criteria air pollutants, dust can affect precursor gases that influence secondary pollutant levels, as with tropospheric O_3 and secondary organic aerosol (SOA). Dust can react with O_3 precursors including NO_x and NO_x reservoir compounds such as dinitrogen pentoxide (N_2O_5) to reduce ground-level concentrations of O_3 (Alexander et al., 2009; Dentener & Crutzen, 1993). Because O_3 photochemically reacts to generate hydroxyl radicals ($^\bullet$OH, the primary radical in the atmosphere), losses of NO_x also reduce the oxidizing capacity of the atmosphere with consequences for the lifetime of volatile organic compounds (VOCs) and the production of SOA. However, the result of reactions between dust and NO_x and NO_x reservoir compounds on air quality depends on dust mineralogy. For example, recent work shows that halogen-bearing dusts emitted from saline playas such as the Salton Sea and the Great Salt Lake can facilitate the formation of nitryl chloride ($ClNO_2$), which photolyzes to regenerate NO_2 and generate a chlorine radical ($Cl^\bullet$) (Mitroo et al., 2019; Royer et al., 2021; Simpson et al., 2015; Thornton et al., 2010). $Cl^\bullet$ is highly reactive with VOCs to increase formation of both SOA and ground-level O_3 (Sarwar et al., 2014; Tanaka et al., 2000). Thus, reactions between dust and different gases may have a positive or negative effect on criteria air pollutants, depending on the reaction pathway.

2.6 Trends and future projections

Multiple lines of evidence suggest that North America is dustier in recent decades. A significant increase in rainwater calcium (Ca^{2+}), detected by the National Atmospheric Deposition Network from 1994 to 2010 in the western United States (Brahney et al., 2013), is one indicator. Using snowpack Ca^{2+} as a surrogate, Clow et al. (2016) showed that aeolian dust deposition on snow has increased by 80% in the southern Rockies during 1993-2014. The most direct evidence came from the NASA Dust Climate Indicator project, which found that the frequency of locally sourced windblown dust storms has increased by 240% between 1990 and 2011 in the Southwest United States (Fig 2) (Tong et al., 2017). Compared to the global trend, dust storms in the US have increased ten times faster, and in the opposite direction (Shao et al., 2013; Tong et al., 2017), although increases were also documented in the Middle East and at high latitude (Bullard et al, 2016).

No significant trends of dust activity are found in South America (Shao et al., 2013), although noticeable interannual variations in dust concentration have been observed, and systematic analysis of dust trends in South America is largely under-studied. A few high dust years were recorded in the weather-based dust dataset (Shao et al., 2013). Recent drying trends in the Americas have produced emerging dust sources or enhanced existing sources. For example, Bucher and Stein (2016) reported a new dust source from Mar Chiquita, Argentina, the largest saline lake in South America. The year-to-year variations of salt dust storms were found to correlate with the size of salt mudflats, originating from a 30-year cycle of expansion and retraction driven by rainfall. Similar to the interannual variations in North America (Tong et al., 2017), dust variations more generally are related to the large-scale changes in the ocean, in particular the ENSO events (Shao et al., 2013).

Climate models have projected robust drying trends in several areas in the Americas, including western North America, Central America and the Amazon Basin in the 21st century (Cook et al, 2014). This expansion of drying areas in the Americas and elsewhere is attributed to increased potential evapotranspiration from global warming. The drying trends, coupled with projected increases in wind speed over major dust sources, are expected to make this region dustier. Using a climate model projection and observed connections between dust and controlling factors, Pu and Ginoux (2017) predicted that the dust loading is likely to increase over eastern South America during the period from December through February and March through May. In North America, dust activity is projected to increase in the southern Great Plains from spring to fall in the latter half of the 21st century, due to reduced precipitation, enhanced land surface bareness, and increased surface wind speed. Conversely, increased precipitation and reduced bareness are expected to reduce dust activity in the northern Great Plains (Pu and Ginoux, 2018). Compared to 1986-2005 levels, fine and coarse dust concentrations could increase by 57% and 38%, respectively, resulting in elevated health responses, including 230% more all-cause mortality, 210% more cardiovascular mortality and 88% more asthma emergency room visits (Achakulwisut et al., 2019).

3. Effects on human health

3.1 Respiratory diseases

When analyzing the health effects of dust storms, we have to consider that the available scientific literature focuses on the short-term effects (Tobias, 2019). Exposure to dust storms results in respiratory morbidity and consequent emergency care and hospitalizations (Meng and Lu, 2007; Griffin 2007; Cadelis et al. 2015; Soleimani et al. 2020; Herrera, 2021). Toxicological studies that reproduce real-world exposures during dust events have shown that mineral dust particles generate inflammatory lung injuries and aggravate allergen-induced tissue eosinophilia (Fussell and Kelly, 2021). Mechanisms of carcinogenicity of cells have also been investigated in relation to the impact of dust borne minerals (montmorillonite) (Ardon-Dryer et al., 2020). In regard to bacteria, endotoxins such as lipopolysaccharides, which is a cell wall component of gram negative bacteria, can cause fever and respiratory stress with short term exposures and, with long term exposure, development and exacerbation of asthma and other irreversible respiratory illnesses (Sandstrom, Bjermer, and Rylander 1992; Vernooy et al. 2002). Many bacterial pathogens have been identified in dust storm samples that include *Acinetobacter calcuaceticus, Bacillus circulans, Bacillus licheniformis, Brevibacterium casei, Corynebacterium aquaticum, Gordonia terrae, Kocuria rosea, Neisseria meningitidis, Pantoeaagglomerans, Pseudomonas aeruginosa, Ralstonia paucula, Staphylococcus epidermidis, Staphylococcus aureus*, as previously reviewed (Griffin 2007).

Allergens and toxins associated with dust storms include fungal spores, pollen, lipopolysaccharides, metals and anthropogenic aerosols emitted from agricultural, industrial, military and civilian activity (see Ichinose et al. 2006; Holmes and Miller 2004; Kuske 2006; Lancaster, Bamford, and Metzger 1995; Sandstrom, Bjermer, and Rylander 1992). Dust storms are known to transport and disperse diverse populations of microorganisms and microbial pathogens on local and global scales (Schuerger et al. 2018; Behzad, Mineta, and Gojobori 2018). Numerous genera of fungi are known allergens and have been identified in dust storm studies (Griffin 2007). Spores of *Alternaria* species are potent allergens and have been identified in many dust studies (Griffin et al. 2007; Griffin, Westphal, and Gray 2006; Ho et al. 2005; Kellogg et al. 2004; Kwaasi et al. 1998; Schlesinger, Mamane, and Grishkan 2007; Wu et al. 2004; Smith et al. 2012).

3.2 Premature deaths

Effects of dust storms on non-accidental death have been studied in the Americas, but with mixed results (Schwartz et al., 1999; Gyan et al., 2005; Crooks et al., 2016). A study of 17 dust storms in Spokane, Washington, USA reported a 24-hour mean PM_{10} concentration of 263 microgram/m^3 during these storms (Schwartz et al., 1999). When compared to the control days, defined as the same time of the year but without dust storms (mean PM_{10} of 42 microgram/m^3), researchers found little evidence of any risk (relative risk = 1.00; 95% confidence interval (CI), 0.81-1.22). They concluded that high coarse particle concentrations from windblown dust are not associated with increased risk of non-accidental death.

A more recent study that looked into a larger pool of dust storms and the entire U.S. population reported positive associations between dust and mortality (Crooks et al., 2016). A total of 141 county-level dust storms were identified using the U.S. National Weather Service storm data for the period of 1993-2005. It was estimated that the non-accidental death rate for the US population increased by 7.4% (95% CI: 1.6%-13.5%) and 6.7% (95% CI: 1.1%-12.6%) at 2-day and 3-day lags, respectively, during dusty days compared to no-dust days. This study also found significant associations between dust storms and cardiovascular mortality in the US (2-day lag) and Arizona (3-day lag), and for other non-accidental mortality in California (lags 1-3 and 0-5) (Crooks et al., 2016). Differences in study results were attributed to either the difference in sample size (17 vs 141 storms) or analysis approaches (e.g., same-day vs lagged responses) (Crooks et al., 2016). Compared to the large number of dust epidemiological studies in other regions, research on dust-induced mortality across the Americas is limited in number and scope. In the Americas, such quantitative risk assessment is either nonexistent or limited to a single region. The nationwide study in the U.S. by Crooks et al. (2016) did not provide the relative risk to PM_{10} concentration—the NWS Storm Data used do not include such information. In addition, the Storm Data set is known to be an incomplete collection of dust storms due to a lack of consistent reporting mechanisms. Long-term dust climatology, such as those reconstructed using surface measurements (Tong et al., 2012, 2017; Lei et al., 2016; Hand et al., 2017), can support future epidemiological studies to fill the knowledge gap.

3.4 Valley fever

Valley fever has been well documented to be associated with dust storm exposures in the Americas (Pappagianis and Einstein, 1978). Among fungal taxa of southwestern North America, Central America, and warm, dry regions of South America, the pathogens *Coccidioides immitis* and *Coccidioides posadasii* (*C. immitis* and *C. posadasii*) are examples of dangerous organisms that exist in the soil. They are the causative agents of coccidioidomycosis, also known as Valley fever (Fiese 1958; Kirkland and Fierer 1996; Sprigg, et al., 2014; Tong et al., 2017; Freedman et al., 2018). Infection with Valley fever occurs when the arthroconidia of the soil dwelling fungi, either *C. immitis* or *C. posadasii*, are inhaled. Recent decades have seen an increasing pool of new information to map the population structure and species delineation for Coccidioides (Figure

2), as summarized by Barker et al. (2019).

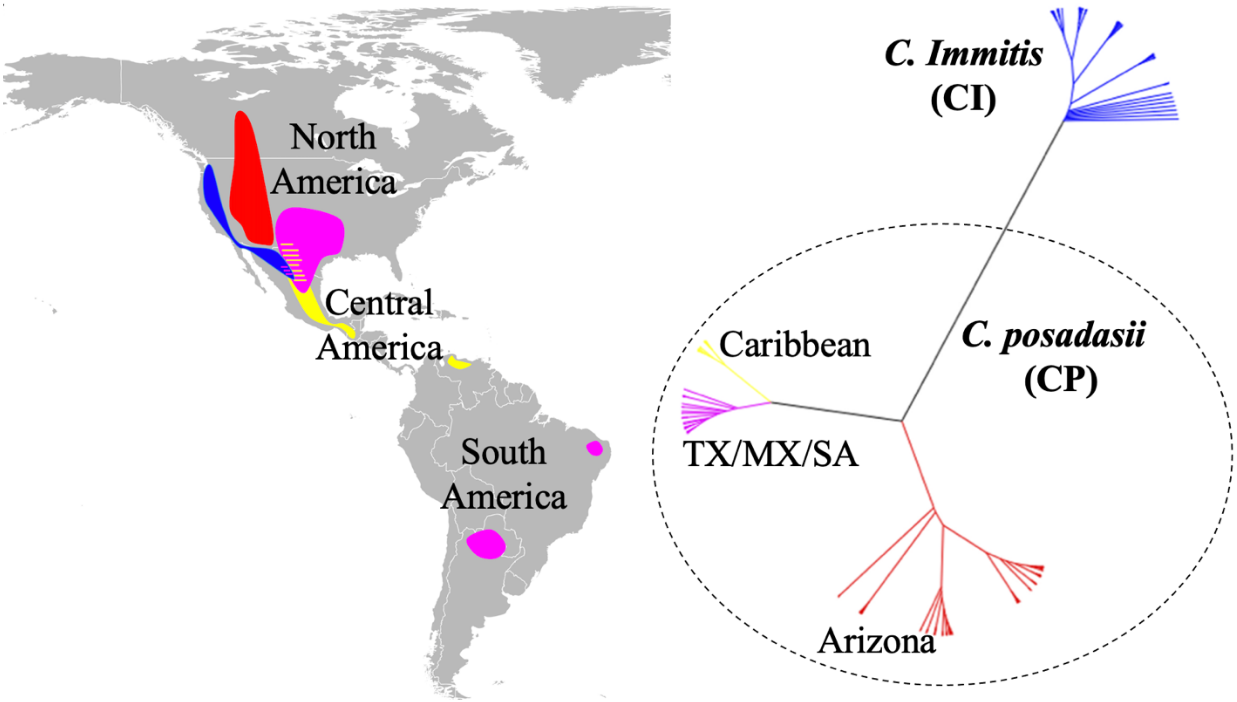

Figure 2. Biographical distribution of *Coccidioides* across the Pan-American Continents. (left) geographic regions of different phylogenetic lineages based on patient origin of the sequenced *Coccidioides* isolates. (right) Collapsed phylogenetic tree representing sequenced genomes from published and some unpublished sequence data, including *C. posadasii* (CP) isolates from Arizona in red, CP from Texas/Mexico/South America in pink, CP from Venezuela and Guatemala in yellow, and *C. immitis* lineage in blue (reproduced from Barker et al., 2019).

Small outbreaks of this disease are routinely reported in the United States of America following regional dust storm events (Schneider et al. 1997; Chatterjee et al. 2017; Park et al. 2005; McCotter et al. 2019). Since 2000, there have been more than 4,000 people killed by Valley fever and hundreds of thousands more infected in the United States alone (CDC, 2020). Annual medical costs, lost income and economic welfare for Valley fever add up $400,000 per case (Gorris, 2021). Using this hospitalization rate, the total health burden of Valley fever infection amounted to $40 billion in the past decade in the United States. It is suggested that climate warming and drought, which lead to more frequent severe dust storms, are the cause. These conditions appear to favor saprobic growth, conidia formation, and air dispersal of *Coccidioides* (Kolivras et al. 2001; Comrie 2005; Zender and Talamantes 2006; Stacy et al. 2012; Lewis et al. 2015).

Despite several decades of interest and research, this link with dust storms remains an open question. Until recently, the ability to detect *Coccidioides* at low abundance in environmental samples was difficult and time-consuming, with low throughput (Barker et al. 2012). In addition, although hotspots of *Coccidioides* in the soils of Arizona and California have been mapped, more comprehensive sampling across space, time, and a wide range of climates is required to adequately describe its climatic parameters (Lauer et al., 2020; Finn et al., 2021). Moreover, although outbreaks are known to occur after large dust storms (e.g. Pappagianis and Einstein 1978, Williams et al. 1997), direct detection of the fungus in air samples has been difficult until recent scientific advancements (Chow et al., 2016; Finn et al., 2021).

The source of *Coccidioides* spores is as important as their dispersal. It has been known to infect native rodent populations (e.g., pocket mouse, kangaroo rat, and ground squirrel) (Emmons and Ashburn 1942; Emmons 1943; Catalan-Dibene et al. 2014) and the fungus has a greater number of genes associated with the breakdown of animal protein (Sharpton et al. 2009). *Coccidioides* may be an endozoan, and may initiate hyphal growth from infected tissues when its rodent host dies (Taylor and Barker 2019). Additionally, recent work has shown higher prevalence of Coccidioides in soils collected from rodent burrows (Kollath et al., 2020). Climate factors affect both the distribution of rodent hosts and growth of fungus in soil. Spread of the fungus from rodent to rodent may be by air or more direct contact (such as contaminated fur), but spread to humans is most likely via air/dust.

3.5 Other Microbe-related Diseases

Viruses have been found associated with organic aerosols as small as < 0.7 µm in diameter (Reche et al., 2017), and are easily transported with dust. Hantavirus pulmonary syndrome (HPS) is a respiratory disease with up to a 30-40% fatality rate, borne by the droppings of certain rodents native to Western Hemisphere drylands from Canada to southern South America, and spreads primarily through inhalation (Gonzalez-Martin, 2019). Reports from Canada (Parkes et al., 2016) to Paraguay (Williams et al., 1997) and in between (McMichael, 2004; Plumlee and Ziegler, 2005; Richardson et al., 2013; Watson et al., 2014) implicate potential spread of hantaviruses in contaminated windblown soil dusts in the Americas, but definitive case studies confirming its transmission in dust aerosols appear lacking.

Kawasaki disease (KD) is a pediatric vascular condition that is one of the most common causes of acquired heart disease in children in the USA as well as Japan. Interannual and seasonal fluctuations of KD cases in Japan and California and seasonal variations of KD in Japan, Hawaii and California were linked to patterns of trans-Pacific wind transport (Rodó et al., 2011). Rodó et al. (2011) stated, “results suggest that the environmental trigger for KD could be wind-borne. Efforts to isolate the causative agent of KD should focus on the microbiology of aerosols.” More recent research (El-Askary et al., 2017) raised the possibility that KD may be associated with a fungus carried in Asian dust.

Some dust-associated microbes found in other regions of the globe would also be expected to be present in the Americas. Aerosolized influenza viruses were detected at a higher frequency when Asian dust was present over Taiwan than when it was not (Chen et al. 2010). Similarly, scientists in Tenerife, Spain noted that they were more likely to detect human enteric viruses in the atmosphere when North African dust was present in the atmosphere than when it was not (Gonzalez-Martin 2018). Although the Foot-and-Mouth disease virus has not been isolated from the atmosphere to date, outbreaks have been noted in livestock populations following Asian dust events that affect Korea and Japan (Joo et al. 2002; Sakamoto and Yoshida 2002; Ozawa et al., 2001; Maki 2012). Bacteriophage whose genomes may harbor virulence genes such as those that enable toxin production and antibiotic resistance, may be transported within the genomes of dust storm bacteria resulting in the transfer of these genes to other microorganisms in downwind environments (Teigell-Perez 2019).

Cyanobacteria, ubiquitous in surface crusts of desert soils and playa sediments which are widely wind-erodible, produce a wide variety of cyanotoxins which are hazardous to humans and animals, through being inflammatory agents, tumor promoters, and causing liver damage (Powell et al., 2015). Wiśniewska et al. (2019) reviewed the presence of cyanobacteria in aerosols and their potential human and ecosystem health effects. Metcalf et al. (2012) calculated that dust storms could lead to inhalation of a sufficient quantity of cyanotoxins to exceed the tolerable daily intake to avoid tumor production.

3.6 Role of imported microorganisms in the urban environment

Dust particles can serve as a vessel to deliver potentially harmful biological substances over great distances into urban areas (Kellogg et al. 2004; Garrison et al. 2006; Kellogg and Griffin, 2006; Schlesinger et al. 2006; Griffin et al. 2007). Viable bacteria and fungi associated with the arrival of African dust have been reported over the U.S. Virgin Islands and the northern Caribbean (Griffin et al., 2001; Griffin et al., 2003), with 10% of the identified microorganisms categorized as opportunistic pathogens for humans. Similar results reported for Barbados (Prospero et al., 2005) suggest that the long-range transport of microorganisms could be linked to climate variability (e.g., El Niño–Southern Oscillation). Rodriguez-Gomez, et al. (2020) found that concentrations of viable bacterial and fungal propagules in the Yucatan Peninsula (Mexico) were higher in summer than in winter, particularly during African dust intrusions, with up to 500% higher-than-average $PM_{2.5}$ and PM_{10} concentrations (Ramirez-Romero et al. 2021). Adachi et al. (2020) and Souza et al. (2019) identified different types of microorganisms and large prokaryotic diversity near Manaus (Brazil) in particles consistent with dust sources in Africa.

Biological particles have been found in the dust storms of arid regions such as the "Four Corners" (Colorado, Arizona, New Mexico and Utah) of western United States (Hallar et al. 2011). Elmassry et al. (2020) found significant differences in abundance and type of bacteria and fungi between calm and dust storm days in West Texas (Lubbock). Medium-to-large cities in America built on or surrounded by arid or semiarid zones (Mazar et al. 2016; Marone et al. 2020) should be monitored for opportunistic pathogens carried by dust (among them, Phoenix, Las Vegas, Albuquerque, Las Cruces, El Paso, Tucson, Denver, in the U.S., Monterrey, Chihuahua and Torreon in Mexico, Riohacha in Colombia, Mendoza and San Juan in Argentina).

Soil dust particles emitted from agriculture (mainly during tillage) contain biological particles, potentially affecting downwind city populations (e.g., Kaiser et al. 1992; Conen et al. 2011; O'Sullivan et al. 2014; Steinke et al. 2016). Although a body of evidence shows that soil dust particles can enhance the concentration and diversity of microorganisms in urban regions, the need remains to characterize them and their potential health consequences. Cities downwind of arid or semiarid zones, including those in the path of dust plumes on intercontinental journeys, are susceptible to dry and wet deposition of microorganisms that have passed through complex environments. Airborne dust carrying opportunistic pathogens, especially those resistant to commonly used antibiotics, deserves further investigation.

3.7 Airborne Dust and COVID-19/SARS-CoV-2

Exposure to airborne particles can exacerbate the symptoms and progress of the Severe Acute Respiratory Syndrome-CoV-2 (COVID-19). Microorganisms in airborne particulate matters or dust can be linked to infectious diseases (Yu et al., 2004; Guangbo et al., 2020; WHO, 2020b). The question is whether COVID-19 is susceptible to similar factors (Sajadi et al., 2020; Wang et al., 2020). Primary environmental factors that could influence respiratory viral transmission include air surface temperatures, relative humidity, and rainfall patterns (Lowen et al. 2008; Tamerius et al. 2013; NAS, 2020). In a study of 257 COVID-19 patients in China, over 94 percent were found with viral, fungal and bacterial co-infections (Zhu, et al., 2020). Similarities in initial COVID-19 symptoms (including fatigue, fever, headache, shortness of breath, and cough) among many respiratory illnesses (including tuberculosis, pneumonia, SARS-CoV-2, influenza, Valley fever) raise questions of the speed in which proper diagnosis can be made and administration of treatment can begin. Valley fever, pneumonia and COVID-19, for example, share symptoms of fatigue, shortness of breath and cough. Heaney, et al., (2021) review diagnoses, interactions and clinical implications between SARS-CoV-2 and Valley fever, and co-infection risks according to medical preconditions, age, ethnicity, and occupation.

Direct and indirect transmission routes of this virus occur via touching infected surfaces (skin-to-skin, touching infected inanimate objects), then mediating the virus infection through the mouth, nose, or eyes (Guangbo et al., 2020; Moriyama et al. 2020; Chang et al. 2020; Peng et al. 2020). Transmission via the inhalation of small, exhaled respiratory air droplets (e.g. close contact within 1m) and aerosols (e.g. presence of microbes and particles <5 m in diameter that remain in the air for long periods of time, transmitted to others over distances greater than 1m) seems to be especially effective (Guangbo et al., 2020; Service, 2020). Coinfection of COVID-19 (and/or its variants) with other microorganisms found in airborne dust is a critical complication (Gould, et al., 2021; Zhu, et al., 2020). Further complications arise when one considers all the possible microorganisms in airborne particulate matter that can be linked to infectious diseases (Yu et al., 2004; Guangbo et al., 2020). The most efficient transmission route in continuing the pandemic of SARS-CoV-2 and its variants is inhalation and exhalation of the viral-aerosol (Guangbo et al., 2020; Moriyama et al. 2020; Peng et al. 2020; Service, 2020). Inhalation of both coronavirus and high concentration airborne dust, together, would likely increase risk of mortality due to severe respiratory illness and cardiac injury (Shi et al. 2020; Madjid et al. 2020).

4. Effects on Environmental Health

4.1 Harmful algae blooms, pathogenic microorganisms, and toxins

The correlation between dust storms and the increase of phytoplankton biomass as well as harmful algal blooms (HABs) has been documented in freshwater lakes, coastal and oceanic regions worldwide (Cropp et al. 2013; Tan and Wang 2014; Winton et al. 2016; Mackey et al. 2017; Abuelgasim & Farahat 2018; Bali et al. 2019; Farahat and Abuelgasim 2019, Tian et al. 2020). In the Gulf of Mexico, blooms of the dinoflagellate *Karenia brevis* (aka, Red Tide), a potential neurotoxin producer, have been linked to Sahara Dust storms (Walsh et al 2001; Lenes and Heil, 2010). Red Tide toxins can cause significant direct mortality to marine organisms and indirect morbidity to terrestrial organisms through bloom-associated aerosol exposures. Cyanobacteria derived toxins which are known to be carried in desert dust storms may cause direct health issues in humans through aerosol exposure (Cox et al. 2009).

Saharan dust deposition in the Atlantic Ocean and the Gulf of Mexico can cause short-lived blooms of *Vibrio* species, many of which are known pathogens to human and marine organisms (Westrich et al. 2016; Westrich et al. 2018). Deposition of macronutrients from anthropogenic dust sources has increased with development of agriculture, urbanization and deforestation (Al-Enezi et al. 2014, Bauer et al. 2016). The increase of biologically available N from dust deposition can result in the enhancement of phytoplankton growth, such as in the low nutrient low chlorophyll (LNLC) regions. It may also change the nutrient stoichiometric and shift the system from N limiting to P limiting (Kim et al. 2011), and consequently alter the phytoplankton composition leading to the growth of some undesirable species. Olsen et al (2019) found that atmospheric loading of dissolved inorganic nitrogen and total phosphorus, mostly derived from local sources, may support algal blooms in Utah Lake and become a major contributor to lake eutrophication—a condition that may advance cyanobacteria prevalence (Ren et al. 2020). Also, organic nitrogen can make up a large portion of total N in wet and dry deposition (Matsumoto et al. 2019). Atmospheric deposition of organic matter has significant effect on the microbial community in water bodies (Rahav et al. 2016, Sisma-Ventura and Rahav 2019): a massive Australian dust storm was reported linked to an extensive ‘bloom’ of *Aspergillus sydowii*, a fungus believed detrimental to corals (Hallegraeff et al. 2014).

Dust and aerosols can provide significant new amounts of iron (Fe) and stimulate the growth of the diazotroph community in offshore oceanic regions (Winton et al. 2016, Farahat and Abuelgasim 2019). Mesocosm experiments demonstrate enhancement of diazotroph growth after polluted aerosols and Sahara dust have been added to seawater from the Eastern Mediterranean Sea; the prevalence of N-fixing cyanobacterium *Trichodesmium* was found associated with Sahara dust as a result of Fe fertilization (Rahav et al. 2016). While historical records reveal a direct relation between *Trichodesmium* and *K. brevis* off the west coast of Florida, further studies show the 'new' and regenerated N derived from the dust associated *Trichodesmium* blooms could not only alleviate N limitation to the growth of *K. brevis*, but potentially initialize and sustain large blooms of *K. brevis* for as long as a couple months (Lenes and Heil, 2010). However, while *Trichodesmium* blooms occur every year in the Gulf of Mexico and in Southwest Florida, outbreaks of *K. brevis* are typically episodic. For example, the massive "Godzilla" Saharan dust storm arrived in the Gulf of Mexico and bordering U.S. states during late June-early July, 2020. Meanwhile, a bloom of *Trichodesmium* was observed off the southwest coast of Florida in June that lasted weeks but *K. brevis* concentrations remained at background levels. Further studies are needed to better understand the underlying mechanisms of the linkage among dust storm, *Trichodesmium*, and *K. brevis* blooms.

4.2 Dust Deposition and Ecosystem Health

Dust deposition can have either positive or negative consequences to ecosystem health. A positive effect is that dust contains key nutrients, such as phosphorus (P) and iron (Fe), that are essential to biological functions that stimulate primary productivity which sequesters atmospheric carbon dioxide (CO_2) in the ocean and terrestrial biosphere (Mahowald, 2011), and is, thereby, a benefit for Earth's climate. Another positive effect is that the African dust transported to South America in winter and spring is thought to fertilize the P-limited soils of the Amazon rainforest and increase primary productivity (Barkley et al., 2019; Prospero et al., 1981; Prospero et al., 2020; Swap et al., 1992; Vitousek & Sanford, 1986; Yu et al., 2015).

Dust also stimulates marine productivity both in the high latitude low nutrient, low chlorophyll oceans by supplying Fe, and productivity in the nitrogen (N)-limited low latitude oceans by providing Fe and P that stimulate nitrogen fixation (Mills et al., 2004; Moore et al., 2013; Tagliabue et al., 2017). A critical consideration is the solubility of nutrients found in dust. While deposited dust has a very long residence time in terrestrial soils, dust only spends a few weeks in the surface ocean before sinking out—thus, nutrients must be readily soluble in seawater to have an appreciable effect on marine productivity (Gaston, 2020; Jickells & Moore, 2015; Okin et al., 2004). Commonly found mineral forms of P and Fe in dust include apatite and iron oxides, respectively, which have very limited solubility. However, recent research shows that nutrient solubility can be affected by particle size (Baker & Jickells, 2006), association of dust with organic aerosol containing chelators such as oxalate (Meskhidze et al., 2017), mineralogy (Journet et al., 2008), and heterogeneous reactions between dust and atmospheric acidic gases (Nenes et al., 2011; Spokes & Jickells, 1995).

In contrast to increasing primary productivity through deposition of key nutrients, dust can also exert negative impacts on ecosystem health and lower primary productivity. Trace metals in dust, such as copper (Cu), can be toxic to phytoplankton and lead to changes in marine community composition (Paytan et al., 2009). Additionally, as covered in other sections of this review, dust storm particulates may contain pathogenic microorganisms, inorganic and organic toxins and natural and anthropogenic radioisotopes that can negatively impact ecosystem health.

4.3 Water supply contamination caused by soil dust

Wherever a drinking water supply is exposed to the atmosphere it is potentially vulnerable to any harmful materials arriving with a dustfall (Middleton and Kang, 2017). Many low-income communities in the Americas lack potable water service, and receive their drinking water delivered by truck or hauled from a site in storage containers. When household water storage containers or the truck-mounted water tanks become soiled by falling dust, they may become contaminated by organic pollutants or heavy metals (Parra, 2019), as well as soil-borne microbes (Farenhorst et al., 2017). The risk of physical, chemical, and/or microbial contamination from atmospheric deposition including soil dusts is of extra concern where rainwater is not treated before being used for drinking, as with cisterns (Gwenzi et al., 2015; Sánchez et al., 2015). Griffin and Kellogg (2004) stated, "…most of the drinking water in the Caribbean is collected from rooftop drainage and stored in cisterns. It remains to be determined if dust contamination of the water could result in numbers of microbes sufficient to cause disease by ingestion." Peters (2011) found that "few households exercised good rainwater harvesting practices" in the Caribbean Grenadine islands, increasing the risk of contamination of drinking water storage tanks from Saharan dust and other sources.

4.4 Food contamination from windblown dust

There is a growing awareness, and documentation, that foodstuffs consumed uncooked, particularly certain fresh fruits and vegetables but also ready-to-eat meats, are prone to contamination by pathogens such as S*almonella* and *Escherichia coli* carried with aeolian dust (Kumar et al., 2018). Helburg and Chu (2016) conclude that "multiple peer-reviewed studies show a quantifiable, consistent trend" of the dispersal of the foodborne bacterial pathogens *Bacillus, Clostridia*, and *Staphylococcus* by dust storms. Mendonca et al. (2020) review various other genera of harmful bacteria which have been isolated in dust and are thought to pose a risk.

Most foods, if coated with dust, likely do not present a health risk if they are properly washed or peeled. Fruits such as melons, which are traditionally not washed thoroughly due to their shell, may transfer pathogens from dust on the rind when sliced, contaminating the edible flesh (Annous et al., 2005).

Some leafy vegetables such as lettuce are difficult to wash thoroughly enough to remove bacteria that have adhered to the plant tissue, such that dust may be a vector of contamination (Brandl, 2006).

If windblown soil dust containing *Salmonella* settles on blossoms of tomato plants shortly before they set fruit, the bacteria can be incorporated into and diffused within the tomato's flesh, leading to ripe tomatoes infused on the inside with *Salmonella* (Kumar et al., 2017). Much the same effect of *Salmonella* internalization through blossom inoculation has been demonstrated with cucumbers (Burris et al., 2020), and *E. coli* has been shown to be incorporated into apples through their blossoms (Burnett et al., 2000). The authors of these papers suggest that the blossom inoculation pathway may explain some otherwise unexplainable recent foodborne illness outbreaks.

4.5 Agricultural hazards associated with dust

Agricultural workers and others whose occupations require frequent contact with and dispersion of soil are at risk of exposure to inhalation of soil particles and contact with soil-borne pathogens. Alexander et al. (2018) reviewed cases from California suggesting that dust-associated respiratory disease is an occupational hazard in agricultural work. Sherwin et al. (1979) reported a series of residents of the California Central Valley who developed silicate pneumonitis: five of the seven worked in vineyards and five died with respiratory failure. Analysis of particles in their lungs demonstrated their composition was consistent with local soil. Nieuwenhuijsen et al. (1999) reported that agricultural workers in California had significant dust exposure during machine harvesting of tree nuts and vegetables and cleaning poultry houses, including some exposures to high levels of endotoxin. Some young Hispanic agricultural workers who died suddenly were found to have pathologic changes in their lungs including mineral dust small airway disease, pneumoconiosis, and other pathologies consistent with chronic bronchitis, emphysema and interstitial fibrosis (Schenker et al., 2009). These changes were reported to be more prominent in farmworkers than in non-farmworkers. Schenker et al. (2009) concluded that mineral dust exposure is associated with increased small airway disease and pneumoconiosis among California farmworkers, but its clinical significance and natural history of these changes remained to be determined. Schenker (2010) stated, based on evidence from farmworkers, that "overall, the evidence supports a causal association of mineral dust exposure and pneumoconiosis." Alexander et al. (2018) concluded that chronic occupational exposure to soil dust may associate with chronic lung disease, advising "this clearly depends on the frequency of exposure, the intensity of exposure and the composition of the dust."

A wide variety of fungal plant pathogens apparently have been established or spread to the Americas through wind and/or associated with dust. These include wheat rust (fungi of the genus *Puccinia*) spreading through the North American Great Plains (Charnecki et al., 2012), and *Peronospora hyoscyami*, the organism that causes the tobacco blue mold, riding on the wind through the Southeast USA (Main and Davis, 1989). The eastward spread of *Triops* *longicaudatus,* a pest of wetland crops such as rice, into the USA Midwestern states of Missouri and Illinois has been suggested to occur in association with wind transport of soils from dried river floodplains (Tindall et al., 2009; Ridings et al., 2010). *Erwinia carotovora*, the causal agent of potato blackleg disease, apparently has spread from the west coast of the US to the interior US through dust-associated wind transport (Franc, 1994). *Pseudomonas syringae,* a widely-distributed pathogen of a wide variety of crops, has also been associated with intercontinentally-transported dust clouds. These two species of phytopathogenic bacteria can serve as cloud condensation nuclei, facilitating their survival in long-distance aeolian transport (Behzad et al., 2018). Another species of *Puccinia*, which causes sugarcane rust, may have been spread to the Caribbean and on to Florida via seasonal intercontinental dust transport from Africa (Purdy et al., 1985); several species of *Mycosphaerella*, which cause severe losses to bananas and plantains, have been suggested to have been transported to the Caribbean from Africa along the same pathway, potentially in dust clouds (Stover, 1962: Burt, 1994). *Massaria platani*, the causative agent of Florida sycamore canker, and *Alternaria dauci*, a species known to infect Florida carrots, were identified in the mid-Atlantic in the transoceanic African dust trade-wind corridor when dust was present in the atmosphere (Griffin et al., 2006; Gonzalez-Martin et al., 2014). Behzad et al. (2018) report that *Hemileia vastatrix,* the fungus causing the coffee leaf rust (Bowden et al., 1971) and *Phakopsora pachyrhizi*, which causes soybean rust (Pan et al., 2006), were apparently introduced into North America in clouds of windborne dust from Africa and Asia, respectively.

Bacterial pathogens present in soil may be readily entrained and transported by wind. A recent study by Thiel et al. (2020) demonstrates that manure bacteria, including enteric pathogens, aerosolize from fertilized soil more easily than do soil bacteria, and their wind tunnel tests indicate that airborne bacterial emission fluxes from freshly fertilized soil were 100-fold higher than a previous estimate of average emissions from land. Confined animal feeding operations (CAFOs) are potent point source emitters of particles into the atmosphere. Twenty-four-hour mean concentrations of PM_{10} as high as 1200 µg m^{-3} have been reported (Hiranuma et al., 2011). They also reported that the particles contained high levels of carbonaceous materials, some of them soluble, and salts. Bacteria are also hitchhikers on dust from CAFOs. Berry et al. (2015) reported strain specific *Eschericia coli* contamination of leafy green vegetables at distances of 180 m downwind from the source CAFO. The U.S. Food and Drug Administration (2021) reported that fugitive dust from a nearby animal operation was suspected to be the cause of a *Salmonella* outbreak on fresh peaches in summer 2020 that caused more than 100 illnesses in 17 USA states. Other manure- or urine-borne contaminants such as hormones are also identified constituents of the fugitive particulates, possibly affecting human and environmental health (Blackwell et al., 2013).

Airborne dust carrying contaminants can transfer harmful substances between different agricultural entities. Examples include transmission of avian influenza between poultry facilities (Ssematimba et al., 2012), transport of the foot-and-mouth-disease virus potentially up to long distances by dust (Garner et al., 2006) and herbicide-bearing dust falling on blossoms that reduce yields of pistachio crops in the San Joaquin Valley of California (Zhang et al., 2019). Seeds coated with insecticides, when planted by drilling, may cause some of the coating to be released into the wind, resulting in toxicity to bees and other beneficial insects (Devarrewaere et al., 2016). Insecticides toxic to honeybees and aquatic organisms are a wind-suspended along with materials from beef cattle feed yards in the US and entrained into downwind particulate matter in a quantity modeled “to kill over a billion honeybees daily” (Peterson et al., 2020). Numerous soil-borne pathogens can be spread by dust. For instance, Nieder et al. (2018) state, “Several soil-borne diseases are capable of transmission to the air (e.g., Q fever, aspergillosis, tularemia, sporotrichosis) and may be then transported by dust”. A particular concern is for pathogens and toxins typically associated with agriculture, but that could be also potentially weaponized against humans, which are capable of being transported on windblown dust. Examples include anthrax (*Bacillus anthracis*) (Dragon and Rennie, 1995), the ricin toxin (Zartman and Jaynes, 2014) and *Coxiella burnetii*, the bacterium which causes Q fever (Baret et al., 1999; Kersh et al., 2010: Hogerwerf et al., 2012).

4.6 Effects on domestic and wild animals

Pesticide, pollen, fungi, heavy metals and other components of soil make up windblown dust which, when inhaled, can be problematic for pets, livestock, and wild animals. When mercury, for example, settles from the air onto soil and water it is a continued hazard, as when humans or animals consume methylmercury-contaminated fish and shellfish. The Government of Canada (2020) identifies predators such as bears and eagles particularly susceptible to bioaccumulation of air pollutants, with potentially fatal illness. Animals can be infected with coccidioidomycosis (Valley fever (see section 3.4)) when airborne fungal spores of *Coccidioides* are inhaled. Means of infection are similar in humans. However, domestic animal habits of frequent contact with and rooting about in the soil, and wildlife living in natural landscapes, very likely increase their risk in *Coccidioidomycosis* endemic areas. A seminal paper by Shubitz (2007) followed by Spickler (2020) reports *Coccidioidomycosis* across many animal species, including horses, cattle, sheep, burros, coyotes, cougars, dolphins, rodents, bats, and snakes. Cats are known to contract Valley fever (Tofflemire and Betbeze, 2010, Arbona, et al., 2020), with non-healing skin lesions a common symptom. Alpacas in the American Southwest have been treated for Valley fever (Butkiewicz and Shubitz, 2019). Dogs, possibly because of their habits as well as their numbers in family households, are commonly infected by *Coccidioides*. People may travel over considerable distances to come into contact with the fungus, but the physical range for pets, livestock and most wild animals is limited; when a pet or an animal in a zoo is diagnosed with Valley fever, the animal is likely to have contracted the disease close to home.

The presence of Valley fever in marine mammals along the U.S. West Coast may help solve questions of survivability of airborne *C. immitis*. Sea otters, dolphins, and whales have been diagnosed with Coccidioidomycosis (Carlson-Bremmer et al. 2012). Stranded California sea lions and Northern Fur seal pups diagnosed with respiratory problems when admitted to California marine mammal care centers had Coccidioides-specific antibodies in their blood sera (Lauer, et al., 2019). Coccidioidomycosis is identified as the most common mycosis in stranded marine mammals along the central California coast (Huckabone et al. 2015; Simeone et al. 2015)—and possibly a cause of the stranding itself. Between 2005 and 2014, 12 California sea lions rescued at one Marine Mammal Center died from Valley fever. Marine mammals do not venture far from waters' edge, though they range considerably north and south off California's shoreline. Infection is assumed to have occurred when these animals came in contact with airborne Coccidioides arthroconidia, possibly from the Mojave Desert (Hector et al. 2011; Thompson III et al. 2015; Guevara et al. 2015; Grayzel et al. 2017). Pacific Ocean marine mammals are often exposed to windblown dust from points well inland. The normal migratory patterns of these mammals, the length of time for symptoms to appear after contracting the disease, and variable weather patterns make it difficult to pinpoint the geographical source of the fungus without further population genomics analysis of the infecting isolates.

4.7 Radioactive contamination (Radionucides) in dust

Soil from which dust emanates is a complex matrix of minerals, organics, water and gases, all of which may be radioactive. Natural forms of radioactivity include radioactive minerals and daughter products of decay. Solid forms include the primary minerals of the soil matrix and solutes including ^{238}U, ^{232}Th, ^{40}K, and ^{210}Pb (Jasaitis et al., 2020; Monged al., 2020; Nenadovic et al., 2012) and ^{14}C, ^{34}S, and ^{15}N in organic matter. Deuterium is found in water, and ^{226}Rn is the primary radioactive gas (Carneiro et al., 2013; Forkapic et al., 2012) and is associated with geology and stress in the earth's crust (D'Alessandro et al., 2020). Exposure to these radioisotopes is hazardous (Jasaitis et al., 2020; Monged et al., 2020; Nenadovic et al., 2012). Photoionization modifies or creates radionuclides such as ^{210}Pb from fission of ^{226}Rn in the atmosphere, and from cosmic inputs of ^{60}Fe formed in supernovae (Warner et al., 2016). Cosmogenic radionuclides, such as ^{7}Be, can be deposited by rain on surfaces (Itoh and Narazaki, 2015). Global fallout of anthropogenic radionuclides from nuclear weapons testing has also added to soil radioactivity (Gharbi et al., 2020; Mezina et al., 2020; Pravalie, 2014).

Anthropogenic sources of soil radioactivity include burning of fossil fuels (Ault et al., 2015), dust input from weapons-testing regions (Igarishi et al., 2009), resuspension of previously deposited radionuclides (Schulting et al., 2018) and releases from nuclear power plants, commercial nuclear fuel reprocessing, nuclear accidents and uranium mining and milling (Hu et al., 2010). Of these anthropogenic sources, probably the wind redistribution of uranium mining spoils and mill tailings are probably most widespread and of most concern to human health

(Blake et al., 2015; Doering et al., 2019; de Souza Pereia et al., 2018; Malin et al., 2010; Velarde, 2011). many cases, legacy mine waste and mill tailings have been exposed to the erosive forces of wind for more than a half century. Few estimates exist of the amount of radioactive U and decay series daughter products that leave the site and deposit downwind (Doering et al., 2019; Rood et al., 2008). A recent increase in respiratory and metabolic diseases in the Navajo indigenous population living close to the Grants uranium mining district in New Mexico, USA, may be associated with bioavailable uranium in respirable dusts (Hettiarachchi et al., 2018). In

Continued atmospheric testing until January 1, 1963 resulted in deposition of numerous un-spent radioactive fuels and fission daughter products across the continental U.S. (Simon et al., 2004) and globally (Gabrieli et al., 2011; Bu et al., 2014). Although stratospheric fallout from high altitude detonations was spread evenly over the landscape from high latitudes to lower latitudes in the northern hemisphere and in greater quantities in more rainy climates, ground based detonations resulted in localized ‘hot spots’ of radionuclide contamination, particularly in semiarid and arid regions prone to dust emissions (Simon et al., 2004). An accidental release of radioactive dust from a deep geological repository in southwestern North America resulted in a temporary spike in local dust radioactivity that returned to pre-release levels consistent with the load of anthropogenic radionuclides in the soil (Thakur and Anderson, 2019).

Today, resuspension of dust from soils contaminated with anthropogenic radionuclide fallout is prevalent in semiarid and arid regions prone to wind erosion. In arid areas with sandy soils and heterogeneous vegetation patterns such as southeastern New Mexico, radioactive dust has been quantified (Arimoto et al., 2002; 2005; Thakur et al., 2012). In more humid climates, disturbance of the vegetative cover by fire releases anthropogenic radionuclides contained in the litter layer as smoke (Strode et al., 2012), and later, the loss of vegetative cover can increase the hazard of soil dust emissions (Whicker et al., 2006a, b). Aeolian transport of radionuclides from the soil can be modeled and predicted, which allows estimation of inhalation doses off previously contaminated, but recently disturbed, soils (Michelotti et al., 2013). Radionuclides in dust are used to estimate the age of atmospheric aerosols (Han and Zender, 2010), and loss or gain of fallout anthropogenic radionuclides has been used to estimate decadal rates of soil redistribution by wind (Van Pelt et al., 2007; Van Pelt 2013; Van Pelt and Ketterer, 2013). The eventual fate of all surface sediments on earth is to be deposited over the oceans either as wet or dry dust deposition or by water erosion and transport in rivers. They then become ideal tracers for ocean currents (van Hulten et al., 2018). Yet, this oceanic deposition is not a dead-end sink, as marine sediments are common, brought to sea surfaces and deposited on land again they remind us of nature’s propensity for recycling.

4.8 Heavy metal contamination (resuspension)

Contaminants such as heavy metals (Schreck et al., 2012) may be carried with aerosols including dust. When they fall out on gardens or agricultural lands-especially in and downwind of urban or industrial areas that tend to have a greater incidence of contaminated soils (Cooper et al., 2020), people, livestock and wildlife consuming those crops are put at risk. The risk may be the highest for leafy vegetables, which have a large proportion of surface area of edible product exposed to the air (Schreck et al., 2012), although root uptake of heavy metals into vegetable crop leaves has also been shown (Li et al., 2017). Heavy metals in agricultural soils may come from many sources.

Native minerals and weathering products supply numerous metallic minerals (Eleftheriadis and Colbeck, 2001; Trapp et al., 2010; Khan et al., 2012; Wang et al., 2019; Nicoll et al., 2020). In addition, redistribution of mining spoils and deposition of industrial emissions result in increased heavy metal concentrations in surface soils that may ride with fugitive dusts (Csavina et al., 2012; Garcia Vargas et al., 2014; Ono et al., 2016; Rodriguez-Espinaosa et al., 2017; Entwistle et al., 2019; Van Pelt et al., 2020a; Li and McDonald-Gillespie, 2020; Vito et al., 2020). Metallic ions in surface soils may also emanate from cosmic sources (Benna et al., 2015). Specific to agriculture, heavy metals are contaminants in fertilizer materials, especially phosphate fertilizers, applied to increase crop growth (Azzi et al., 2017; Dharma-Wardana, 2018; Wang et al., 2020). Heavy metals have been found in organic fertilizer (Gong et al., 2019). Dzul-Caamal et al., (2020) report that these contaminants result in biomass loss of the common earthworm *Eisenia foetida*.

Pesticides and herbicides have revolutionized production agriculture. Pesticides absorbed or attached to dust particles (Richards et al., 2016) may be wind-eroded after application (Glotfelty and Caro, 1975) and drift into unintended locations where they pose a risk, as into inhabited areas or into croplands certified as organic and required to be pesticide-free or rangelands without a history of pesticide application (Bento et al., 2017; Alonso et al., 2018). Several studies have shown that exposure is a function of distance from fields where pesticides are applied (Gunier et al., 2011), occupation (Bennett et al., 2017; Smith et al., 2017) and season (Smith et al., 2017). New pesticides and classes of pesticides are constantly being developed to replace older technologies to which crop pests have become resistant or to limit environmental impacts. Pesticides found in house dust are found to reflect the pesticides in use at the time (Bennett et al., 2017). Pesticides coated or attached on soil particles entrained as dust is toxic to humans, particularly to the farm workers often exposed (Smith and Gunther, 1978; Spencer et al., 1980). Pesticides are also present in urban dusts due to lawn and household use (Richards et al., 2016); they may exist in gas phase before attaching to dust particles either in the atmosphere or on the deposition surface (Yao et al., 2008; Socorro et al., 2016). In studies of herbicides transported on dust, Alonso et al. (2018) found glyphosate and atrazine, commonly used herbicides, in the soils and rainfall of Argentina. Glyphosate degrades into a daughter product named aminomethylphosphoric acid (AMPA) and both hold tightly onto particulate surfaces. AMPA has a much longer half-life than glyphosate and tends to accumulate in the soil and thus is present in greater concentrations and for longer periods than glyphosate (Aparicio et al., 2013). In semi-arid regions with bare soil surfaces, wind may entrain the surface soils and transport the glyphosate and AMPA from the field into adjacent agroecosystems (Aparicio et al., 2017; Bento et al., 2017). These compounds are also components in respirable dust emanating from eroding agricultural soils (Mendez et al., 2017).

4.9 Ocean acidification and dust

Oceans become acidic when ocean dissolved carbon dioxide concentrations rise. A significant amount of this CO_2 is absorbed by the oceans (Tessin, 2020). Primary productivity in the oceans depends on availability of certain macro- and micro-nutrients. Among the macro-nutrients, N and P, and among the micronutrients, Fe, Co, and Zn, play important roles (Srinivas et al., 2015; Mahowald et al., 2011). Atmospheric transport and deposition of these macro- and micronutrients to the oceans may impact their surface biogeochemistry (Prospero et al., 2009). For example, Fe is transported primarily to the oceans from land via atmospheric dust deposition (Duce et al., 2009; Martin, 1990). The arid Sahara and the Sahel region of Sub-Saharan Africa are copious sources of this dust, where every year millions of tons are transported by strong winds over thousands of miles to the Amazon region of South America and the Caribbean (Prospero et al., 2014, Yu et al., 2020).

Silica components of dust and microalgae create diatoms such as the siliceous marine phytoplankton. These diatoms account for 20 percent of the world's photosynthesis (Bopp et al., 2003; Li et al., 2017), and are found in the Fe-limited regions of the oceans (Hettiarachchi et al., 2020). They play a crucial role in the export of organic C from surface waters to the deep oceans (Malviya et al., 2016). Various biochemical processes such as photosynthesis, nitrogen fixation, and chlorophyll synthesis are affected by the availability of Fe as it controls the marine primary productivity and efficiency of the biological C pump (Li et al., 2017; Breitbarth et al., 2010). Laboratory studies show that ocean acidification could lower the bioavailability of dissolved Fe, which is crucial for marine phytoplankton (Shi et al., 2010). Although higher aerosol dust deposition on the ocean surfaces could result in greater availability of Fe, scientists have posited that rising seawater temperatures and lower pH could alter this Fe bioavailability - a crucial factor in marine phytoplankton production (Jickells et al., 2005; Li et al., 2017; Liu et al., 2002).

4.10 Solar power plants

Renewable energies (RE) in general, and solar energy in particular, can contribute to mitigate climate change by reducing the GHG emissions while still satisfying the demand for energy (IPCC, 2011; Owusu & Asumadu-Sarkodie, 2016). Desert areas are excellent regions for both solar photovoltaic (PV) and concentrated solar power (CSP) plants due to their large solar irradiation (Köberle et al., 2015; Barbosa et al., 2017). The overall performance of these power plants can largely be impacted by dust accumulation or soiling on the insolation-receiving surfaces (Al-Addous et al., 2019) and/or solar radiation attenuation by atmospheric dust (Polo and Estalayo, 2015; del Hoyo et al, 2020).

Soiling leads not only to reflectance degradation but also reduces the lifespan of PV cells due to overheating and shading (Sarver et al., 2013; Shi et al., 2020). Deposition rates onto solar power cells depend on factors such as wind speed, cell orientation, angle of incidence and relative humidity (hygroscopic aerosol growth) (Goossens et al., 1993; Hammond et al., 1997; Chen et al., 2019). This soiling combined with water scarcity in arid regions represents a challenge for current as well as future projects (Xu et al., 2016). Cleaning and mitigation methods have become a fundamental component of the solar industry due to soiling's dramatic impact in degrading energy production (Gupta et al., 2019), which is greater as the particle size increases (Shi et al., 2020). For instance, sand storms have been found to reduce PV panel efficiency up to 80% in one hour (Ghazy et al., 2014). Artificial cleaning techniques involve either manual labor or self-cleaning mechanisms (Jamil et al., 2017; Gupta et al., 2019). The latter comprises a range of methods such as hydrophobic and hydrophilic surfaces, mechanical dispositive for dust removal, electrostatic shields and robotic devices (Jamil et al., 2017). The applications of these methods depend on the region and associated costs. For instance, washing methods are difficult to implement in areas of water scarcity, such as deserts. Other mitigation measures required interventions in the surrounding of PV panels (Ghazy et al., 2014), such as concreting the surface or planting grass where possible, which suppose a major challenge in dry regions and would not prevent deposition of dust generated offsite. A proper selection of cleaning methods also depends on the mechanisms driving dust accumulation. A particular phenomenon is bird dropping, which increases dust accumulation by acting as adhesive for the particles (Gupta et al., 2019). In this case, a mechanical brushing system cannot be used (Ghazi et al., 2014). Therefore, several elements, along with associated costs, have to be taken into account for mitigating soiling impacts, such as the nature of dust accumulation, dust composition and the governing meteorological conditions.

5. Safety Concerns

In addition to its role in human and environmental health, airborne dust and related phenomena are a major safety hazard to transportation, especially for motor vehicles on dust-affected highways, with hundreds of associated fatalities. Concern grows, too, about dust hazards to aviation, marine navigation, and railroads.

5.1 Roadway safety

During windblown dust events, driver distraction and disorientation, loss of awareness of the road and other vehicles, and sudden changes in vehicle speed, increases the risk of an accident (Ashley et al., 2015). Coarse dust and sand on the roadway can also cause loss of traction and loss of vehicular control, adding to crash risk (Day, 1993; Pan et al., 2021). Dust also appears associated with greater crash severity than other hazardous weather. Burritt and Hyers (1981) point out that blowing dust and sand events favor the occurrence of "chain reaction" multi-vehicle crashes or numerous crashes clustered together in dust-affected stretches of roadway. Any form of airborne dust/sand sufficient to reduce roadway visibility is a hazard to motor vehicles, although haboob dust events, presenting thick obscurations suddenly encountered from clear conditions, are undoubtedly more treacherous to drivers than synoptic-scale dust events, which steadily reduce visibility over larger areas and longer times and may give drivers time to adjust to conditions. Microscale, ephemeral near-ground dust plumes known in the Southwest USA as "dust channels" are extremely hazardous, due to their localized nature and difficulty to detect with conventional meteorological or air quality networks or remote sensing platforms. Dust and sand hazard to motorists is a result not only of wind erosion of natural dryland surfaces, but also of emissions from temporarily fallow and wind-erodible croplands, part of regional agricultural practices (Li et al., 2018), or fields being tilled (Crooks et al., 2016) that emit un-anticipated dust plumes in fair weather. Construction areas where the soil cover has been disturbed or removed can be a source of fugitive dust in any climate (Weber, 2014). Highways traversing land in dry climates that had once been used but are now abandoned destroy surface soil crusts and leave surfaces barren and erodible become a source of dust. This is true in the heavily-travelled, crash-prone corridor between Phoenix and Tucson, Arizona (Hyers and Marcus, 1981; Lougeay et al, 1987; Raman et al., 2014).

Dust hazard to road transportation is well-documented in the southwestern US (Figure 3), the region of the nation where dust is most frequently encountered (Prospero et al., 2002). The "Interstate 5 dust storm crashes" in central California on 29 November 1991 raised national awareness of the problem, as at least 33 collisions involving at least 164 vehicles and 349 persons within a ten-minute period along a few kilometers of dust-blinded freeway left 151 people injured and 17 dead (Pauley et al., 1996). In the dusty desert counties of southeast California, the percentage of fatalities in wind-related accidents is roughly double the deaths in accidents coded for weather other than wind—and with the probability of wind-related accidents increased in low visibility—it suggests that dust contributed to the incidents (Bhattachan et al., 2019). Blowing dust is Arizona's third deadliest weather hazard, killing over 150 persons and injuring more than 1300 in a recent 50-year period (Lader et al., 2016). In Arizona, crashes in dusty conditions have a higher-than-average ratio of fatalities to injuries (Burritt and Hyers, 1981), possibly because of high speed limits and sudden, unexpected, small scale events of blinding dust. Not far to the east, Interstate 10 highway crosses the dust-emitting Lordsburg Playa in southwestern New Mexico (Eibedingil et al., 2021); this single short stretch of road was the site of 117 dust-and-sand-related highway crashes between 1980 and 2017, with at least 41 fatalities since 1965 and 21 since 2012 (New Mexico Department of Transportation, 2018; Botkin and Hutchison, 2020; Van Pelt et al., 2020). The "Black Tuesday Storm" of 14 April 2015 generated dust in the Great Basin Desert of western Utah, limited visibility on Interstate 80 and caused a 17-vehicle pileup resulting in one death and 25 injuries (Nicoll et al., 2020). However, roads in almost every part of the United States have the potential to be affected by windblown dust, especially during extensive droughts. For instance, Goudie (2014) documented dust-related fatal highway crashes that took place in six states in a single year. Weber (2014) reported that blowing dust on Route 108 near Carlinville, Illinois, in the agricultural Corn Belt of the central USA, reduced visibility to about one meter and resulted in several collisions and temporary highway closure. Windblown dust in eastern Arkansas, in the humid southeast United States, caused at least two multi-vehicle crashes that injured 11 persons and killed one in April 2016 (Breslin, 2016).

Figure 3. *a*) A scene of multi-vehicle crashes on I-10 highway at Lordsburg Playa near New Mexico and Arizona border on May 22, 2014 (photo courtesy of New Mexico State Police and Motor Transportation Police), *b*) A typical *haboo*b dust storm observed near Phoenix, Arizona on August 2, 2018. Inside the haboob, there is blinding sand and dust as visibility can drop to zero (Photo source: Washington Post), *c*) A plume of blowing dust passing across I-10 in San Simon, southeastern Arizona, May 16, 2016 (Source: CBS 5, Tucson, Arizona), and *d*) San Simon Valley dust source area next to I-10 in southern Arizona with abandoned and unprotected land (photo courtesy Arizona Department of Transportation).

5.2 Aviation safety

Aviation transportation depends critically on timely, planned and uninterrupted flight operations. Even short delays result in millions of dollars of economic loss. Aviation is vulnerable to dust that reduces visibility (Monteiro et al., 2020), damages engines and instrument sensors and is implicated in icing during flight (Ackerman et al., 2015). Dust storms affect air traffic management and disrupt takeoffs and landings, yet rarely influence procedures in whole airport zones, wider regions, or even entire routes (Monteiro et al., 2020). Helicopter operations are another concern (McDonald, 2013): rotor "downwash" may lift loose soil, lower visibility and reduce pilot orientation and situational awareness (Jasion and Shrimpton, 2012).

Airport activities near dust sources are often disrupted due to reduced horizontal visibility. Many studies and research flight campaigns prove that mineral dust particles represent one of the most effective ice nucleation agents (Cziczo et al, 2013), which can increase ice formation and subsequent high risk dramatically along aircraft routes (Haggerty et al., 2019; Nickovic, et al., 2021). Two aircraft accidents, where elevated Saharan dust had been present, ended in catastrophic epilogue—the June 2009 Air France flight (AF477) and the July 2014 Air Algérie flight (AH5017)—according to official investigations (BEA, 2014; BEA, 2016) and Nickovic, et al (2021). Several studies (Olofsson et al., 2003; Belo-Pereira, 2015; Nickovic, et al., 2021) propose predicting a new icing index with included mineral dust as icing agent. All effects reduce the number of engine flight cycles, shorten standard maintenance intervals, require engine replacements and increase overall costs—a case in point, several hundreds of million dollars for a fleet of 110 commercial aircraft (Nasser, 2019).

Aircraft turbines are also susceptible to damage from mineral dust particles through the instant effects from intensive dust storms, accumulated damage over time (Song et al., 2016)—a consequence of long-term operations in dust-prone regions—or melting of ingested mineral dusts in new high-operating-temperature turbines (Clarkson et al., 2016; Song et al., 2016); this problem is recognized from decades of concern over engine intake of volcanic ash. Conventional dust forecasts do not indicate the level of possible dust melting. Nickovic et al. (2012) show that when modeled dust concentration is combined with its mineralogy composition, the time and location of melting conditions can be predicted with reasonable accuracy (Nickovic and Cvetkovic, 2019).

Brownout refers to extremely thick clouds of dust and sand raised by aircraft operating close to the ground in dry terrain or over loose soils. It is a specific hazard with regards to helicopter rotor 'downwash' that hits the ground with high velocity (McDonald, 2013; Jasion and Shrimpton, 2012). The result is loss of vision, orientation and situational awareness to the pilot as well as ground personnel. The chance of aircraft mechanical failure as well as uncontrolled contact with the ground or obstacles is increased. Brownout is a great safety concern, especially in desert regions including those of the USA where multiple crashes have resulted in fatalities and injuries (Ramee et al., 2021).

5.3 Marine Navigation

Low visibility is a safety concern in marine operations. When the Sahara extreme dust event "Godzilla" (see Section 2.1) spread over the Greater Caribbean, the Gulf of Mexico and the southern United States from Texas through Florida, between June 21-24, 2020, visibility dropped into international standard scales of low and moderate, in many locations: from the typical 10 to 30 km of visibility to 5 and 7 km. Boat and ship captains risk disorientation, as do helicopter pilots, becoming a hazard to nearby vessels, moorings, and port facilities.

Strong winds and blinding dust were reported cause when the container ship, *Ever Given*, ran aground in the Suez Canal on 23 March 2021 (Mohamed, Jaganathan and Tan, 2021)—and later confirmed by the Suez Canal Authority that reported "… the accident [was] mainly due to the lack of visibility …", blinding dust accompanied by 40 knot (46 mph) winds (Van Boom and Keane, 2021). Possible human or canal-ship hydrodynamic roles in the accident had been investigated also (Raghaven, Taylor and Mellen, 2021). The ship blocked international trade for six days before being freed on 29 March. Estimates show a multi-billion-Euro consequence in fines, lost and delayed international trade and efforts to release the *Ever Given.* A day prior to the grounding of the ship, a 72-hour prediction of the dust storm and the weather conditions that caused it was publicly available at the WMO SDS-WAS site (http://dust.aemet.es/).

5.4 Railroad safety and health

Excessive windblown dust or (more commonly) sand on railroad tracks is a safety and reliability hazard to railroads traversing desert regions (Bruno et al., 2018; Raffaele and Bruno, 2020). Western Hemisphere problems seem less severe today, but railway infrastructure in the Americas has been set back by blowing sand in the past. Examples include: extensive coastal sand dune movement hindered development of a railway in Oregon that resulted in some of the first extensive campaigns for sand dune stabilization via revegetation (Reckendorf et al., 1985); sand blown onto Southern Pacific Railroad tracks resulted in numerous derailments in the early 20th century in the Coachella Valley in the desert region of southern California (Ward, 2014); and windblown sand caused train derailments and re-routings in the US Great Plains during the protracted drought of the 1950s (Finnell, 1954).

Railroad train cars carrying ore coal, or other soil/mineral material insufficiently covered or stabilized under windy conditions can lead to aeolian entrainment of particles that blow onto areas near the tracks. Coal-carrying freight trains often trail more than 100 open coal cars that can generate fugitive coal-dust (Jaffe et al., 2015), which has been directly associated with several forms of lung disease (Schins and Borm, 1999). In a study in Vancouver, Canada, passing coal trains caused significant short-term increases in particulate matter concentrations in an adjacent residential neighborhood of up to 100 g/m^3 (Akaoka et al., 2017). The dust also represents an ecosystem health hazard to biota in proximity to the railway (Hapke et al., 2019).

6. Mitigation Measures

6.1 Observations and prediction of sand and dust storms

To mitigate harmful effects of sand and dust storms, observations, prediction, as well as early warning advisory and assessment systems are critical for regions affected by aeolian, windblown, sand and dust (Yin et al., 2005; Sprigg et al., 2008). In response to the United Nations General Assemblies (UNGA) resolution A/RES/70/195 and an appeal by the UN Secretary General, the United Nations Environment Programme (UNEP), the World Meteorological Organization and the United Nations Convention to Combat Desertification (UNCCD) conducted together a "Global Assessment of Sand and Dust Storms" (UNEP, WMO, UNCCD, 2016). The assessment report, which was recognized in UN General Assembly (UNGA) resolution A/RES/71/219, sets out proposals for consolidated and coordinated technical and policy options to respond to sand and dust storm issues. The World Meteorological Organization (WMO) was one of the first UN Agencies to address the problem. In 2007, the 15th World Meteorological Congress highlighted the importance of the problem and endorsed launching of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS). The main objective of the SDS-WAS regional centers is to facilitate research and user access to observation, assessment and forecast products—particularly for national meteorological and hydrological services—as well as to contribute to enhancement of capacity-building. The SDS-WAS project is realized under the WMO World Weather Research Programme (WWRP) and Global Atmosphere Watch (GAW) and coordinated by the SDS-WAS Steering Committee (the SC meets annually) supported by the WMO Secretariat. For development and realization of the SDS-WAS, its Science and Implementation Plan for 2015-2020 was prepared (WMO, 2015) and approved by the 17th World Meteorological Congress. The SDS-WAS Steering Committee formulates science priorities and updates the Science Implementation Plan periodically (WMO, 2020). As of 2021, more than 25 organizations provide daily global or regional dust forecasts in different geographic regions through 9 global models and more than 15 regional models that contribute to the SDS-WAS.

The WMO SDS-WAS consists of three Regional Nodes: The Northern Africa-Middle East-Europe Node (with its Center hosted by Spain), the Asia Node (its Center hosted by China) and the Pan-America Node for North, Central and South American collaboration, coordinated through the WMO Pan-America Center in Barbados, West Indies. Geographically centrally located for the Americas, Barbados holds the longest-running, scientific, continuous dust sampling site (55+ years at Ragged Point) that continues to provide unique information on the character and variability of trans-Atlantic crossing of Saharan dust (Prospero et al., 2021). The Cape San Juan Atmospheric Observatory managed by the University of Puerto Rico - Rio Piedras Campus (a regional WMO GAW station and part of the NOAA GML Federated Aerosol Network) also provides a long record of aerosol and dust properties that goes back to 2004 (Andrews et al., 2019). The Center's Dust Regional Atmospheric Model (DREAM) and Weather Research Forecast-Chemistry (WRF-Chem) models provide hands-on educational opportunities for local university students and early warning for Saharan dust into the Americas. In 2020, a new ensemble dust prediction project was funded by the US National Aeronautics and Space Agency (NASA), in partnership with WMO SDS-WAS Pan American Center, WHO/Pan-American Health Organization, and several federal and local agencies, to provide real-time forecasts of dust storms over North America (WMO, 2021). Although air quality continues to improve in this region, the frequency of high-impact extreme events, such as dust storms and wildland fires, has increased rapidly in the past decades and is projected to rise further in response to climate change. This ensemble forecast system will leverage two operational/research programs: the National Air Quality Forecast Capability (NAQFC) and the International Cooperative for Aerosol Prediction (ICAP). There is a plan to include more model predictions in the future. Furthermore, this project will work with stakeholders to prepare customized data packages for three applications: 1) producing air quality metrics for the City Health Dashboard, a health initiative serving 750 largest US cities; 2) providing real-time ensemble dust prediction as a pilot project WMO Pan-American SDS-WAS node and 3) working with WHO/Pan-American Health Organization (PAHO) to provide prediction and observations of wildfires and air quality to its member countries (WMO, 2021).

Dust aerosols from the African continent (mainly the Sahara and the Sahel) contribute to an increase in seasonal respiratory health problems with associated morbidity and mortality in the Caribbean region (Gyan et al., 2005; Akpinar-Elci et al., 2015; Cadelis et al., 2015; Lillianne et al. 2019). At present, Puerto Rico and other small islands in the Caribbean region lack the capability to provide air pollutant assessments, either in near real-time or forecast mode. The NWS National Air Quality Forecast Capability (NAQFC) is responsible for developing and implementing operational air quality forecast guidance for the United States. The current operational predictions include ozone, smoke, dust, and PM_{10} and $PM_{2.5}$. However, at the National Weather Service in San Juan-Puerto Rico, the Weather Field Office (WFO) lacks resources for air quality monitoring. Therefore, since 2018 a multidisciplinary team of universities, agencies and non-governmental organizations located in the Caribbean region are characterizing the periodic trans-Atlantic dispersal of African dust and its impacts on the health of people in small island states (SIS) of the region. This initiative is led by the University of Puerto Rico-Medical Sciences Campus, Environmental Health Department and funded by NASA's Applied Sciences Health and Air Quality program. The team is co-designing this new tool in collaboration with NOAA-AOML (NOAA-Coastwatch) and the Caribbean Coastal and Ocean Observing System (CARICOOS) providing essential information to decision makers and agencies.

6.2 Soil conservation efforts

Hugh Hammond Bennett, the progenitor of soil conservation, used the dust cloud emanating from a 'black blizzard' dust storm in the North American Great Plains during the Dust Bowl to convince the Congress of the United States to create the Soil Conservation Service, now the USDA Natural Resources Conservation Service, over 80 years ago. Regardless of new technologies developed by this government agency, localized dust emissions from the soil surface still happen (Ravi et al., 2011; Hand et al., 2017; Kandakji et al., 2020).

Dust created by anthropogenic activity is, of course, not just an American problem. It affects all continents (Marx et al., 2014), as witnessed by measurement of desert dust chemistry and deposition rates into alpine and Antarctic environments. This technique has also been used in the US to document the consequences of westward migration of agricultural and industrial activity in the 1800s (Neff et al., 2008) and recent dust increases (Ballantyne et al., 2011). Increasing pressure on the landscape from anthropogenic and climatic stressors is expected to increase wind erosion and dust emissions in the future (Duniway et al., 2019). Although anthropogenic impacts can be mitigated by conservation management, climatic stressors are more difficult to control and are postulated as the primary reason for recent increases of dust in the western United States (Achakuwisut et al., 2017; 2018; 2019). Long-term drought along with the expansion of agricultural activity coupled with inappropriate land management has been credited with the creation of the Dust Bowl in the North American Great Plains in the 1930s (Cunfer, 2011; Lee and Gill, 2015; Bolles et al., 2019) and a recent multi-year drought in southern California is resulting in degradation of ecosystem and soil health (Warter et al., 2021).

Conventional crop production involves tillage of the soil, with resulting loss of vegetative cover and a bare soil surface susceptible to wind erosion. Vegetation controls wind erosion by anchoring the surface with roots and residues and by modifying the force of wind striking the surface (Li et al., 2007; Mayaud et al., 2016). The understanding that soil properties, vegetative cover, and wind speed control soil erosion and dust emissions has led to creation of computer models to predict wind erosion. These can be used to compare potential rates of erosion and dust emissions with different management policies (Feng and Sharratt, 2007a,b; Pierre et al., 2014). For example, conservation tillage such as reduced tillage and no-tillage can effectively control wind erosion and dust emission (Ervin and Lee, 1994; Thorne et al., 2003; Bewick et al., 2008; Kennedy and Wilson, 2009; Van Pelt et al., 2017a; Lin et al., 2021), even though intrinsic soil erodibility and dust emissivity may increase under such systems (Van Pelt et al., 2013). In areas with degraded soil resources, conservation tillage may restore soil productivity through trapping of ambient dust and sequestration of soil carbon (Lahmar et al., 2012; Li et al., 2014; Schlatter et al., 2018), however the simple addition of biosolids has little or no effect on the intrinsic soil erodibility (Pi et al., 2018).

The increase of dust in the western US cannot be entirely attributed to crop production, as most of the land remains in native plant communities used for grazing (Duniway et al., 2019). Grazing reduces vegetative cover and, if grazing exceeds the ability of the ecosystem to replace the biomass, the vegetation community is damaged. Grazing has been credited with increased atmospheric dust loading (Neff et al., 2008) through damage to vegetation and soil crusts (Belnap et al., 2009; Baddock et al., 2011) and may account for 92-93% of the total dust load (Nauman et al., 2018). Reducing stocking rates can mitigate the grazing effects on surface erodibility (Aubault et al., 2015). Other anthropogenic disturbances such as residential construction, industrial development, and excessive water use also increase atmospheric dust loading (Frie et al., 2019). Both physical (Klose et al., 2019) and biological soil surface crusts (Pointing and Belnap, 2014) reduce dust emissions, while fire removes vegetative cover, which increases susceptibility of the soil surface to wind erosion and dust emission (Sankey et al., 2009; Van Pelt et al., 2017b). Recent attempts to reduce wind erosion and dust emissions in areas experiencing desertification have proven effective where land has been retired from production (Wei et al., 2020). Restoration of the soil ecosystem by establishing biological crusts (Chiquoine et al., 2016), planting a species mix that will persist on the landscape (Butterfield et al., 2017), and removal of invasive shrub species (Havrilla et al., 2017) is shown to reduce erosion and dust emissions. Post-fire restoration is more difficult and restorative treatments may exacerbate short-term dust emissions by disturbing the soil (Miller et al., 2012; Duniway et al., 2015) before vegetative cover is restored. Time and rainfall infiltration are soils' ultimate healers.

6.3 Dust mitigation for transportation

Mitigation of the dust safety hazard on highways may be accomplished by any method of wind erosion control to reduce particulate emission from nearby "hotspots". Such efforts have been implemented by state transportation agencies in Arizona (in the Phoenix-Tucson corridor) and New Mexico (at Lordsburg Playa). Highways in dust-prone regions may be extensively re-engineered to reduce risks. The reworking of a 16-km stretch of Interstate 10 near Casa Grande, Arizona began in 2016 at a cost of at least $72 million (Larson, 2020). A recent multi-million-dollar project on Interstate 10 between Tucson and Phoenix, a 'hot spot' for windblown dust-related accidents, is intended to warn motorists of blinding dust potential (Arizona Department of Transportation, 2019). Dust, weather and visibility sensors, closed-circuit cameras, and an X-band radar were installed adjacent to the highway. Vehicle sensors were embedded in the roadway. When conditions degrade, overhead message boards display warnings, and the speed limit is reduced. The system began full operation during summer 2020. Roadways can be closed or highway patrol vehicles may slow and guide convoys of motorists through dust-prone areas when dust is predicted or observed, but doing so causes traffic congestion, delays in delivery of goods or services, increases costs for public safety agencies, and may lead to crashes elsewhere and damage to secondary roads if motorists seek other routes to bypass a closed stretch of highway.

An alternative, often complementary, approach to reduce dust-related motor vehicle crashes is to educate and inform motorists to consider avoiding travel during dust storms but, if they must take to the road, provide them information on how to do so safely. The USA National Weather Service began distributing a "Dust Storm Driving Safety" pamphlet in 1982 (NOAA, 1982). In it, drivers were advised to never stop on the pavement, to pull off the roadway, turn off headlights and take feet off the brake. In some cases, vehicles approaching from the rear have been guided by the advance car's lights, even off the roadway, and triggered a collision with the parked vehicle (Novlan et al., 2007). If conditions prevent pulling off the road, the pamphlet advises motorists to proceed at reduced speed with lights on, using the center line as a guide. These guidelines prevail still, as in 2012, the Arizona Department of Transportation began the campaign, "Pull Aside, Stay Alive" (Reid et al., 2015).

Mitigation of aircraft brownout hazard has included field-based (Gillies et al., 2010) and numerical modeling (Jasion and Shrimpton, 2012) to understand brownout intensity and duration—a function of aircraft type and design (Ghosh and Rajagopalan, 2021), engine configuration and characteristics (Vulpio et al., 2021), land surface conditions and pilot education (McDonald, 2013), and development of sensors and engineering controls that would avoid or overcome the phenomenon (summarized, for example, in Shimkin et al., 2020). Cognitive training of pilots may also increase their situational awareness in brownout conditions and reduce the hazard (Innes et al., 2021).

6.4 Valley fever surveillance

While the pathogenic fungus *Coccidioides* is known to be endemic throughout hot and arid regions in the Americas, public health surveillance for this disease is limited to the United States. Coccidioidomycosis has been included on the Nationally Notifiable Disease Surveillance (NNDS) list since 1985 (Benedict et al., 2019). In the U.S. approximately 15,000 cases are reported to public health annually from 26 States currently, with nearly 95% of the cases coming from Arizona and California. This surveillance is conducted by mandatory reporting of positive laboratory results to public health authorities and may also be interviewed for compatible symptoms, typically in low endemic or non-endemic states with much lower-case burdens. Valley fever cases in the U.S. have increased drastically in the last decade. Reported cases of Valley fever reached a record high of 22,634 in 2011, and, after a decline to 8,232 in 2014, increased to 15,611 cases in 2018. (Benedict et al., 2019; Sondermeyer Cooksey et al., 2020). While the reasons for this recent increase are not completely understood, it has been postulated that increased awareness and improved diagnostics, rising temperatures, severe droughts, and increased urbanization have played important roles (Colson et. al., 2014; Pearson et. al. 2019). In 2019, the number of cases quickly reached the levels near 2011, with Arizona and California alone reporting 19,362 cases (CDC, 2021). The reasons for annual variability are not fully understood but are thought to be related to a number of factors, including preceding period of precipitation patterns and related soil moisture followed by a dry period to increase dust emissions (Stacy et al., 2012; Tamerius et al., 2011; Coopersmith et al., 2018).

Although coccidioidomycosis causes a substantial amount of morbidity, the mortality is relatively low. In the U.S. there are approximately 200 Coccidioidomycosis-related deaths each year, from primary or contributing causes listed on death certificates. However, one study in Arizona found this may be an underreported cause of death and the true burden could be at least twofold higher (Jones et al., 2018). Studies have created vulnerability maps of areas and populations at higher risk of severe forms of Coccidioidomycosis (Shriber et al. 2017). Results from these types of studies can only identify locations of greater concern based on social demographic variables and do not map actual distribution.

A national surveillance system allows systematic reporting and collection of burden of disease and geographic distribution. Some of the most extensive understanding of the impact of Valley fever have come from epidemiological studies from Arizona and California (Tsang et al., 2010; Sondermeyer Cooksey et al., 2019). Investigations into some of low and non-endemic states showed a similar spectrum of disease and long delays in diagnosis (Benedict et. al 2018). A major limitation of all these studies is reliance on using person-case data, which is linked to the cases of home residence to assess the ecological distribution and range of this fungus. In areas of newly endemic regions there have been surveillance efforts that go beyond the standard case-based laboratory reporting. Following the initial discovery of three Valley fever cases that were locally-acquired in south-central Washington State, public health agencies employed several alternative surveillance efforts including: 1) using domestic animal serology testing to examine Valley fever in pets (Chow et al 2017); 2) performing genomic sequencing of human specimens to identify cases that were locally-acquired or from travel (Oltean et al 2019); 3) conducting targeted soil sampling around human and animal cases for suspected exposure in order to better understand the extent of geographic distribution in this area (Marsden-Haug et al., 2012; Litvintseva et al., 2015). Predictive modeling studies based on climatic variables have estimated expansion of distributions both north and central in the United States (Gorris et al., 2018; Gorris et al., 2019). These trends have also been shown in models that included environmental factors (Weaver et al., 2020).

Further work and technologies to detect the fungus itself directly in the environment can allow more opportunities to conduct environmental surveillance over time in the air (Chow et al., 2016; Bowers et al, 2018). A recent proof of concept for air sampling directly for the fungus that causes Valley fever shows the potential for added value routine air monitoring to improve surveillance (Gade et al 2020). As soil habitat niche models have improved there is opportunity to develop predictive systems to track dust emissions from soils that are likely habitat of *Coccidioides* spp. (Sprigg et al., 2014). Ideally, prediction and prediction of future environmental and climatic conditions that may increase disease prevalence would be ideal for assisting public health and healthcare professionals in preparing for outbreak seasons.

7. Global Implications and Research/Operation Gaps

Dust affects human health and safety and the environment in all continents, as witnessed by observations of desert dust deposition into oceans, alpine, and Antarctic environments (McConnell et al., 2007; Gabriele et al., 2011; Marx et al., 2014). Many of the dust effects found in the Pan-American region also exist in other parts of the world. Figure 4 provides a graphical summary of documented or anecdotally reported health and safety effects discussed in the current study. Among these risks, Valley fever infection is the only one endemic to the Pan-American region. Similar infectious diseases caused by dust-borne microorganisms, such as Meningitis and Rift Valley fever, however, have been reported in Africa, Asia, western Europe, and Middle East (Kellogg and Griffin, 2006; García-Pando et al., 2014; Jost et al., 2010). Cyanobacteria, ubiquitous in surface crusts of desert soils and playa sediments which are widely wind-erodible, produce a wide variety of cyanotoxins which are hazardous to humans and animals, being inflammatory agents, tumor promoters, and causing liver damage (Powell et al., 2015). Wiśniewska et al. (2019) reviewed the presence of cyanobacteria in aerosols and their potential human and ecosystem health effects. Metcalf et al. (2012) calculated that dust storms could lead to inhalation of a sufficient quantity of cyanotoxins to exceed the tolerable daily intake to avoid tumor production. Aerosolized influenza viruses were detected at a higher frequency when Asian dust was present over Taiwan than when it was not (Chen et al. 2010). Similarly, scientists in Tenerife, Spain noted that they were more likely to detect human enteric viruses in the atmosphere when North African dust was present in the atmosphere than when it was not (Gonzalez-Martin 2018). Although the Foot-and-Mouth disease virus has not been isolated from the atmosphere to date, outbreaks have been noted in livestock populations following Asian dust events that affect Korea and Japan (Joo et al. 2002; Sakamoto and Yoshida 2002; Ozawa et al., 2001; Maki 2012). Bacteriophage whose genomes may harbor virulence genes such as those that enable toxin production and antibiotic resistance, may be transported within the genomes of dust storm bacteria resulting in the transfer of these genes to other microorganisms in downwind environments (Teigell-Perez 2019).

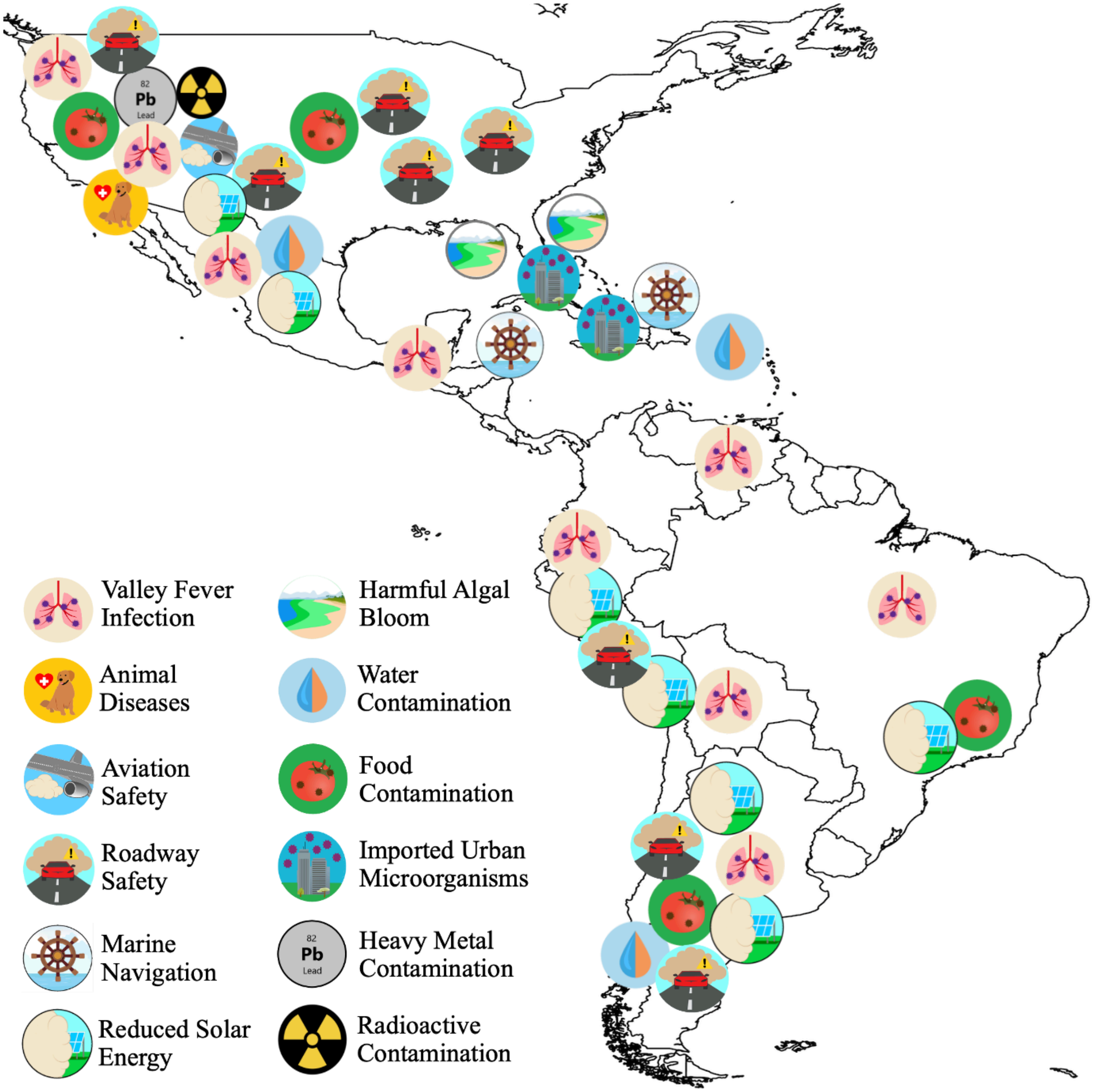

Figure 4. Summary of health and safety effects of airborne dust in the Pan-American region.

Besides microbial infections, there are more than 100 studies, most in Asia, Europe, Middle East, and Australia, that yield quantitative results of the human mortality effects of desert dust particles and exposures (for example, Karanasiou et al., 2012; De Longueville et al., 2013; Zhang et al., 2016; Hashizume et al., 2020). These studies cover a range of particle sizes, population age groups, geographical areas, and different health endpoints, such as total mortality, respiratory mortality, circulatory mortality, cardiovascular mortality and cerebrovascular mortality. Most of these studies found evidence that dust storms and mortality are linked, usually expressed as % risk per 10 µg/m^3 PM$_{10}$ concentration. In comparison, such quantitative risk assessment is either nonexistent or limited to a single area in the Americas. The nationwide study in the U.S. by Crooks et al. (2016) did not provide the relative risk to PM$_{10}$ concentration—the NWS Storm Data used do not include such information. In addition, the Storm Data set is known to be an incomplete collection of dust storms due to a lack of consistent reporting mechanisms. Long-term dust climatology, such as those reconstructed using surface measurements (Tong et al., 2012, 2017; Lei et al., 2016; Hand et al., 2017), can support future epidemiological studies to fill the knowledge gap in this region.

Similarly, the effects of dust particles on transportation (air, road and sea) safety, and ocean and terrestrial ecosystems are also global and found across the world (Griffin and Kellogg, 2004; Middleton, 2020). This has led to active mitigation efforts along railway lines, most evident in China (Shi et al., 2020) and Iran (Mehdipour and Baniamerian, 2019). Visibility loss and dust melting on engines pose threats to aviation globally. On April 1, 2015, for example, Doha, Qatar experienced an extreme dust storm with measured PM$_{10}$ concentrations exceeding 1,000,000 g/m^3. Most of dust models at the Barcelona SDS-WAS successfully predicted the incoming episode. The intensity of the event qualified it to be included in the Rolls-Royce "Duration of exposure versus ash concentration (DEvAC)" chart (Lekki et a., 2017). Over the last 20 years, there have been more than 150 recorded cases with engine power-loss and damage caused by tiny cloud ice crystals. Nickovic and Cvetkovic (2019) examined two aircraft accidents, the June 2009 Air France flight (AF477) and the July 2014Air Algérie flight (AH5017), for which icing linked to convective weather conditions has been officially reported as the most likely reason for catastrophic consequences. Using a coupled atmosphere-dust model with an included parameterization for ice nucleation triggered by dust aerosols, they showed that the predicted ice particle number sharply increases at approximate locations and times of accidents where desert dust was brought up by convective circulation (Nickovic and Cvetkovic, 2019) (Figure 5).

Figure 5. Dust storm and melting on aircraft engines during a dust storm on April 1, 2015 in Doha, Qatar: (left) the storm observed by NASA Aqua satellite; (center) reduced visibility in the city (red dot in the left panel); (right) predicted melting intensity for the Doha, Qatar episode from Nickovic and Cvetkovic (2019).

Despite considerable progress, large gaps remain in the knowledge of dust and the risks it poses to the society and environment. Table 1 summarizes some of the most pressing ones related to dust effects on human and environmental health and safety, as well as dust observations and modeling research needed to fill these gaps. There is a lack of process-level understanding of the linkages between dust and its health endpoints, a global issue but even more so in the Pan-American region, and especially so in South America, where studies of health and safety effects of dust are extremely lacking. The information of dust composition, including viable dust-borne microorganisms that cause Valley fever among humans and animals, is critical to understand the full health effects of dust particles. Such knowledge is also critical to understand the environmental effects of dust particles, including the impacts of dust deposition on marine and terrestrial biosphere productivity. On the dust risks to highway transportation safety, the detection and prediction of small-scale "killer" dust plumes adjacent to roadways represents a major challenge, which calls for new research to deploy next-generation low-cost sensors and satellites near sources at the right timing. There is also a need to document dust related highway accidents properly by transportation and public safety agencies. Improved coding is required to better represennt weather conditions, such as using explicitly "blowing dust/dust" instead of "wind" if soil dust becomes airborne and impairs visibility. For all of these risks, better coordination and communication are needed to improve public awareness of dust hazard, and to transition research capabilities into health and safety application operations.

Table 1. Summary of current gaps and needs and recommendations for future work in dust research and services in the Pan-American region and beyond.

Gaps/Needs	**Recommended Future Work**

Human Health	
. The cause-effect between dust and health outcomes is still lacking; 2. Knowledge of composition and health effects of dust-borne microorganisms is still limited; 3. Need for operational links between dust observations, model prediction, and public health advisories. 4. The design of epidemiological studies to clearly identify exposure to desert dust. 5. Long-term studies are lacking. 6. Studies in South America are lacking 7. Public awareness of dust health risks may be too low.	. Transdisciplinary studies on cause-effect relationships between dust and disease burden. 2. Low-cost, mobile, and accurate measurements of dust composition, including dust-borne microbes during emission and atmospheric transport. 3. Better collaboration and communication to improve public awareness of dust hazard risk. 4. Standardized modelling of desert dust exposure should be used. 5. Studies on long-term effects, such as cohort studies, are needed. 6. Increased encouragement and funding of dust health endpoint research in South America are needed. 7. Increase publicity and outreach to raise community awareness of dust health hazards, especially in vulnerable communities, and for vulnerable groups (children, elderly, persons with respiratory conditions).
Environmental Health	
. Assessment of actual microbe transmission through dust still lacking; 2. The impact of dust deposition on marine and terrestrial biosphere productivity poorly constrained.	. Valley fever surveillance among animals and marine mammals; dust data for risk assessment; 2. Routine quantification of metals and nutrient content in dust samples in addition to solubility/ bioavailability measurements. Quantitative studies of ecosystem-scale response to dust deposition.
Safety	

. Detection of small-scale dust plumes adjacent to highways is difficult; 2. Dust-associated highway accidents not properly recorded in highway crash/ public safety data (e.g., listed as “wind”). 3. Citizen awareness of/response to dust forecasts/warnings by meteorological and air quality agencies may be lacking, and the public may not know proper actions to take to avoid dust safety and health hazards. 4. Dust hazard prediction for ground transportation and aviation is challenging.	. Improved remote sensing; low-cost sensor deployment; improved data access/utilization; 2. Improved coding needed of actual weather associated with road accidents; 3. Increase public awareness of dust hazard; awareness campaigns such as “Pull Aside, Stay Alive,” provide informational materials at locations such as highway rest areas, automobile rental facilities, and through news media and social media; add dust-related driving safety questions to defensive driving courses and driver licensing examinations. 4. Improved dust prediction products and routine utilization in safety applications;
Dust Observations (In-situ and Remote Sensing)	

. Lack of routine ground-based measurements near dust sources and along transport pathways away from urban centers and protected areas 2. Lack of high-resolution source maps; 3. Low density of in-situ dust monitoring in South America. 4. Missing key remote sensing capabilities missing, including dust particle optical properties not well known; overpass times for polar orbiting instruments not ideal for dust detection; nighttime and below-cloud dust not well detected with remote sensing; satellite imager resolution not high enough to detect high-risk small events; 5. In situ measurements of particle dynamics (emission, transport, chemical evolution, and in-cloud processes) are very limited.	. Plan and sustain ground-based measurement sites near likely sources, along transport pathways and rural receptor communities, not just large population centers and protected areas (national parks, wilderness areas). 2. Regional and global dust source maps with high spatial and temporal resolutions. 3. Increase support for dust observation networks and studies in South America. 4. Future satellite missions with coverage during peak dust hours, better detection at night and below cloud, and detection of dust chemistry/mineralogy/optical properties; new sensors and new technologies such as CubeSats for dust detection at much finer spatial scales. 5. Near-source and transport path dust measurements, laboratory analysis, theoretical calculation of extinction and scattering properties to improve dust optical models used in remote-sensing retrievals.
Modelling and Forecasting	
. Downscaling capability for dust prediction and early warning from global to regional and local scales still lacking for specific regions/areas of the Americas; 2. Assimilation of available satellite, lidar/ceilometer and in-situ dust observations not regularly used by dust forecast models; 3. Small-scale variations in soil characteristics, vegetation, land use and topography cause errors in parameterizing surface shear stress threshold in dust emission models;	. Closer collaboration of NOAA, NCAR, NASA and NRL global modelling facilities with the WMO SDS-WAS Pan-American Node. 2. Coordinated international efforts combining ground-based observations with Earth Observation data and dust prediction models. 3. Stochastic models and turbulence-resolving numerical simulations, such as large-eddy simulation, can provide greater understanding of the turbulent transport of dust and sand;

8. Conclusion

This work reviews the current understanding of and gaps in the health and safety effects of airborne soil particles, commonly referred to as dust, with a focus on the Pan-American region. The current knowledge of dust risks, especially in the Americas, is rather fragmented and based largely upon anecdotal, regional studies and reports. The gap between the knowledge pool and public awareness can be costly or even deadly for the affected communities. Dust in the Americas has been associated with unique health and safety effects, mostly notably *Coccidioidomycosis* or Valley fever, a fungal infection that has spread to many parts of the region with an annual health burden in the order of billions of dollars. Besides human health, dust also affects environmental health through providing nutrients to increase phytoplankton biomass, contaminating water supplies, soil, and food (crops/fruits/vegetables and ready-to-eat meat), spreading crop pathogens, pests, and unintended herbicides and pesticides, causing Valley fever among domestic and wild animals and livestock, transporting heavy metals, radionuclides, and other contaminant compounds, and reducing solar power generation. Dust is also a well-documented hazard to road transportation, aviation and marine navigation, in particular in the southwestern US where blowing dust is one of the deadliest weather hazards. Projected climate change is expected to amplify the health and economic burdens of dust in some parts of the Pan-American region, making it critical to develop effective measures to mitigate these harmful effects. Current efforts include regional and international collaborations to enhance dust observations and prediction capability, implementing soil conservation measures, designing specific dust mitigation and public awareness projects for transportation safety, and conducting Valley fever surveillance. While this work emphasizes on the Pan-American region, many of the dust effects found in this region also exist in other parts of the world.

Gaps in knowledge remain in critical understanding the dust risks to human and environmental health and safety. Among the most pressing issues is a lack of process-level understanding of the linkages between dust and its health endpoints, including the prevailing Valley fever among humans and animals. Furthermore, operational links between dust observations, dust prediction, and public health /safety advisories are still missing, even more so in South America than North America and the Caribbean. Another significant challenge of mitigating dust effects is the inability of satellites, models and surface-based monitoring networks to observe and predict small-scale dust events that are responsible for the majority of fatal accidents. To address these challenges, it is important to advance dust research through both observations and modeling, to provide the needed capability for implementing mitigation measures.

Finally, it is important to engage in capacity building in the affected communities, particularly in regions with fewer resources, through collaborative frameworks such as the WMO Sand and Dust Storm Warning and Advisory System (SDS-WAS) and the Pan-American Health Organization (PAHO). This review provides a major update and overview of dust activity and its effects in South America, a region of the world that has been largely overlooked in global dust assessments. Through the preparation of this report, it became clear there is a general dearth of dust studies in the region as the missing sectors (e.g., Figure 4). However, many of these sectors are known at least from anecdotal records to be dust producers and many cases near major metropolitan areas. For example, the shores of the Parapetí and San Juan rivers in Bolivia are very active at the end of the austral winter in a largely rural region for which no health impacts in the local population are on record. Inspection of social media reports show the presence of haboobs in the agricultural areas within 100 km from the megalopolis of Sao Pablo, Brazil or major dust clouds arriving to the city of Comodoro Rivadavia (Argentina), located hundred km downwind from the Colhué Huapi dry lake. To the extent of our research, no epidemiological studies are on record investigating the health impact of these recurrent events. Therefore, it is imperative to improve surveillance network and carry survey studies in major swaths of the region away from metropolitan areas as several indirect pieces of information are indicating that dust activity in the region is much larger than previously estimated. Whether these regional efforts succeed will depend on the successes and failures of local and regional policies and interdisciplinary social and environmental science (Sprigg and Steinberg, 2016).

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Data Availability Statement

The dust source data are available from UNCCD Sand and Dust Storms Source Base-map, aviable at https://maps.unccd.int/sds/. The biographical distribution data of *Coccidioides* are taken from Barker et al. (2019). Dust simulation data during the Doha, Qatar dust event are from Nickovic and Cvetkovic (2019).

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