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Key Points:

- Human exposure to dust has been associated with adverse health effects, including asthma, fungal infections, and premature death
- Dust provides nutrients to ecosystems, pollutes water and food, spreads pathogens and radionuclides, and reduces solar generation
- Dust is a major safety hazard to road transportation, aviation, and marine navigation

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

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Abstract Risks associated with dust hazards are often underappreciated, a gap between the knowledge pool and public awareness that can be costly for impacted communities. This study reviews the emission sources and chemical, physical, and biological characteristics of airborne soil particles (dust) and their effects on human and environmental health and safety in the Pan-American region. American dust originates from both local sources (western United States, northern Mexico, Peru, Bolivia, Chile, and Argentina) and long-range transport from Africa and Asia. Dust properties, as well as the trends and interactions with criteria air pollutants, are summarized. Human exposure to dust is associated with adverse health effects, including asthma, allergies, fungal infections, and premature death. In the Americas, a well-documented and striking effect of soil dust is its association with Coccidioidomycosis, commonly known as Valley fever, an infection caused by inhalation of soil-dwelling fungi unique to this region. Besides human health, dust affects environmental health through nutrients that increase phytoplankton biomass, contaminants that diminish water supply and affect food (crops/fruits/vegetables and ready-to-eat meat), spread crop and marine pathogens, cause Valley fever among domestic and wild animals, transport heavy metals, radionuclides and microplastics, and reduce solar and wind power generation. Dust is also a safety hazard to road transportation and aviation, in the southwestern US where blowing dust is one of the deadliest weather hazards. To mitigate the harmful effects, coordinated regional and international efforts are needed to enhance dust observations and prediction capabilities, soil conservation measures, and Valley fever and other disease surveillance.

Plain Language Summary Soil particles suspended in the air, commonly known as dust, impose substantial risks to many sectors of 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

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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, microplastics, heavy metals and radionuclides, and reducing solar and wind 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 aeolian processes (wind erosion), 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 categories 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 stimulate marine and terrestrial productivity, as in the Amazon Basin (Barkley et al., 2019; Goudie & Middleton, 2006; Knippertz & Stuut, 2014; Mills et al., 2004; Prospero et al., 2020; Yu et al., 2015). However, exposure to dust particles is associated with adverse health effects (World Health Organization, 2021), in particular, cardiovascular mortality (Crooks et al., 2016) and respiratory diseases (Tobias et al., 2019) including asthma (Kanatani et al., 2010), and health effects such as Valley fever (Coccidioidomycosis), an infection caused by inhalation of soil-dwelling fungi believed unique to the Americas. The Valley fever disease is partly under scrutiny because of its mysterious spread—the US Centers for Disease Control and Prevention (CDC) reports that incidence rates of Valley fever increased by 800% between 1998 and 2011 (CDC, 2013)—in the same regions frequently impacted by dust storms (Tong et al., 2017). Dust storm frequency and Valley fever incidences are strongly correlated, more so than other known factors, in two major endemic centers, Maricopa and Pima Counties of Arizona in the US Southwest (Tong et al., 2017, 2022). Outside the US Southwest, the information of Valley fever incidence rates or trends is limited and incomplete, since regular reporting systems are not in place (Hector & Laniado-Laborin, 2005; Sarafoglou et al., 2020).

The socioeconomic impacts of dust storms extend beyond public health consequences. Dust storms are well known ground transportation safety hazards (Ashley et al., 2015; Lader et al., 2016; J. Li, Kandakji, et al., 2018; Van Pelt, Tatarko, et al., 2020). Behind extreme heat and flooding, windblown dust is the third largest cause of weather-related fatalities in Arizona, where 157 people have died and 1,324 were injured in dust-caused accidents between 1955 and 2011 (Lader et al., 2016). Small, short-lived, and local-scale dust storms are responsible for most fatal dust-related highway accidents but are notoriously difficult to detect and predict (Lader et al., 2016). Regarding air transportation, dust is a hazard and growing concern in both military and civilian aviation (Baddock et al., 2013). Dust storms reduce the recreational values of landscapes (Hand et al., 2016), decrease the performance of solar and wind power plants (Polo & Estalayo, 2015), and spread agricultural (Gonzalez-Martin et al., 2014) and human pathogens (Goudie, 2014), all of which harm local and regional economies. Loss through wind and water erosion 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 and adjustments in land and water use practices (Bell et al., 2016). In the 1930s, the United States (US) experienced one of the worst environmental catastrophes in its history, the "Dust Bowl," a period of many large dust storms caused by extended drought, high winds, and poor land management (J. A. Lee & Gill, 2015). Dust storms buried farms and forced hundreds of thousands of farmers to abandon their homes and 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. The Dust Bowl greatly amplified the human health effects of windblown soil dust. Brown et al. (1935) carried out in Kansas the first US public health study of dust storms, concluding 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" was coined (Gates, 1938) to reference the dreaded and mysterious respiratory illness to which many persons living through the Dust Bowl were exposed: "dust bronchitis" entered the medical literature as a related and perhaps more appropriate condition (Toomey & Petersilge, 1944). More recently, "haboob lung syndrome" was discovered and named 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 foresee a drying trend in the late 21st century over the subtropics (Cook et al., 2015; Prein et al., 2016; Schubert et al., 2004; Seager et al., 2007). This 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) project that dust activity will decrease in the northern Great Plains but increase in the southern Great Plains in the coming decades over North America. Further, water use practices have diverted water away from lakes and rivers, drying out these water bodies, which leads to increased dust production from now-dry lake beds, with Owens (dry) Lake in California being one of the best-known examples in the Americas (J. Wang et al., 2018). Desiccated by water diversion to Los Angeles, Owens (dry) Lake has long produced substantial levels of particulate matter that often exceed air quality standards set by the US Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (NAAQS) (Cahill et al., 1996). Similar desiccation of the Salton Sea and Great Salt Lake is underway, along with expected increased dust emissions from these drying lake beds (Goodman et al., 2019). In addition to raising PM to unhealthy levels, dust emissions also impact budgets of gaseous criteria air pollutants including ozone (Dentener et al., 1996; Usher et al., 2003). Besides local sources, the Pan-America 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, risks associated with dust hazards are often underappreciated (Middleton, 2018, 2020), particularly so in the Americas. Compared to regions in the "Global Dust Belt" with major dust sources (Africa, the Middle East and Asia), the Americas, and especially South America, have received less attention in global dust studies. The body of knowledge of windblown dust of the Americas is 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 (WMO) formed the international Sand and Dust Storm Warning Advisory and Assessment 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). Key national and inter-governmental public health and climate assessments neither mention nor adequately discuss dust hazards. 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 US, even though the first known case was reported in Argentina in 1892 and coccidioidomycosis has been found across Mexico into 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, and gaps in knowledge are identified for future research and public health and safety policy making for the region. Second, we consolidate scattered information into an inventory so that researchers and policy makers can better comprehend the global, regional and local context for dust as a health and safety hazard. Section 2 reviews the local and remote sources of dust and its chemical, physical, and biological characteristics. The effects of dust on human and environmental health are presented in Sections 3 and 4, respectively. The safety concerns of dust are addressed in Section 5. Other critical issues are discussed in Section 6. In Section 7, we summarize the measures to mitigate dust effects through early warning, soil conservation, public awareness and public health surveillance. We discuss the global effects and existing gaps in knowledge and practices in Section 8 and conclude in Section 9.

2. Dust in the Americas

Dust particles in the Americas originate from local sources (Gillette & Hanson, 1989; Ginoux et al., 2012; Prospero et al., 2002; Yin & Sprigg, 2010) and from long-range dust transport across the Atlantic and Pacific Oceans (Prospero et al., 1981, 2014, 2020, 2021; Husar et al., 2001; Raga et al., 2021; VanCuren & Cahill, 2002). 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 herein.

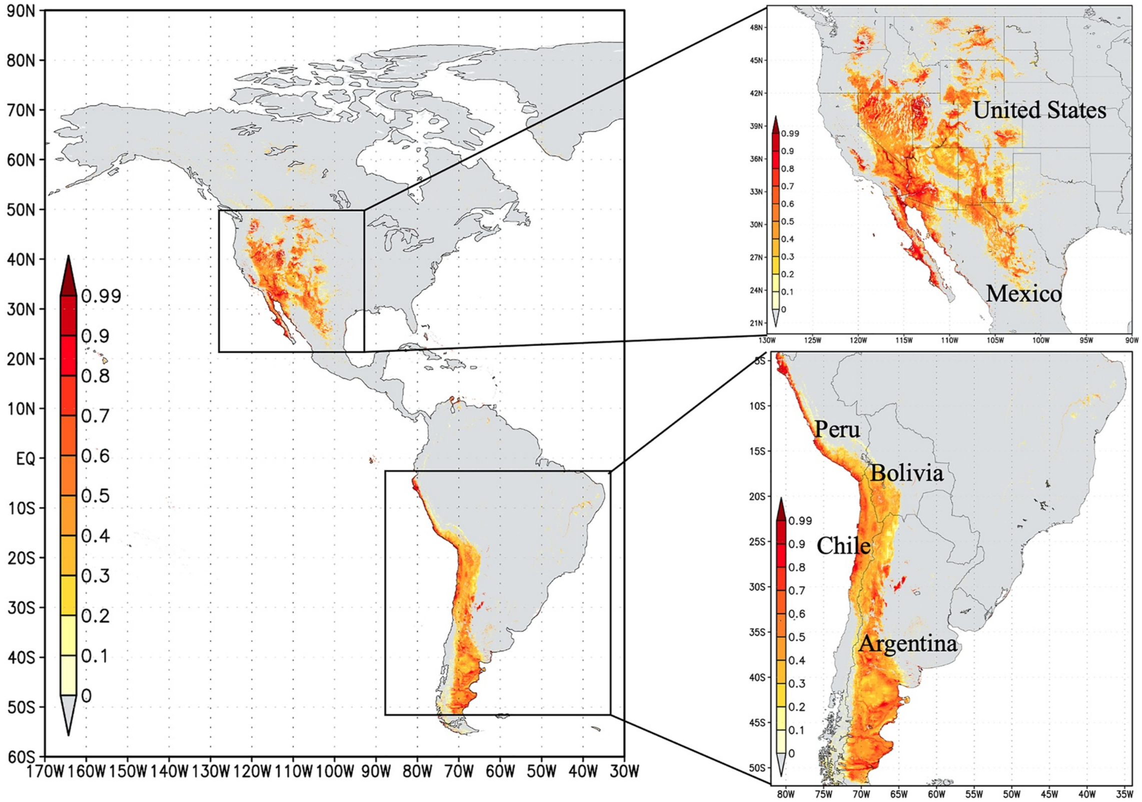

Figure 1. Present-day sand and dust storm sources across Pan-America (source: United Nations Convention to Combat Desertification, Vukovic, 2019; Vukovic Vimic, 2021). The colors represent Sand and Dust Storm Annual Index from low (0) to high intensity (1).

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 African dust transport to the Americas and the Saharan Air Layer (SAL) has been summarized by Prospero et al. (2021). An estimated average of 64 Tg of aerosols composed mainly of desert dust affects North America each year (Yu et al., 2012). Dust emitted from the Saharan desert and Sahel impacts the Americas, especially across the Caribbean, throughout the year. During boreal winter, African dust is transported primarily over the Southern Greater Caribbean and Northern South America. The more intensive dust episodes occur during boreal spring and summer over most of the Caribbean Islands, the Gulf of Mexico, and Southeastern US (Prospero & Mayol-Bracero, 2013; Prospero et al., 1981). Asian dust, especially from the Taklamakan and Gobi deserts, is emitted year-round, but the western coast of North America and the Hawaiian Islands feel greatest impact in boreal 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 and the Amazon Basin, North America and the Hawaiian Islands (Yu et al., 2019). Further, atmospheric deposition of dust has built soils, as in Bermuda and portions of Hawaii, Florida, Caribbean islands, and South America (Chadwick et al., 1999; Muhs et al., 2007; Prospero et al., 1987; Swap et al., 1992, 1996).

Although agricultural fertilization by this transported dust is considered a positive, the negative health effects are not. Dust transported from Africa frequently elevates airborne PM_{10} to unhealthy levels according to the World Health Organization (WHO, e.g., 15 μg/m^3 for 24-hr average) with measured increases of $PM_{2.5}$ in the Caribbean, parts of North America, including South Florida and Texas, and South America (Bozlaker et al., 2019; Prospero, 2001; Prospero et al., 2014). Dusts transported from Africa and Asia increase background PM concentrations that exceed acceptable levels in parts of western North America (Fischer et al., 2009), and lower air quality on the US east coast, including New England (DeBell et al., 2004). For an extreme example, the plume from a large Asian dust event traveled into North America in 1998, leaving a chemical fingerprint of deposited dust inland to the state of Minnesota (Husar et al., 2001). The "Godzilla" African dust event during 13–18 June 2020, one of the largest and strongest SAL in the past 50 years, was sufficient to increase PM to levels that allowed researchers to view the unusually strong associated environmental signatures (Pu & Jin, 2021; Yu et al., 2021). The dust plume related with the SAL was tracked in detail by geostationary and polar orbiting satellites throughout much of the episode. Typically, SAL profiles reveal an easily identified brown haze off the northwestern African coast, where the more significant events show dust that eventually dilutes, barely recognized as it propagates through the Caribbean Islands. But in the "Godzilla" case, the SAL and its associated African dust plume contained mineral quantities within the dust that acted and persisted as a tracer on its westward journey through the Greater Caribbean, Gulf of Mexico and South Central US. The plume then turned toward the Southeast US coast and back over the Atlantic basin—an estimated 10,000 km excursion.

Some content of long-range transported dust from Asia and Africa is in the form of microbes, trace metals, and other pollutants (Bozlaker et al., 2019; Prospero et al., 2005; D. J. Smith et al., 2012). While long-range transported PM and local-or regional-sourced PM concentrations in cities are comparable, the health consequences of distant sources of windblown dust lack comparable attention. Yet, anecdotal evidence exists that long-range dust events have triggered increased respiratory illness and hospitalization, which will be further discussed in Sections 2.4 and 3.5.

2.2. Pan-America-Sourced Airborne Dust

Local dust sources in the Americas generally fall into two categories: (a) natural sources from wind erosion over deserts, and (b) anthropogenic sources from soil disturbed by human and animal activities (Gillette & Passi, 1988; Ginoux et al., 2012; Prospero et al., 2002). Figure 1 represents the average intensity of dust sources that can be exposed to wind erosion in all seasons, but not necessarily with the same potential to produce sand and dust storms.

In North America, dust sources are distributed predominantly in northern Mexico and the western US. They are generally driven by convective (mesoscale) or non-convective (synoptic scale) windstorms (Novlan et al., 2007; Rivera Rivera et al., 2009). Major SDS sources in Mexico include the Baja California Peninsula (Morales-Acuña et al., 2019) and the Chihuahuan Desert (Baddock et al., 2011, 2016, 2021; Rivera Rivera et al., 2010). Large areas of the US Great Basin, Mojave Desert, Colorado Plateau, the Sonoran Desert of Arizona, the former "Dust Bowl" region in the southern High Plains, the Red River Valley of North Dakota, and northern Montana are noted for their frequent blowing dust episodes (Ravi et al., 2011). The Canadian Prairies were also known dust sources during the Dust Bowl period, due largely to the problem of anthropogenic land use, which has been improved significantly in particular since the 1990s (Fox et al., 2012). The U.S. portion of the Chihuahuan Desert, from far southeastern 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). Considerable dust is blown from dry lake beds (playas) in North America, such as the Great Salt Lake playas (Nicoll et al., 2020), the Owens lakebed in east-central California (Cahill et al., 1996; Reheis, 1997), the Salton Sea in southern California (Frie et al., 2019), 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 (Kandakji et al., 2020; J. A. Lee et al., 2012; P. Li, Liu, et al., 2018). The Columbia Plateau in the inland Pacific Northwest of the US is affected frequently by windblown dust associated with agriculture (Sharratt & Collins, 2018; Sharratt & Lauer, 2006). Abandoned fields becoming dust sources (Colson et al., 2016; Hyers & Marcus, 1981) are an economic issue in western North America with drought-limited water supply and warming climate. Dust sources may emerge from military training, extensive in the Western US (Belnap et al., 2007; Urban et al., 2018), from highway rights of way, as on the Colorado Plateau (Nauman et al., 2018) and from fine particles in mine excavations and waste piles, such as over the Tri-State Mining District of Oklahoma, Kansas and Missouri which, during extreme weather conditions, in one case contributed up to 10% of annual Pb mass flux to a lake 18 km distant from the source (J. Li & McDonald-Gillespie, 2020).

South America has five particularly large, active dust production areas: (a) the main source, the Salar de Uyuni, a large salt flat located in a closed basin in the Bolivian Altiplano (Gaiero et al., 2013; Ravi et al., 2011); (b) along the west coastal Atacama Desert extending from northern Chile to southern Peru—an occasionally (fewer than 1–3 dust events per year) active area with thick dust clouds that bring abundant dust into the equatorial South Pacific Ocean (Reyers et al., 2019); (c) an area known locally as the Arid Diagonal, from west and central Bolivia

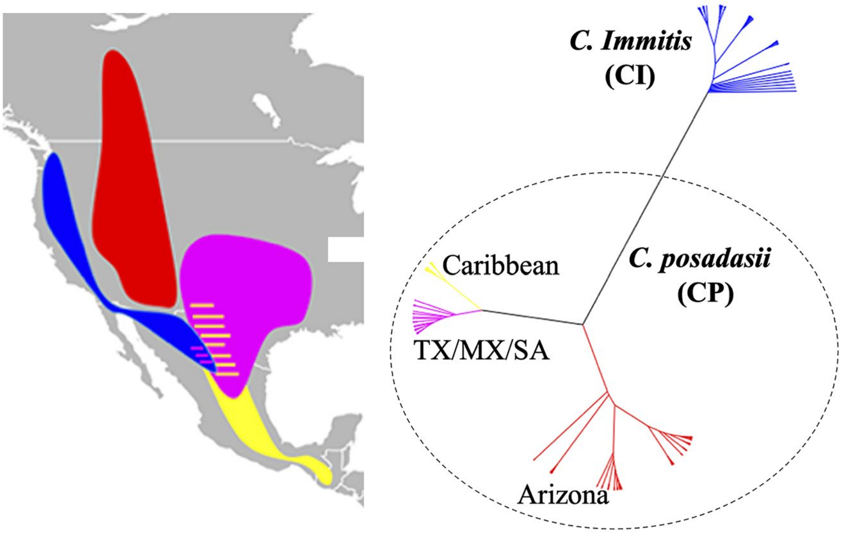

Figure 2. Biographical distribution of coccidioidomycosis patient isolates across Pan-America. (left) geographic regions of different phylogenetic lineages based on patient origin of the sequenced *Coccidioides* isolates—thus, infection location is unknown. (right) Collapsed phylogenetic tree representing 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).

into Argentina, including the lee-side of the Andes (Milana & Kröhling, 2017; Pérez-Ramírez et al., 2017); (d) the central and west side of the Las Pampas region, and (e) Argentina's Patagonian Desert, a frequent dust generator (Cosentino et al., 2019; Shao et al., 2013) that contributes dust to Antarctica (Bullard et al., 2016; McConnell et al., 2007). Some of these sources exhibit annual regularity, as with the Salar of Uyuni or the dry shores of the Río Piraí, Río Grande, Río Parapetí and Río Pilcomayo in Bolivia (May 2013). Another source, the Mar Chiquita lake in Argentina arises from large decadal water level fluctuations (Carabajal & Boy, 2021; Troin et al., 2010). Seasonality in the Patagonia region is pronounced. The most active dust source is the dry bed of lake Colhué Huapi, with abundant, thick dust clouds reported several times a year (Gassó & Torres, 2019). In general, abundant rains in winter and spring result in accumulation of sediment and wind-erodible soil to entrain in summer. Other sources in this region include riverbeds active at the end of the austral winter and tidal lakes (Gassó & Stein, 2007; Gassó et al., 2010). Important contributors to local airborne dust are the strong katabatic winds and occasional polar fronts that reach the lee of the Andes. As in North America, grazing on semiarid land appears to have increased dust deposition rates between 19th and 20th centuries (Field et al., 2011).

Satellite remote sensing observations are key to characterize the major transport paths and to establish source-receptor relationships (Baddock et al., 2021; Mahler et al., 2006; Yin et al., 2007). Broad-swath imagery, from polar-orbiting instruments such as the US National Aeronautics and Space Administration (NASA) Earth Observing System MODerate resolution Imaging Spectroradiometers (MODIS) and the National Oceanic and Atmospheric Administration (NOAA) Visible Infrared Imaging Radiometer Suite (VIIRS), offer the spatial and, to a less extent, temporal coverage needed to track major dust plumes across oceans and continents (D. Kim et al., 2019; Yu et al., 2019). Instruments in geostationary orbits, such as NOAA's Advanced Baseline Imager (ABI), may sample a region many times per hour to identify local, often small scale, dust sources otherwise obscured as a plume expands or is engulfed with other plumes. These instruments usually distinguish mineral dust from other aerosols based on source location, plume morphology and color, and/or coarse particle size. Multi-angle imaging of optical manifestations of particle shape can help identify dust (e.g., Kalashnikova & Kahn, 2006). As dust size distributions are generally dominated by super-micron particles, infrared imagers such as the Atmospheric InfraRed Sounder (AIRS) on NASA's Aqua satellite can track global dust transport (DeSouza-Machado et al., 2006). The spatial distribution of dust storm sources is illustrated in Figure 1, derived from the Sand and Dust Storms Source Base-map (https://maps.unccd.int/sds/) of the United Nations Convention to Combat Desertification (UNCCD). The map represents gridded (geo-referenced) information on the distribution, intensity and variability of sand and dust sources drawn 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 to 2018 (Vukovic, 2019; Vukovic Vimic, 2021).

2.3. Chemical and Physical Characteristics of American Dust

Dust 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 dust particle are controlled by mineral parent material, climate, time, and associated life forms (Weil & Brady, 2016). Mineral particles that make up soil are grouped into three diameter classes: sand (coarsest of the particles, 54–2000 μm in diameter), silt (2–53 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 lakebeds (playas), dust particles may be composed of the tests of aquatic metazoans and plankton (Bristow & Moller, 2018). Physical characteristics of individual dust particles are used to identify their source location (G. Wang et al., 2017).

Individual dust particles also carry a chemical signature of mineralogy, weathering products, and adsorbed surficial coatings formed during dust genesis. These natural chemical signatures can be used to identify dust source regions (Frie et al., 2019; G. Wang et al., 2017; Z. 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, Shekhter, et al., 2020). 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 (Balabanova et al., 2017; Beamer et al., 2012; J. Li & McDonald-Gillespie, 2020; Nicoll et al., 2020; Rasmussen et al., 2013; Trapp et al., 2010; Van Pelt, Shekhter, et al., 2020). As expected, anthropogenic metals in dust are more prominent in urban and industrial areas than in rural areas (Eleftheriadis & Colbeck, 2001).

Mining and smelting are primary sources of anthropogenic metals in dust. These contaminants may arise from actual mining activities to create dust, such as Ore crushing, smokestack emissions, smelting and erosion of slags (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 & Taylor, 2017; Garcia-Vargas et al., 2014; J. Li & McDonald-Gillespie, 2020; Ono et al., 2016). 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). B. Chen et al. (2016) modeled impacts on atmospheric metals from a copper smelter, and others (Garcia-Vargas et al., 2014; Van Pelt, Shekhter, et al., 2020) have documented the spread of smelter-associated soil dust—spatial patterns of contamination are determined by the distance from the smelter, dominant direction of 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; X. Wang et al., 2020).

Agricultural operations in semi-arid and arid environments are another potent dust source (Katra, 2020). Soil dust particles emitted from agriculture (mainly during tillage) can affect downwind cities (see Conen et al., 2011; Kaiser et al., 1992; O'Sullivan et al., 2014; Steinke et al., 2016). Management of these agricultural soil systems affect 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).

2.4. Biota in Dust

Microbes found in dust include algae (Tesson et al., 2016), arachaeans (Wehking et al., 2018), bacteria, viruses (Gonzalez-Martin et al., 2013), and fungi (Fröhlich-Nowoisky et al., 2012). Direct count analyses of topsoil from various desert environments show that bacterial and viral populations range from $\sim 10^3$ to 10^7 per gram (Gonzalez-Martin et al., 2013). Fungal populations typically occur at $\sim 10^6$ per gram (Karpovich-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). Many bacterial pathogens in dust storm samples have been identified 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). Cyanobacteria, ubiquitous in surface crusts of desert soils and playa sediments, produce cyanotoxins hazardous to humans and animals (Metcalf et al., 2012).

Fungi multiply by spores that can be transported on winds to new environments, their survival dependent on the time of day they are released (Lagomarsino Oneto et al., 2020). Fungal spores can be aerosolized and remain viable in biomass burning and be transported thousands of kilometers in smoke (Mims & Mims, 2004)—and viable within plumes of windblown dust (Hector et al., 2011). Elmassry et al. (2021) found significant differences in abundance and type of bacteria and fungi between calm and dust storm days in West Texas (Lubbock). Aerosolized fungi are important pathogens in the environment (see Sections 3.4 and 3.5 herein). Some fungi are potent plant pathogens (D. Kim et al., 2019) that hitchhike long distances on intercontinental dust (Toepfer et al., 2011).

Microbes have been documented to travel across and between continents attached to dust particles (Favet et al., 2013; Katra et al., 2014; Rosselli et al., 2015). Viable bacteria and fungi associated with the arrival of African dust have been reported over the US Virgin Islands and northern Caribbean (Griffin et al., 2001, 2003), with 10% of the identified microorganisms categorized as opportunistic pathogens for humans, discussed further in Section 3. 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 (Ramírez-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.

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 al., 2016). Nematodes, soil-borne plant parasites, have been documented to spread on wind-borne sediments in natural and agricultural ecosystems (de Rooij-van der Goes et al., 2014; Vanstone et al., 2008). Wind transport of soils from dried river floodplains is suspected in the spread of *Triops longicaudatus* (tadpole shrimp), a pest of wetland crops such as rice, into the US states of Missouri and Illinois (Ridings et al., 2010; Tindall et al., 2009). Insects as large as locusts have been transported across the Atlantic to the Caribbean and South America in Africa dust clouds (Rosenberg & 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 (A. D. Allen et al., 2015; Hara 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 bacteria and fungi remained viable in wind-transported dust (Azua-Bustos et al., 2019). Microbes can survive in the smoke plumes from wildland fires (Kobziar et al., 2018). They can serve as ice nucleation agents in clouds (Amato et al., 2015; O'Sullivan et al., 2016). Jenkins and Underwood (1998), on the other hand, have found transport of zooplankton by anemochory (wind dispersal of organisms) limited and unlikely over 1 year at two sites near Springfield, Illinois, US. Further research is needed to understand the environmental factors controlling dispersal of dust-borne organisms.

Transport of harmful microorganisms by dust plumes pose potentially substantial health risks in urban areas near or downwind to dust source areas. Although a body of evidence shows that soil dust particles can enhance the concentration and diversity of microorganisms in urban regions (Garrison et al., 2006; Griffin et al., 2007; Kellogg & Griffin, 2006; Kellogg et al., 2004; Schlesinger et al., 2006), 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. Medium-to-large cities in Americas and elsewhere built on or surrounded by arid or semiarid zones (Marone et al., 2020; Mazar et al., 2016) 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).

2.5. Microplastics in the Dust

Dust and windblown events play important roles in dispersion and transportation of microplastics. Microplastics, or small plastic particles and fibers (<5 mm) generated during the decomposition of mismanaged waste, have been detected ubiquitously in terrestrial, freshwater, and marine systems, as well as the atmosphere. Due to their small size, light weight, and synthetic nature, they are very susceptible to wind entrainment. A recent study showed that 98% of deposit samples from protected areas in the U.S. contained microplastics (Brahney et al., 2020). Atmospheric transport is a major pathway of microplastics to be redistributed and deposited in environments, including remote regions (Evangeliou et al., 2020), mountainous regions, and protected areas. It was estimated that the amount of plastic deposition could reach >1,000 metric tons in western U.S. protected lands annually (Brahney et al., 2020).

The sources of atmospheric microplastics include re-suspension from ground surfaces, vehicle tires, and brakes, and sea surface aerosols in marine and ocean environments are a microplastic sink (S. Allen et al., 2020; Brahney et al., 2021; Munyaneza et al., 2022). Re-emission from agricultural fields is another contribution factor as wastewater biosolids are widely used as fertilizer and plastic mulch is often added to soils to increase temperature while retaining moisture (H. Zhang et al., 2021). Dust from the biosolids-applied fields is enriched with microplastics and per- and polyfluoroalkyl substances (PFAS) (Borthakur et al., 2022). Inhalation of airborne microplastics can cause inflammation in airways and bronchi, as well as breath irritation and oxidative stress in lung tissues (Brahney et al., 2021). Moreover, chronic exposure to microplastics may lead to injury and death (Prata, 2018). Plastic pollution is one of the most pressing environmental concerns in the 21st century. It is estimated that the plastics accumulated from the mismanaged waste may be increasing 2- to 10-fold on the decadal time scale (Brahney et al., 2021). Compared to that of marine and ocean plastics, our knowledge of atmospheric microplastics is relatively limited. Research gaps exist regarding their sources, dispersion, and accumulation mechanisms, and, more importantly, on how windblown dust events affects their transport and deposition particularly concerning the impact on environmental, ecological, and human health (Borthakur et al., 2022; Y. Zhang et al., 2020).

2.6. Interactions With Air Pollution

Dust affects multiple criteria air pollutants regulated by the US 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 ($NO_x \equiv NO + NO_2$) (Cwiertny et al., 2008; Dentener et al., 1996; Usher et al., 2003). Dust may 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 may decrease dust lifetime in the atmosphere (Andreae & Rosenfeld, 2008).

In addition to direct impact on criteria air pollutants, dust can affect precursor gases that in turn influence secondary pollutant levels, as with tropospheric O_3 and secondary organic aerosol (SOA). Dust may 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 (B. 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 methane (CH_4), 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, halogen-bearing dusts emitted from saline playas such as the Salton Sea and the Great Salt Lake facilitate 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.

2.7. Dust Trends

Multiple lines of evidence suggest that North America has become dustier in recent decades than in the 1990s (Brahney et al., 2013; Clow et al., 2016; Lambert et al., 2020; Tong et al., 2017). A significant increase in rainwater calcium (Ca^{2+}), detected by the National Atmospheric Deposition Network from 1994 to 2010 in the western US (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 increased 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 increased 240% between 1990 and 2011 in the Southwest US (see Figure 2 in Tong et al., 2017). Dust storms in the US have increased ten-fold faster than global trends, which have tended downward (Shao et al., 2013; Tong et al., 2017), although increases have been documented in the Middle East and at high latitudes (Bullard et al., 2016). Increasing trends of up to 5%/year in dust optical depth are observed throughout the Great Plains during 2000–2018, due likely to agricultural expansion (Lambert et al., 2020). The frequency of high-concentration dust events was reported to decrease over the Western US, although the frequency of smaller dust events shows significant increasing trends for the same period (2000–2021) (Aryal & Evans, 2022). The rapid warming of high latitudes is causing rapid melting of glaciers, exposing sediments which are entrained by the wind as periglacial dust in Canada and Alaska, US. For example, Bachelder et al. (2020) quantified the concentration, size and composition of dust associated with an actively retreating glacier in Yukon Territory, Canada. They found that PM_{10} and $PM_{2.5}$ concentrations from dust at a National Park visitor's center popular with tourists sometimes exceeded WHO air quality guidelines.

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 still lacking. A few high dust years were recorded in the weather-based dust data set (Shao et al., 2013). Measurements of dust flux at the Marcos Juárez (MJ) site in the Pampas found no trend in the 14-year observations between May 2004 and June 2018 (Cosentino et al., 2019). Recent drying trends in the Americas have produced emerging dust sources or enhanced existing ones. For example, Bucher and Stein (2016) reported a new dust source from Mar Chiquita, Argentina, the largest saline lake in South America. Year-to-year variations of saline dust storms correlate with the size of salt mudflats that originate from a 30-year cycle of expansion and retraction driven by rainfall. Like interannual variations in North America (Tong et al., 2017), dust variations generally relate to large-scale changes in the ocean, in particular, ENSO events (Shao et al., 2013).

3. Effects on Human Health

Unlike the numerous investigations performed in the Global Dust Belt extending from Africa through the Middle East to Asia, there have been much fewer population-based studies of dust health effects in the Americas, with the exception of fungal infection. Among these existing studies, the methodologies of the studies were far from consistent, they were conducted in different locations, and the health effects being investigated (mortality, intensive care admission, hospital admission, emergency room utilization) were quite different.

3.1. Respiratory Diseases

Exposure to dust storms results in respiratory morbidity and consequent emergency care and hospitalizations (Griffin, 2007; Herrera- Molina et al., 2021; Meng & Lu, 2007; Soleimani et al., 2020). One of the first systematic studies of the human health consequences of dust from drying playas (saline lakes), and one of the first population-level studies of dust health effects in the Americas, was done by Gomez et al. (1992) investigating the respiratory health of persons living downwind of drying Old Wives Lake, Saskatchewan, Canada, which produced plumes of dust composed of sodium sulfate salts and silicate minerals. Compared to persons living outside of the paths of the plumes, residents exposed to the alkaline, saline dust experienced an increased prevalence of current cough, current wheeze, chronic cough, chronic wheeze, chronic eye irritation, and chronic nasal irritation. More recently, Smoyer-Tomic et al. (2004) and Yusa et al. (2015) reviewed the likely human health consequences of drought in Canada, specifically including dust storms with their impacts on the respiratory system. Toxicological studies that reproduce real-world exposures during dust events show that mineral dust particles generate inflammatory lung injury and aggravate allergen-induced tissue eosinophilia (Fussell & 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).

Dust-borne allergens and toxins associated with respiratory stress include fungal spores, pollen, metals and anthropogenic aerosols emitted from agricultural, industrial, military and civilian activity (see Holmes & Miller, 2004; Ichinose et al., 2006; Kuske, 2006; Lancaster et al., 1995; Sandstrom et al., 1992). Numerous genera of fungi, such *Alternaria* species, are potent allergens identified in many dust studies (Griffin et al., 2006, 2007; Ho et al., 2005; Kellogg et al., 2004; Kwaasi et al., 1998; Schlesinger et al., 2006; D. J. Smith et al., 2012; Wu et al., 2004). Regarding bacteria, endotoxins such as lipopolysaccharides, a cell wall component of gram-negative bacteria, can cause fever and respiratory stress under short term exposures and, with long term exposure, development and exacerbation of asthma and other irreversible respiratory illnesses (Sandstrom et al., 1992; Vernooy et al., 2002).

Gyan et al. (2005) reported that African dust was associated with increased pediatric asthma accident and emergency admissions in Trinidad, while Prospero et al. (2008) found no such relationship with pediatric asthma attendance rates in Barbados. Monteil (2008) pointed out the conflicting results and called for more thorough studies with standardized protocols. Cadelis et al. (2014) concluded that "The PM_{10} and $PM_{2.5–10}$ pollutants contained in the Saharan dust increased the risk of visiting the health emergency department for children with asthma in Guadeloupe." Akpinar-Elci et al. (2015) inferred a broad relationship between dust and emergency room visits for asthma in Grenada. Nichols (2020) examined the associations between Saharan dust days and pediatric asthma emergency room visits on four Caribbean islands from 2015 to 2017. They found a general regional increased risk with Saharan $PM_{2.5}$ but no significant association with Saharan PM_{10}, and this relationship varied by individual year and location (island) (Nichols, 2020).

3.2. Other Morbidity Effects

In continental North America, Hefflin et al. (1994) found increased emergency room visits for respiratory disorders on the day of a dust event and 2 days thereafter in the arid Columbia Plateau of southeastern Washington state, USA. Schwartz et al. (1999) found no statistically significant increase in mortality on the day of a dust event or the next day, and Slaughter et al. (2005) did not detect associations between any size fraction of PM and emergency room visits or hospital admissions for respiratory or cardiovascular disease. In the adjoining state of Idaho, also prone to dust storms, Norton and Gunter (1999) did not see a correlation between PM_{10} and respiratory diseases in the general population. Rublee et al. (2020), looking at data for the USA as a whole, reported a 4.8% increase in total intensive care unit admissions on local dust storm days and 9.2% and 7.5% increases in for respiratory disease on the day of a dust event and 5 days later, respectively.

There have been several epidemiological studies of the effects of blowing dust on human health in the Chihuahuan Desert of southern New Mexico and western Texas, USA. Increased odds of hospitalization for asthma and acute bronchitis were detected on dust days and for up to 3 days thereafter in El Paso, Texas, with the greatest impacts being seen in children (especially girls, for acute bronchitis) and persons with low income (Grineski et al., 2011). Herrera-Molina et al. (2021) found the relative risks of hospitalizations for multiple diseases over a 5-year period in El Paso were significantly associated with windblown dust exposure on the day of the event and for up to 7 days later. Rodopoulou et al. (2014) noted a connection between concentrations of PM_{10} and $PM_{2.5}$ and emergency room utilization for cardiovascular conditions in the warm season in Las Cruces, New Mexico, USA, where blowing dust is frequent.

A few past studies examined the connection between African dust transport to human health in Caribbean islands. L. M. Lewis et al. (2020) identified positive associations between increases in outdoor PM exposure, which would include but were not limited to African dust, and outpatient asthma-related healthcare use in Puerto Rico. Viel et al. (2019) looked at the association between Saharan dust intrusions and birth outcomes on the island of Guadeloupe, showing an association between mean PM_{10} concentration and the proportion of intense dust events and preterm births. A follow-up study also found a relationship between increased PM_{10} and low birth weight (Viel et al., 2020).

3.3. Premature Deaths

Effects of dust storms on non-accidental death have been studied in the Americas, but with mixed results (Crooks et al., 2016; Schwartz et al., 1999). A study of 17 US dust storms in Spokane, Washington, reported a 24-hr mean PM_{10} concentration of 263 μg/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 μg/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.

Crooks et al. (2016) looked into a larger pool of dust storms across the US and found dust and mortality were correlated. 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- 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 days) (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 Storm Data used to identify dust storms do not include such information. Too, the Storm Data set is incomplete due to inconsistent reporting mechanisms (Ardon-Dryer et al., 2023; Tong et al., 2022). Potential links between dust storms and health consequences are complicated by health surveillance shortcomings and many unreported small-scale sources of airborne dust genesis, for example, agricultural tilling, microscale "dust channels," and dust devils that throw dry soils upward to 100 m and more (Sprigg, 2016; Sprigg et al., 2014, 2022; Vukovic et al., 2014). Long-term dust climatologies, such as those reconstructed using surface measurements (Hand et al., 2017; Lei et al., 2016; Tong et al., 2017), can support future epidemiological studies to fill the knowledge gap.

3.4. Valley Fever

Coccidioidomycosis (Valley fever) has been well documented, with outbreaks known to occur after large dust storms and exposure from large dust events (Pappagianis & Einstein, 1978; Williams et al., 1997). 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 soil-dwelling organisms. They are the causative agents of coccidioidomycosis (Fiese, 1958; Freedman et al., 2018; Kirkland & Fierer, 1996; Sprigg et al., 2014; Tong et al., 2017). Infection with Valley fever occurs when the arthroconidia of the fungi, either *C. immitis* or *C. posadasii*, are inhaled. An increasing pool of new information to map the population structure and species delineation for *Coccidioides* has emerged (Figure 2), summarized by Barker et al. (2019).

Small outbreaks of this disease are reported often in the US after regional dust events (Chatterjee et al., 2017; McCotter et al., 2019; Pappagianis & Einstein, 1978; Park et al., 2005; Schneider et al., 1997). Since 2000, more than 4,000 people have died from Valley fever and hundreds of thousands more were infected in the US alone (CDC, 2020). Annual medical costs, lost income and economic welfare for Valley fever sum to $400,000 per case (Gorris et al., 2021). Considering the average hospitalization rate, the total health burden of Valley fever infection amounted to $40 billion in the past decade in the US. It is suggested that climate warming and drought, which lead to more frequent windblown dust storms and anthropogenic fugitive dust from unpaved roads, are the cause (Padua y Gabriel, 1999; Tong et al., 2017). These conditions appear to favor saprobic growth, conidia formation, and air dispersal of *Coccidioides* (Comrie, 2005; Kolivras et al., 2001; E. R. Lewis et al., 2015; Stacy et al., 2012; Zender & Talamantes, 2006).

In spite of several decades of interest and research, questions remain unanswered regarding this link with dust storms (Tong et al., 2022). Sprigg et al. (2014) suggest that confidence in dust storm-Valley fever links will require more detailed disease surveillance. Until recently, the ability to detect *Coccidioides* at low abundance in environmental samples has been difficult and time-consuming (Chow et al., 2017; Finn et al., 2021), 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 climates is required for adequate description of its climatic parameters (Finn et al., 2021; Lauer et al., 2020).

The source of *Coccidioides* spores is as important as their dispersal. Spores have been known to infect native rodent populations (e.g., pocket mouse, kangaroo rat, and ground squirrel; Emmons, 1943; Emmons & Ashburn, 1942; Catalán-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 & Barker, 2019). Also, 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., 2018), 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 spread primarily through inhalation (Gonzalez-Martin, 2019). Reports from Canada (Parkes et al., 2016) to Argentina and in between (Douglas et al., 2022; McMichael, 2004; Plumlee & 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. Greifenhagen and Noland (2003) pointed out that under conditions of extreme drought, dust transported long distances from the semiarid Great Plains could conceivably introduce new pathogens to the temperate regions of eastern Canada, and under conditions of drought and wind, the bacteria that cause rickettsial diseases in humans, such as *Q* fever, could be transported in soil dust from infected pastures.

Kawasaki disease (KD) is a pediatric vascular condition that is a common cause of acquired heart disease in children in US, Chile, as well as in other countries such 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. A statistical association between KD and meteorological variables was reported for Santiago, Chile and it was suggested that windborne desert dust may include a causative agent for the disease (Jorquera et al., 2015).

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 (P. S. 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). Bacteriophages 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 et al., 2019).

Cyanobacteria, ubiquitous in surface crusts of desert soils and playa sediments which are widely wind-erodible, produce a wide variety of cyanotoxins that are hazardous to humans and animals, being inflammatory agents, tumor promoters, and cause 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. Airborne Dust and COVID-19/SARS-CoV-2

Exposure to airborne particles may exacerbate the symptoms and progress of the Severe Acute Respiratory Syndrome-CoV-2 (COVID-19). In a study of 257 COVID-19 patients in China, over 94% were found with viral fungal and bacterial co-infections (Zhu et al., 2020). X. Wang et al. (2020) also reached a similar conclusion: COVID-19 infection often comes along with bacterial and fungal co-infections. Questions of the speed in which proper diagnoses can be made and administration of treatment can begin are raised, since other viruses, fungi and bacteria can spread through the air on dust particles (), and have similarities in initial COVID-19 symptoms (including fatigue, fever, headache, shortness of breath, cough) among many respiratory illnesses (including tuberculosis, pneumonia, SARS-CoV-2, influenza and Valley fever). Valley fever, pneumonia, and COVID-19, for example, all share symptoms of fatigue, shortness of breath and cough.

Direct and indirect transmission routes of COVID-19 virus are via touching infected surfaces (skin-to-skin, touching infected inanimate objects), then mediating the virus infection through the mouth, nose, or eyes (Moriyama et al., 2020; Peng et al., 2020; Qu et al., 2020). Transmission via inhalation of small, exhaled respiratory air droplets (e.g., close contact within 1m) and aerosols (e.g., presence of microbes and particles <5 μm in diameter that remain in the air for long periods of time and transmitted to others over distances greater than 1 m) is likely effective (Qu et al., 2020; Service, 2020; Vergadi et al., 2022). The most efficient transmission route amid the ongoing pandemic of SARS-CoV-2 and its variants is inhalation and exhalation of the viral-aerosol (Moriyama et al., 2020; Peng et al., 2020; Qu 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 (Madjid et al., 2020; C. Shi, Yu, et al., 2020). Many unanswered questions exist regarding whether or how severe the dust storms impact the COVID-19 pandemic in both indoor and outdoor settings.

Coinfection of COVID-19 (and/or its variants) with other microorganisms in airborne dust is a critical complication (Zhu et al., 2020). Further complications arise when all the possible microorganisms in airborne particles that can be linked to infectious diseases are considered (Qu et al., 2020). Superimposed COVID-19 pneumonia on Coccidioidomycosis disseminated infection has been reported, in which patient was diagnosed positive for COVID-19 via DNA PCR and *Coccidioides* reactivation via antibody testing (Passeri et al., 2022). Endotracheal aspirates collected for bacterial culture from a patient with COVID-19 grew white fluffy mold on blood and inhibitory mold agar plates after 6 days (Nielsen et al., 2021). The mold was identified as *Coccidioides* immitis/*Coccidioides* posadasii by matrix-assisted laser desorption ionization–time of flight mass spectrometry. The isolate was further identified as *Coccidioides* posadasii by internal transcribed spacer ribosomal DNA sequencing (Nielsen et al., 2021).

4. Effects on Environmental Health

4.1. Harmful Algae Blooms, Pathogenic Microorganisms, and Toxins

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

Saharan dust deposition in the Atlantic Ocean and the Gulf of Mexico produce short-lived blooms of *Vibrio* species, many of which are known human and marine organism pathogens (Westrich et al., 2016, 2018). Agriculture, urbanization and deforestation have increased deposition of macronutrients from anthropogenic dust sources (Al-Enezi et al., 2014; Bauer et al., 2016). The increase of biologically available N from dust deposition can enhance phytoplankton growth, such as in the low-nutrient low-chlorophyll (LNLC) regions. It may also change the nutrient stoichiometry and shift the system from N- limiting to P- limiting (T.-W. Kim et al., 2011), consequently altering the phytoplankton composition and growth of some undesirable species. Olsen et al. (2018) 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). Impact of dust inputs on marine phytoplankton productivity and biological C-pump is evident from a sedimentological study in the Gulf of California (Arellano-Torres et al., 2020). Also, organic nitrogen makes 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 & 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 provide significant new amounts of iron (Fe) and stimulate growth of the offshore oceanic diazotroph community (Farahat & Abuelgasim, 2019; Winton et al., 2016). Mesocosm experiments demonstrate diazotroph growth enhancement after polluted aerosols and Saharan dust have been added to water from the Eastern Mediterranean Sea; the prevalence of N-fixing cyanobacterium *Trichodesmium* was found associated with Saharan 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 alleviate N limitation to the growth of *K. brevis* and potentially initialize and sustain large blooms of *K. brevis* for as long as a couple months (Lenes & 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 US states during late June-early July 2020; in June a bloom of *Trichodesmium* was observed off the southwest coast of Florida that lasted weeks—but *K. brevis* concentrations remained at background levels (Florida Fish and Wildlife Conservation Commission, 2020). Further study is needed to better understand the underlying mechanisms of the linkage among dust storms, *Trichodesmium*, and *K. brevis* blooms.

4.2. Dust Deposition and Ecosystem Health

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

While deposited dusts may be creating conditions for HABs, they may also be stimulating primary productivity of non-HAB-forming marine biota: as in high latitude low nutrient, low chlorophyll oceans by supplying Fe and productivity in the nitrogen (N)-limited low latitude oceans with Fe and P to stimulate nitrogen fixation (Mills et al., 2004; Moore et al., 2013; Tagliabue et al., 2017). A critical point 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, 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 may exert negative impact on ecosystem health and reduce 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 particles may contain pathogenic microorganisms, microplastics, inorganic and organic toxins and natural and anthropogenic radioisotopes deleterious to ecosystem health. A notable example is transport of large quantities of African dust to the Caribbean that are linked to pathogens that degrade coral reef health (Shinn et al., 2000).

4.3. Water Supply Contamination Caused by Soil Dust

Wherever a drinking water supply is exposed to the atmosphere it is potentially vulnerable to contaminants arriving with dustfall (Middleton & Kang, 2017). Many low-income communities in the Americas lack potable water. Drinking water often must be delivered by truck or hauled from a site in storage containers. Household water storage containers and truck-mounted water tanks soiled by falling dust may be contaminated by organic pollutants or heavy metals (Parra et al., 2019) and soil-borne microbes (Farenhorst et al., 2017). Risks of physical, chemical, and/or microbial contamination from atmospheric dust deposition is of extra concern when untreated rainwater is used for drinking, as from cisterns (Gwenzi et al., 2015; Sánchez et al., 2017). 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 in drinking water storage tanks from airborne dust.

4.4. Food Contamination From Windblown Dust

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* that can be carried with aeolian dust (Kumar et al., 2018). Hellberg and Chu (2016) conclude that "multiple peer-reviewed studies show a quantifiable, consistent trend" of the dispersal of the foodborne bacterial pathogens *Bacillus, Clostridium*, and *Staphylococcus* by dust storms. Mendonca et al. (2020) review various genera of harmful bacteria that have been isolated in dust and are thought to pose a risk.

Most foods, if coated with dust, likely are not a health risk if properly washed or peeled. However, a risk may exist for leaf-based foodstuffs. The hygroscopic components of aerosols become deliquescent on transpiring leaves, which may take up the solutions by cuticle and stomata. This "hydraulic activation of stomata" (HAS), referring to the deliquescent aerosols affecting stomatal walls, could render aerosols to work as "desiccants", reducing the tolerance of plants to drought conditions (Burkhardt, 2010). In addition, some leafy vegetables such as lettuce are difficult to wash thoroughly enough to remove bacteria that have adhered to the plant tissue. Thus dust may be a vector of contamination (Brandl, 2006). 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 inside (Annous et al., 2005).

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). Similarly, *Salmonella* internalization in cucumbers through blossom inoculation (Burris et al., 2020) and *E. coli* incorporated into apples through their blossoms (Burnett et al., 2000) have been observed. 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 soil are at risk of exposure to inhalation of soil particles and contact with soil-borne pathogens, including toxic pesticides and herbicides (C. A. Smith & Gunther, 1978; Spencer et al., 1980). By sampling and measuring the particulate matter in the cabs of tractors, Green et al. (1990) concluded that farmers in the Prairie Provinces of Canada had a potential risk for pneumoconiosis related to exposure to mineral dust and its associated organic materials. A review of California farm workers (R. Alexander et al., 2018) suggests that dust-associated respiratory disease is an occupational hazard. Sherwin et al. (1979) reported of California Central Valley residents who developed silicate pneumonitis: five of the seven worked in vineyards and five died with respiratory failure—the composition of particles found in their lungs was consistent with local soil. Nieuwenhuijsen et al. (1999) reported that machine harvesting of tree nuts and vegetables and cleaning poultry houses exposed California agricultural workers to significant levels of dust, including 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)—changes 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 the clinical significance and natural history of these changes remain undetermined. Schenker (2010) stated, based on evidence from farmworkers, that "overall, the evidence supports a causal association of mineral dust exposure and pneumoconiosis." R. Alexander et al. (2018) concluded that chronic occupational exposure to soil dust may associate with chronic lung disease that "depends on the frequency of exposure, the intensity of exposure and the composition of the dust."

It is apparent that a variety of fungal plant pathogens have been established or spread to the Americas through wind and/or associated with dust, including wheat rust (fungi of the genus *Puccinia*) spread through the North American Great Plains, and *Peronospora hyoscyami*, the organism that causes tobacco blue mold (Main & Davis, 1989). *Erwinia carotovora*, the causal agent of potato blackleg disease, apparently spreads from the US west coast to the interior US through dust-associated wind transport (Franc, 1994). *Pseudomonas syringae*, a widely distributed pathogen of a variety of crops, has been associated with intercontinental transport of dust. 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 spread from Africa to the Caribbean and to Florida via seasonal winds and dust (Purdy et al., 1985); several species of *Mycosphaerell*a, which inflict severe losses to bananas and plantains, may be transported to the Caribbean from Africa along the same pathway, potentially in dust clouds (Burt, 1991; Stover, 1962). *Massaria platani*, the causative agent of Florida sycamore canker, and *Alternaria dauci*, a species that infects Florida carrots, were found in the mid-Atlantic transoceanic African trade-wind corridor when atmospheric dust was present (Gonzalez-Martin et al., 2014; Griffin et al., 2006). Behzad et al. (2018) report that *Hemileia vastatrix*, the fungus behind 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.

Thiel et al. (2020) demonstrate that manure bacteria, including enteric pathogens, aerosolize from fertilized soil more easily than do soil bacteria; their wind tunnel tests show airborne bacterial emission fluxes from freshly fertilized soil are 100-fold higher than previous estimates 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 1,200 μg m^{-3}—particles replete with carbonaceous materials (some soluble) and salts—have been reported (Hiranuma et al., 2011). Bacteria also hitchhike 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 the suspected cause of a *Salmonella* outbreak on fresh peaches in summer 2020 that triggered more than 100 illnesses in 17 US states. Other manure- or urine-borne contaminants such as hormones are constituents of fugitive dust particles, 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 (Sematimba et al., 2012), transport of the foot-and-mouth-disease virus potentially to great 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 (L. Zhang et al., 2019). Seeds coated with insecticides, when planted by drills may release the coating, which is toxic to bees and other beneficial insects, into the wind (Devarrewaere et al., 2016). Insecticides toxic to honeybees and aquatic organisms are wind-suspended along with materials from 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). As to soil-borne pathogens mentioned earlier, Nieder et al. (2018) identify "several soil-borne diseases … capable of transmission to the air (e.g., *Q* fever, aspergillosis, tularemia, sporotrichosis) … then transported by dust." Of particular concern are pathogens and toxins typically associated with agriculture, but that could potentially be weaponized. Examples include anthrax (*Bacillus anthracis*) (Dragon & Rennie, 1995), the ricin toxin (Zartman & 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

Airborne, inhalable pesticide, pollen, fungi, heavy metals and other components of soil are problematic for pets, livestock, and wild animals as well as humans. 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. Humans and their pets can be infected with inhaled *Coccidioides* arthroconidia (See Valley fever discussion in Section 3.4 and Sprigg, 2016), but 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) 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 (Arbona et al., 2020; Tofflemire & Betbeze, 2010), with non-healing skin lesions a common symptom. Alpacas in the American Southwest have been treated for Valley fever (Butkiewicz & 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 encounter 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 met with airborne *Coccidioides* arthroconidia, possibly from the Mojave Desert (Grayzel et al., 2017; Guevara et al., 2015; Hector et al., 2011; Thompson et al., 2015). 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 (Radionuclides) in Dust

In the complex matrix of Earth's soil minerals, organics, water and gases, any and all 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 et 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) associated with geology and stress in the earth's crust (D'Alessandro et al., 2020). Cosmogenic radionuclides, such as ^{7}Be, can be rain-deposited on surfaces (Itoh & Narazaki, 2015). Global fallout of anthropogenic radionuclides from nuclear weapons tests adds 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 from weapons-testing regions, 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). Exposure to these radioisotopes is hazardous (Jasaitis et al., 2020; Monged et al., 2020; Nenadovic et al., 2012).

Of these natural and anthropogenic sources, probably the wind redistribution of uranium mining spoils and mill tailings are most widespread and of most concern to human health (Blake et al., 2015; de Souza Pereia et al., 2018; Doering et al., 2019; Malin & Petrzelka, 2010; Velarde, 2011). In many cases, legacy mine waste and mill tailings have been exposed to the erosive forces of wind for more than a half century, but 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, 2020).

Continued atmospheric nuclear tests to 1 January 1963, resulted in deposition of un-spent radioactive fuels and fission daughter products across the continental US (Simon et al., 2004) and the world (Bu et al., 2014). There were 100 atmospheric nuclear tests at the Nevada Test Site (NTS) from 1951 to 1962 and a smaller number of tests at other locations in the USA, as well as thousands of atmospheric nuclear tests worldwide. These and a few underground tests released fallout particles that were carried by the wind. The entire United States population exhibited an increasing leukemia rate during and for several years after the open air nuclear testing; the rate fell sharply thereafter (Archer, 1987). Residents of southwestern Utah, directly downwind of the NTS, showed increased rates of cancer, especially in organs most sensitive to radionuclides (Johnson, 1984). In addition, other nuclear experiments at the NTS released plutonium onto the desert surface (Cizdziel et al., 1998). Dust samples collected at residences in the surrounding states contained excess plutonium not related to global background fallout, apparently resuspended by the wind from the test site (Cizdziel et al., 1998). Increased incidence of cancers has also been detected in residents downwind of plutonium production facilities at Rocky Flats, Colorado (Johnson, 1981) and Hanford, Washington (Grossman et al., 2003), likely at least partially related to aeolian resuspension of radionuclides: however, other chemicals associated with plutonium production may pose a greater health risk at Rocky Flats (Till et al., 2002).

Although stratospheric fallout from high altitude detonations spread evenly over the landscape from high to low northern hemisphere latitudes 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 & Ward, 2019). Miller and McClain (2007) review potential health problems when aerosolized depleted uranium used in munitions and manufacturing is inhaled.

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 after, the loss of vegetative cover increases the hazard of soil dust emissions (Whicker, Pinder, & Bresehars, 2006; Whicker, Pinder, Breshears, & Eberhart, 2006). Aeolian transport of radionuclides from the soil can be modeled and predicted to allow 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 & Zender, 2010), and loss or gain of fallout anthropogenic radionuclides has been used to estimate decadal rates of soil redistribution by wind (Van Pelt, 2013; Van Pelt & Ketterer, 2013; Van Pelt et al., 2007). The eventual fate of all surface sediments on Earth is into 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 return to sea surfaces and deposit again on land, they remind us of nature's propensity for recycling.

4.8. Heavy Metal Contamination (Resuspension)

Contaminants such as heavy metals (Schreck et al., 2012) carried with aerosols including dust fall out on gardens or agricultural lands—especially in and downwind of urban and industrial areas that tend to have more of this type of contaminated soil (Cooper et al., 2020). People, livestock and wildlife consuming those crops are at risk. Leafy vegetables with large proportion of edible surface area exposed to the air may pose the greater risk (Schreck et al., 2012), while root uptake of heavy metals into vegetable crop leaves is also a problem (F.-L. Li, Shi, et al., 2017). Heavy metals in agricultural soils come from many sources including deposition of metal-bearing dusts.

Native minerals and weathering products supply numerous metallic minerals (Eleftheriadis & Colbeck, 2001; Nicoll et al., 2020; Trapp et al., 2010; Z. Wang et al., 2019). And redistribution of mining spoils and deposition of industrial emissions increase heavy metal concentrations in surface soils that may ride with fugitive dusts (Csavina et al., 2012; Entwistle et al., 2019; J. Li & McDonald-Gillespie, 2020; Ono et al., 2016; Rodriguez-Espinaosa et al., 2017; Van Pelt, Shekhter, et al., 2020; Vito et al., 2020). Metallic ions in surface soils may have cosmic sources (Benna et al., 2015). Specific to agriculture, heavy metals are contaminants in fertilizer materials, especially phosphate based, applied to increase crop growth (Azzi et al., 2017; Dharma-Wardana, 2018; X. Wang et al., 2020); heavy metals found in organic fertilizer (Gong et al., 2019). Dzul-Caamal et al. (2020) report that these contaminants cause biomass loss in 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 eroded with the wind (Glotfelty & Caro, 1975) and drift into unintended locations where they pose a risk, as into inhabited areas, croplands certified as organic and required to be pesticide-free, or rangelands with no history of pesticide application (Alonso et al., 2018; Bento et al., 2017). Exposure is a function of distance from where pesticides are applied (Gunier et al., 2011), occupation density of where they land (Bennett et al., 2019; M. N. Smith et al., 2017) and season of required use (M. N. Smith et al., 2017). New pesticides and classes of pesticides are always being developed to replace older technologies for which crop pests have become resistant, to address new pest invasions, and to limit environmental impacts. Pesticides found in house dust reflect the pesticides in use at the time (Bennett et al., 2019). 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). In studies of herbicides transported on dust, Alonso et al. (2018) found glyphosate and atrazine, commonly used herbicides, in Argentine soils and rainfall. Glyphosate degrades into a daughter product, aminomethylphosphoric acid (AMPA)—both hold tightly onto particle surfaces. AMPA has a much longer half-life than glyphosate. It tends to accumulate in the soil and thus is present in greater concentrations and for longer periods than glyphosate (Aparicio et al., 2013). As with other contaminants 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 from eroding agricultural soils (Mendez et al., 2017).

4.9. Ocean Acidification

A significant amount of CO_2 is absorbed by the oceans (Tessin, 2020). Oceans become acidic when dissolved carbon dioxide concentrations rise. How it gets this way is complex and may begin with a discussion of oceanic primary productivity, which depends on availability of certain macro- and micro-nutrients. Atmospheric transport and deposition of these nutrients impact ocean 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 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., 2010). Silica components of dust and microalgae create diatoms such as the siliceous marine phytoplankton. These diatoms account for 20% of the world's photosynthesis (Bopp et al., 2003; F.-L. Li, Shi, et al., 2017), and are found in the Fe-limited regions of the oceans (Hettiarachchi et al., 2020). They play a crucial role in 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 availability of Fe as it controls the marine primary productivity and efficiency of the biological C pump (Breitbarth et al., 2010; X. Li, Roevros, et al., 2017). Laboratory studies show that ocean acidification could lower the bioavailability of dissolved Fe, which is crucial for marine phytoplankton (D. 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; F.-L. Li, Shi, et al., 2017; Liu & Millero, 2002).

4.10. Renewable Energy (Solar and Wind Energy)

Renewable energies, such as solar and wind, help to mitigate air pollution and climate change by reducing the emissions of air pollutants and greenhouse gases while still satisfying energy demands (Al-Dousari et al., 2019; IPCC, 2011; Ma et al., 2015; Owusu & Asumadu-Sarkodie, 2016). Therefore, the effects of dust on renewable energy will be indirectly associated with environmental health. Desert areas are excellent regions for both solar photovoltaic (PV) and concentrated solar power plants due to their large solar irradiation (Barbosa et al., 2017; Köberle et al., 2015). Clear, open spaces that allow free air flow are best for locating wind farms, which makes nearly frictionless, offshore and arid land deserts ideal for siting renewable energy sources such as wind and solar farms. Unfortunately, arid lands with loose soils easily lofted into the free atmosphere bring particles that erode and coat substances on wind blades (Khalfallah & Koliub, 2007; Sagol et al., 2013) and damage, contaminate, and clog gears and mechanisms of the turbines and operating mechanisms themselves (Guerrero-Lemus et al., 2015; Pasqualetti, 2004).

Overall performance of these power stations can be hindered by dust accumulation or soiling on the insolation-receiving surfaces (Al-Addous et al., 2019; Cordero et al., 2018) and/or solar radiation attenuation by atmospheric dust (Polo & Estalayo, 2015; Del Hoyo et al., 2020). The coating of surfaces with dust (soiling) leads not only to reflectance degradation but also reduces the lifespan of PV cells due to overheating and shading (Sarver et al., 2013; C. Shi, Yu, et al., 2020). Dust deposition rates onto solar power cells depend on factors such as wind speed, cell orientation, angle of incidence and relative humidity (hygroscopic aerosol growth) (J. Chen et al., 2019; Goossens et al., 1993; Hammond et al., 1997). This soiling combined with water scarcity in arid regions represents a challenge for current as well as future projects (Xu et al., 2016). For instance, the combination of high dust deposition rates and low precipitation amounts was found to cause up to 39% annual energy losses in the northern coastal part of the Atacama Desert, while the losses are much smaller where rainfalls are more frequent or soiling is less (Cordero et al., 2018). Cleaning and mitigation are fundamental to the solar industry due to soiling degradation of energy production (Gupta et al., 2019)—large dust particles have greater consequence than small particles (C. Shi, Yu, et al., 2020). For instance sand and dust storms are found to reduce PV panel efficiency up to 80% in 1 hr (Ghazi et al., 2014). Artificial cleaning techniques comprise a range of methods such as hydrophobic and hydrophilic surfaces, mechanical dispositive for dust removal, electrostatic shields and robotic devices (Jamil et al., 2017). Applications of these methods depend on the region and associated costs, and may require other mitigation measures such as concreting the surface or planting grass, which would not prevent deposition of dust generated offsite. Other causes of dust accumulation may occur, as triggered, for example, by bird droppings that act as an adhesive for 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, must be taken into account in order to mitigate soiling impacts, such as the nature of dust accumulation, dust composition and the governing meteorological conditions.

Limited scientific literature is available on the impact of dust on wind farms energy production partly due to the protection of intellectual property in a competitive market (Shalby et al., 2022). The few studies conducted on this topic consider wind farms in the Middle East. To the best of our knowledge, no equivalent study has been conducted in the Americas. This dust impact on wind turbines can be either through dust accumulation on blade surfaces (Sagol et al., 2013) and/or impact in the equipment inside the nacelles (Al-Khayat et al., 2021). The former perturbs the roughness lengths potentially disturbing the flow field and thereby reducing the power generation by the turbine (Sagol et al., 2013). The latter, however, results in the clogging of nacelles filters causing decreasing cooling efficiency thereby affecting operation and performance of turbines (Al-Khayat et al., 2021; Shalby et al., 2022). Cleaning frequency needs to be optimized to avoid too much dust accumulation in nacelles to prevent significant performance losses (Al-Khayat et al., 2021).

The use of numerical dust prediction would not only be beneficial for better operation and maintenance of both solar energy plants and wind farms but would also contribute to aggregate energy from different production sources optimizing profit of the electricity market (Al-Khayat et al., 2021; Gomes et al., 2020).

5. Safety Concerns

In addition to endangering human and environmental health, airborne dust and related phenomena, such as high winds, are a major safety hazard in transportation, especially motor vehicles on dust-affected highways and associated support fatalities. Concern grows, too, about 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 change in vehicle speed, increase risk of accidents (Ashley et al., 2015). Coarse dust and sand on the roadway cause loss of traction and of vehicular control (Day, 1993; Pan et al., 2006). Dust also appears associated with greater crash severity than other hazardous weather. Burritt and Hyers (1981) point out that

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Figure 3. (a) A scene of multi-vehicle crashes on I-10 highway at Lordsburg Playa near the New Mexico and Arizona border on 22 May 2014 (photo courtesy of New Mexico State Police and Motor Transportation Police), (b) A typical *haboo*b dust storm observed near Phoenix, Arizona on 2 August 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, 16 May 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).

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 and life—although haboob dust events that steadily reduce visibility over larger areas and longer times may give drivers time to adjust to conditions, their typical thick obscurations if suddenly encountered from clear conditions are undoubtedly more treacherous to drivers than synoptic-scale dust events. Microscale, ephemeral near-ground dust plumes known in the Southwest US as "dust channels" are extremely hazardous, due to their local nature and difficulty to detect with conventional meteorological or air quality networks or remote sensing platforms. Dust and sand hazard to motorists may come from many factors: wind erosion of natural dryland surfaces; emissions from temporarily fallow and wind-erodible croplands (J. Li, Kandakji, et al., 2018); cattle feed lots; fields being tilled (Crooks et al., 2016) that emit un-anticipated dust plumes in fair weather; land disturbed by road, housing and industry development can be a source of fugitive dust in any climate (Weber et al., 2014); off-road recreation where surface crusts (desert pavement) are broken; vehicles driven on unpaved roadways; etc. The heavily traveled, crash-prone corridor between Phoenix and Tucson, Arizona is an example (Hyers & Marcus, 1981; Lougeay et al., 1987; Raman et al., 2014).

Dust hazard to road transportation is well-documented in the southwest US (Figure 3), a region where blowing 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: at least 33 collisions involved an estimated 164 vehicles and 349 persons within a ten-minute period along a few kilometers of dust-blinded freeway and left 151 people injured and 17 dead (Day, 1993; 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. Bhattachan et al. (2019) suggest that dust contributed to these incidents, given that wind-related accidents increase when visibility is low. Blowing dust is Arizona's third deadliest weather hazard, killing over 150 people and injuring more than 1,300 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 & 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 naturally-ephemeral, dust-emitting Lordsburg Playa in southwest 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 (Botkin & Hutchinson, 2020;

New Mexico Department of Transportation, 2018; Van Pelt, Tatarko, 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 with one death and 25 injuries (Nicoll et al., 2020). However, roads in almost every part of the US have potential to be affected by windblown dust: Goudie (2014) documented dust-related fatal highway crashes that took place in six states in a single year, Weber et al. (2014) reported that blowing dust on Route 108 near Carlinville, Illinois, in the agricultural Corn Belt of the central US, reduced visibility to about a meter and resulted in several collisions and temporary highway closure, and Breslin (2016) investigated an April 2016 windblown dust event in eastern Arkansas—in the humid southeast US—that caused at least two multi-vehicle crashes that injured 11 people. Dust storms in the Canadian Prairies (E. E. Wheaton, 1992; E. Wheaton et al., 2008) and undoubtedly other nations such as Australia, Germany, Iran, Kuwait, and Saudi Arabia (Middleton et al., 2019; Miri & Middleton, 2022) have led to fatal highway accidents.

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., 2022), and dust particles damage 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, wide regions, or even entire routes (Monteiro et al., 2022). Helicopter operations are another concern (McDonald, 2013), where rotor "downwash" may lift loose soil, reduce visibility and interrupt pilot orientation and situational awareness (Jasion & Shrimpton, 2012).

Airport activities near dust sources are often compromised by 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 catastrophe: a June 2009 Air France flight (AF477) and a July 2014 Air Algérie flight (AH5017); see BEA (2014, 2016), Nickovic et al. (2021), and Section 7 of this review. Airborne dust will reduce the number of engine flight cycles, shorten standard maintenance intervals, require engine replacement 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 damaged when mineral dust particles are encountered, both at the moment of impact and accumulated damage over time (Song et al., 2016)—a consequence of long-term operations in dust-prone regions and melting of ingested mineral dusts in new high-operating-temperature turbines (Clarkson et al., 2016; Song et al., 2016). These are lessons learned in decades of study on engine intake of volcanic ash. Conventional dust forecasts do not address the level of possible dust melt (a gap in operations discussed further in Section 7).

Another flight risk, "brownout," refers to extremely dense clouds of dust and sand raised by aircraft operating near ground in dry terrain or over loose soils. It is a particular hazard with helicopter rotor downwash that hits the ground with high velocity (Jasion & Shrimpton, 2012; McDonald, 2013). The result is loss of vision, orientation, and situational awareness to the pilot as well as to ground personnel. The chance of aircraft mechanical failure as well as uncontrolled contact with the ground or obstacles is increased. Brownout is a significant safety issue, especially in desert regions (Ramee et al., 2021).

5.3. Marine Navigation

Low visibility is a 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 21 and 24 June 2020, visibility dropped in many locations into international standard scales of low and moderate—from the typical 10–30 km of visibility to 5 and 7 km. Boat and ship captains risked disorientation, as did helicopter pilots, and became a hazard to nearby vessels, moorings and port facilities.

5.4. Railroad Safety and Health

Excessive windblown dust or (more commonly) sand on railroad tracks is a safety and reliability hazard to railroads through desert regions (Bruno et al., 2018; Raffaele & Bruno, 2020). Western Hemisphere problems seem not as severe as those in Asia (especially Iran and China) 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 arid 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 that is insufficiently covered or stabilized under windy conditions can lead to aeolian entrainment of particles that blow onto areas near and downwind of the tracks. Coal-carrying freight trains often trail more than 100 open coal cars that can generate fugitive coal dusts (Jaffe et al., 2015), which has been directly associated with several forms of lung disease (Schins & 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—up to ~100 μg/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. Other Critical Issues

6.1. Climate Change and Dust Effects

Climate models have projected robust drying trends in several areas across Pan-America, including western North America, Central America and the Amazon Basin in the 21st century (Cook et al., 2014). This Pan-American expansion of drying areas 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) predict 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 more vegetation are expected to reduce dust activity in the northern Great Plains (Pu & Ginoux, 2017).

The projected changes in climate and dust activities are expected to impact human health. Compared to 1986–2005 levels, fine and coarse dust concentrations could increase by 57% and 38%, respectively, resulting in elevated health issues, including 230% more all-cause mortality, 210% more cardiovascular mortality and 88% more asthma emergency room visits (Achakulwisut et al., 2019). Due to the projected changes in temperature and precipitation, the area potentially endemic to Valley fever will more than double by 2100 in the western US (Gorris et al., 2019). It remains elusive what roles climate change will play for other health and safety effects.

6.2. High-Latitude Dust Sources

Besides the sources in tropical and mid-latitude arid regions shown in Figure 1, there are emerging dust sources in higher latitudes (>50°N or S), particularly in proglacial and periglacial regions (Crusius et al., 2011; Prospero et al., 2012). At high latitudes, dust emissions are controlled not only by the typical physical processes encountered in hot environments such as strong winds, but also by other processes specific to cold environments, such low temperatures, low dewpoints, permafrost and niveo-aeolian activity (Bullard et al., 2016). At present, high-latitude sources are estimated to cover half a million km^2 and contribute at least 80–100 Tg yr^{-1} of dust emission to the Earth system (~5% of the global dust budget) (Bullard et al., 2016). In North America, high latitude dust sources include the Gulf of Alaska coastline (Crusius et al., 2011) and Pallliser's triangle in southern Saskatchewan and Alberta of Canada (Bullard et al., 2016). Small scale dust emissions are also known to occur in selected periglacial settings in Arctic Canada (Bachelder et al., 2020; Nickling, 1978). In

South America, Patagonia, a large landmass located between 39 and 55S, is the dominant high latitude dust source (Foth et al., 2019). The sparse vegetation and semiarid climate in this region are inductive to wind erosion during drier summer months, although dust events also were also observed in other seasons (Gaiero et al., 2013). Patagonia was a dominant source of dust in the Southern Hemisphere during glacial periods (Basile et al., 1997). The present day dust sources include reworked loess, alluvial fans, dry lakebeds and riverbeds, and occasional resuspension of volcanic dust particles (Gaiero et al., 2003; Gassó et al., 2010; N. M. Mahowald et al., 2006).

6.3. Environmental Justice

Across the world, it remains unclear how dust particles contribute the disparity of population exposure to $PM_{2.5}$. The "State of the Air" 2021 report of the American Lung Association found that more than 40% of USA residents or 135 million people are breathing unhealthy levels of ozone or particle pollution, with people of color being more than three-fold more likely to be breathing the most polluted air than white people (American Lung Association, 2021). A study of $PM_{2.5}$ exposure caused by each emission type shows that almost all sources contribute to systematic exposure disparity experience by people of color (Tessum et al., 2021). These studies either focused on anthropogenic sources only or treated natural sources as exceptional events and it remains unclear how dust emissions contribute to this disparity. However, historically underserved and socially vulnerable communities may have a higher exposure to dust, due to proximity to industrial activity or a higher proportion of unpaved roads which release fugitive dust. Measurements of samples collected by citizen scientists in Marion County (Indiana, US) did reveal that renters are more likely to contain higher levels of heavy metals (lead, zinc and copper) in soil dust than homeowners (Dietrich et al., 2022). This issue needs to be further examined in future studies.

7. Mitigation Measures

7.1. Observations and Prediction of Sand and Dust Storms

To mitigate harmful effects of sand and dust storms, observations and forecasts as well as early warning advisory and assessment systems are critical for regions affected by aeolian (windblown) sand and dust (Sprigg et al., 2008; Yin et al., 2005). 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 Program (UNEP), the WMO and the UNCCD conducted, together, a "Global Assessment of Sand and Dust Storms" (UNEP, WMO, UNCCD, 2016). The assessment report, which was recognized in UNGA resolution A/RES/71/219, sets out proposals to consolidate and coordinate technical and policy options to respond to sand and dust storm issues. The WMO was one of the first UN agencies to address the problem. In 2007, the 15th World Meteorological Congress highlighted the importance of windblown dust and endorsed launch of the SDS-WAS. The main objectives apply regional centers to facilitate research and user access to observation, assessment and forecast products—particularly as an asset for national meteorological and hydrological services—as well as to enhance capacity-building. The SDS-WAS project is organized under the WMO World Weather Research Program (WWRP) and Global Atmosphere Watch (GAW), coordinated by the SDS-WAS Steering Committee (SC) (the SC meets annually) supported by the WMO Secretariat. For development and realization of the SDS-WAS, a Science and Implementation Plan for 2015–2020 was prepared (WMO, 2015) and approved by the 17th World Meteorological Congress. The SDS-WAS SC recommends 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, or Centers: The Northern Africa-Middle East-Europe Node, the Asia Node and the Pan-America Node for North, Central and South American collaboration. In addition, two new SDS-WAS regional initiatives took placein the Gulf Cooperation Council (GCC) countries and the West Asia region. Geographically centrally located for the Americas, Barbados holds the longest-running, scientific, continuous dust sampling site (55+ years at Ragged Point: Zuidema et al., 2019), which 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 Global Monitoring Laboratory Federated Aerosol Network) provides a continuous record of aerosol and dust properties from 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 NASA, in partnership with the SDS-WAS Pan America Center, WHO/Pan-American Health Organization, and federal and local agencies, to provide real-time forecasts of dust storms over North America (WMO, 2021). Although air quality continues to improve in North American, the frequency of high-impact extreme events, such as dust storms and wildland fires, has increased rapidly in recent 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). A plan is in place to include additional model predictions in future. Plans include, with stakeholders, customized data packages for three applications: (a) air quality metrics for the City Health Dashboard to serve 750 of the largest US cities; (b) real-time ensemble dust prediction as a pilot project for the Pan-America SDS-WAS node; and (c) with the WHO/Pan-American Health Organization (PAHO), provide prediction and observations of wildfires and air quality to its member countries (WMO, 2021).

The NWS NAQFC has responsibility to develop and implement operational air quality forecast guidance for the US. The current NAQFC forecasts cover the Continental US, Alaska and Hawaii (P. Lee et al., 2017). At present, Puerto Rico and other Caribbean Small Island States (SIS) lack capability to provide near-real-time air pollutant assessments or air quality forecasts. Current forecast operations of NWS San Juan-Puerto Rico Field Office include ozone, smoke, dust, and PM_{10} and $PM_{2.5}$, but since 2018 a multidisciplinary team of universities, agencies and non-governmental organizations located in the Caribbean region have had to fill the need to characterize and inform authorities of trans-Atlantic Africa dust and health impacts in SIS. 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 NOAA-AOML (NOAA-Coastwatch) and the Caribbean Coastal and Ocean Observing System (CARICOOS) are helping to design this new information tool to assist in strategic planning, policy makings and public services.

7.2. 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. Early wind erosion studies, led by Austin W. Zingg and William S. Chepil at the High Plains Wind Erosion Laboratory in Kansas, USA, focused on developing a fundamental understanding of the processes of wind erosion and soil properties that affect wind erosion with laboratory and portable wind tunnels (Chepil, 1960; Chepil and Woodruff, 1954, 1959, 1963; Chepil et al., 1962). The works by Chepil and co-workers aimed at elaborating the roles of key factors in wind erosion, including soil structure, climate and surface conditions (roughness, vegetative materials etc.). The understanding that soil properties, vegetative cover, and wind speed control soil erosion and dust emissions has led to computer models to predict wind erosion. The initial attempt by Chepil and Woodruff (1959, 1963) to model wind erosion was extended by Woodruff and Siddoway (1965) to develop the first widely used dust emission model, called the Wind Erosion Equation (WEQ). Computer models such as WEQ are used to compare potential rates of erosion and dust emissions with different management policies (Feng and Sharratt, 2007a, 2007b; Pierre et al., 2014). For example, conservation tillage, such as reduced tillage and no-tillage, can effectively control wind erosion and dust emission (Bewick et al., 2008; Lin et al., 2021; Thorne et al., 2003), although intrinsic soil erodibility and dust emissivity may increase under such systems (Van Pelt et al., 2013).

Conventional crop production involves tillage of the soil, with resulting loss of vegetative cover and a bare soil surface susceptible to wind erosion. In areas with degraded soil resources, conservation tillage may restore soil productivity by trapping ambient dust and sequestration of soil carbon (Lahmar et al., 2012; 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 (Baddock et al., 2011). 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). Restoration of the soil ecosystem by establishing biological crusts (Chiquoine et al., 2016), planting a species mix that will persist on the landscape (Yang et al., 2022), and removal of invasive shrub species (Havrilla et al., 2017) are 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 before vegetative cover is restored (Duniway et al., 2019).

Soil conservation initiatives in Canada have been proved successful to mitigate blowing dust from agricultural fields and the Canadian Prairies (Fox et al., 2012). Soil losses in the Canadian Prairie Provinces were estimated to be as high as $700 million per year, with wind erosion being the largest cost (Dregne, 2002). In 1935, Canada established the Prairie Farm Rehabilitation Administration (PFRA) to stimulate drought rehabilitation across Canada (Marchildon et al., 2008). Several local and regional initiatives, including the Alberta No-Till Farmer's Association (ANTFA), Alberta Conservation Tillage Society (ACTS), Saskatchewan Soil Conservation Association, Pembina Valley Conservation District (PVCD), No-Till on the Prairies (NTOTP) and Zero Tillage Production Manual (ZTPM), were developed to promote and implement wind erosion prevention techniques or provide information to farmers on adopting these practices (see Table 1 of Fox et al., 2012).

7.3. Dust Mitigation for Transportation

Highway dust safety hazards may be reduced by any method of wind erosion control on 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 re-engineered to reduce risks. The reworking of 16 kms of Interstate 10 near Casa Grande, Arizona began in 2016 at a cost of at least $72 million (Larson, 2020). The most recent re-engineering of 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 section 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 NWS began distributing a “Dust Storm Driving Safety” pamphlet in 1982 (NOAA, 1982). In it, drivers are 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 if 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, as in 2012, the Arizona Department of Transportation began the campaign, “Pull Aside, Stay Alive” (Reid et al., 2015).

For aircraft and airports, mitigation of brownout hazard has included field-based (Gillies et al., 2010) and numerical modeling (Jasion & Shrimpton, 2012) to understand brownout intensity and duration—a function of aircraft type and design (Ghosh & Rajagopalan, 2022), 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, e.g., 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).

7.4. Valley Fever Surveillance

At the time of writing, routine public health surveillance for this disease is limited to the US. 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 departments annually from 26 States currently, with nearly 95% of the cases coming from Arizona and California; however, Valley fever cases are not required to be reported in many states. This surveillance is conducted by mandatory reporting of positive laboratory results to public health authorities and may include interviews for compatible symptoms, typically in low endemic or non-endemic states with much lower-case burdens. Valley fever cases in the US have increased drastically in the last decade, reaching a record high of 22,634 in 2011, and, after a decline to 8,232 in 2014, increasing 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 is postulated that increased awareness and improved diagnostics, rising air temperatures, severe droughts, and increased urbanization have played important roles (Colson et al., 2016; Pearson et al., 2019). In 2019, case numbers quickly reached levels near those of 2011, with Arizona and California alone reporting 19,362 cases (CDC, 2021). The reasons for annual variability are not fully understood but are believed related to several factors, including preceding period of precipitation patterns and related soil moisture followed by a dry period to increase dust emissions (Coopersmith et al., 2017; Stacy et al., 2012; Tamerius & Comrie, 2011).

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

A national surveillance system such as in the USA allows systematic reporting and collection of burden of disease and geographic distribution. Some of the most extensive understanding of Valley fever is drawn from Arizona and California epidemiological studies (Sondermeyer Cooksey et al., 2020; Tsang et al., 2010). Investigations into low and non-endemic states showed similar spectra of disease and long delays in diagnosis (Benedict et al., 2018). A major limitation of all these studies is the 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 some surveillance efforts 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: (a) domestic animal serology tests to examine Valley fever in pets (Chow et al., 2017); (b) genomic sequencing of human specimens to identify cases that were locally-acquired or from travel (Oltean et al., 2019); and (c) targeted soil sampling around human and animal cases for suspected exposure in order to better understand the extent of geographic distribution in this area (Litvintseva et al., 2015). Predictive modeling studies based on climatic variables have estimated expansion of *Coccidioides* distributions both northward and eastward in the United States (Gorris et al., 2018, 2019). Models that included environmental factors also show these trends (Weaver et al., 2020).

Further work and technologies to detect the fungus itself directly in the environment would allow more environmental surveillance (Bowers et al., 2019; Chow et al., 2016). 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). Outlooks of future environmental and climatic conditions that may increase disease prevalence would inform long range strategies for health research and public service.

8. Global Implications and Research/Operation Gaps

Airborne dust carries global implications (Gabriele et al., 2011; McConnell et al., 2007). The effects on the Americas 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 this current study. Among these risks, Valley fever infection is

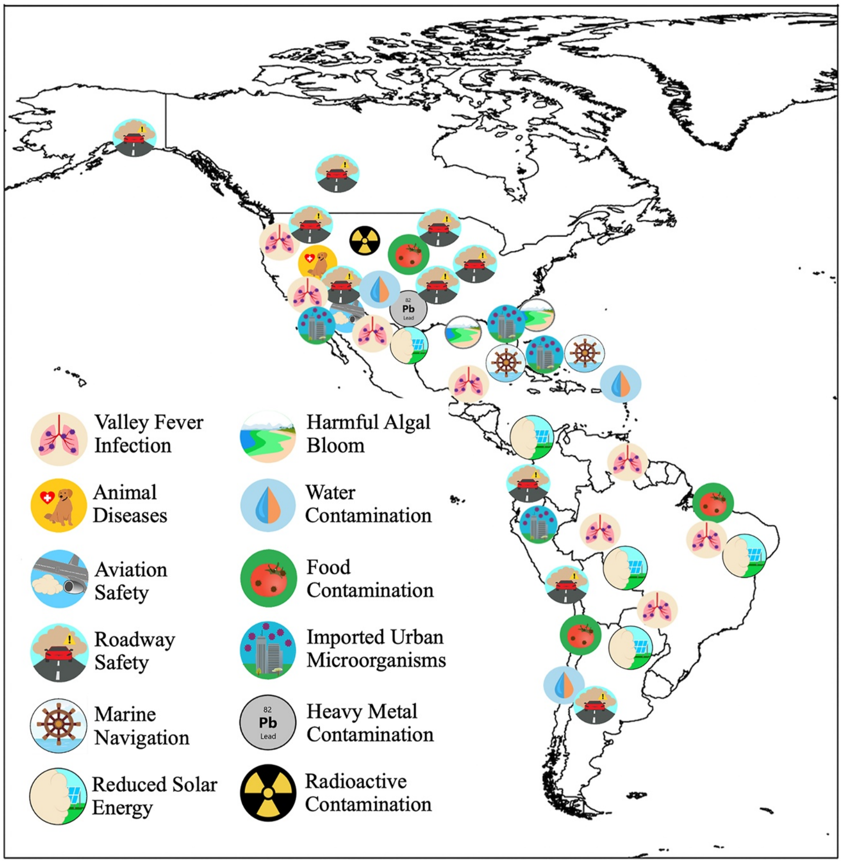

Figure 4. Summary of health and safety effects of airborne dust across Pan-America.

the only one that is believed endemic to the Americas. However, similar infectious diseases caused by dust-borne microorganisms, such as meningitis and Rift Valley fever, have been reported in Africa, Asia, western Europe, and Middle East (García-Pando et al., 2014; Jost et al., 2010; Kellogg & Griffin, 2006). Aerosolized influenza viruses were detected at a higher frequency when dust was present than when it was not in Asia (P. S. Chen et al., 2010). Similarly, scientists in Europe noted that they were more likely to detect human enteric viruses in the atmosphere when North African dust was present in the atmosphere (Gonzalez-Martin et al., 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; Maki et al., 2012; Ozawa et al., 2001; Sakamoto & Yoshida, 2002).

Besides microbial infections, hundreds of studies, most in the Global Dust Belt and Australia, yield quantitative results of the human mortality and morbidity effects of dust particles (e.g., De Longueville et al., 2013; Hashizume et al., 2020; Karanasiou et al., 2012; X. Zhang et al., 2016). 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, cerebrovascular mortality, emergency department attendance and hospitalizations for various conditions. Most found evidence that dust storms and mortality are linked, usually expressed as % risk per 10 μg/m^3 PM_{10} concentration. In comparison, in the Americas, such quantitative risk assessment is either nonexistent or limited to a single area. The nationwide US study 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 incomplete for dust storms due to a lack of consistent reporting mechanisms (Tong et al., 2022). Long-term dust climatologies, such as those reconstructed using surface measurements (Hand et al., 2017; Lei et al., 2016; Tong et al., 2012, 2017), can support future epidemiological studies to fill the knowledge gap in this region.

Similarly, the effects of dust particles on transportation (air, land, and sea) safety, and ocean and terrestrial ecosystems are also global (Griffin & Kellogg, 2004; Middleton, 2020). Clearing railway lines of wind-blown drifting sand has been a perennial problem, most evident in China (L. Shi, Wang, & Li, 2020) and Iran (Mehdipour & Baniamerian, 2019). The 1 April 2015, Doha, Qatar extreme dust event, mentioned in Section 5.2, is raised again here to suggest, for important practical reasons, that some advances in research may be near ready for operations (Figure 5). Measured dust concentrations in the Qatar case exceeded 1,000,000 μg/m^3 (Irfan et al., 2017), and most models at the Barcelona SDS-WAS had predicted the incoming episode—the intensity of which qualified it for inclusion in the Rolls-Royce "Duration of exposure versus ash concentration (DEvAC)" chart for hazard to aircraft engines (Lekki, 2017). Looking toward practical, important operational ends, over the last 20 years, more than 150 cases of engine power-loss and damage caused by cloud ice crystals have been recorded.

Initial reports blamed strong winds and blinding dust when the container ship, *Ever Given*, ran aground in the Suez Canal on 23 March 2021 (Guardian, 2021). As investigations continued, the Suez Canal Authority repeated "… the accident [was] mainly due to the lack of visibility …," blinding dust accompanied by 40 knot (~20 m/s) winds (Van Boom & Keane, 2021). The ship blocked international trade for 6 days before being freed on 29 March, with estimates of multi-billion-Euro consequences in fines, lost and delayed international trade and efforts to release the ship. Help in the form of dust and wind forecasts and observed environmental conditions for the safe navigation of the Canal and for the investigation afterward had been available before, during and after the accident. The day prior to the ship's grounding, a 72-hr prediction of the dust storm and the weather conditions that caused it were publicly accessible at the WMO SDS-WAS (http://dust.aemet.es/), with observations and analyses available thereafter.

Despite considerable progress, large gaps remain in knowledge of dust and the risks it poses to society and the environment. Table 1 summarizes some of the most pressing, as well as observations and modeling research needed to fill them. There is lack of process-level understanding of the linkages between dust and its health endpoints, a global issue but even more so across Pan-America, and especially in South America, where studies of health and safety effects of dust are particularly missing. Information on dust composition, including viable dust-borne microorganisms that cause Valley fever and may cause other diseases (for which even less is known) 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. As to dust risks to highway transportation safety, the detection and prediction of small-scale "killer" dust plumes adjacent to roadways represents a major challenge (Sprigg et al., 2022), which calls for new research to deploy next-generation low-cost sensors and satellites near sources at the right time. There is also a need to document dust related

Figure 5. Dust storm and melting on aircraft engines during a dust storm on 1 April 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, Cvetkovic, et al. (2019) and Nickovic, Vukovic, et al. (2019).

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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	
1. The cause-effect between dust and health outcomes is still lacking	1. Transdisciplinary studies on cause-effect relationships between dust and disease burden
2. Knowledge of composition and health effects of dust-borne microorganisms is still limited	2. Low-cost, mobile, and accurate measurements of dust composition, including dust-borne microbes during emission and atmospheric transport
3. Need for operational links between dust observations, model prediction, and public health advisories	3. Better collaboration and communication to improve public awareness of dust hazard risk
4. The design of epidemiological studies to clearly identify exposure to desert dust	4. Standardized modeling of desert dust exposure
5. Long-term studies are lacking	5. Studies on long-term effects, such as cohort studies
6. Studies in South America are lacking	6. Increased encouragement and funding of dust health endpoint research in South America
7. Disparity in dust exposure	7. Contribution of dust to environmental equity
8. Public awareness of dust health risks may be too low	8. Increase publicity and outreach to raise community awareness of dust health hazards, especially in vulnerable communities, and for vulnerable groups (children, the elderly, persons with respiratory conditions)
Environmental health	
1. Assessment of actual microbe transmission through dust still lacking	1. Valley fever surveillance among animals and marine mammals; dust data for risk assessment
2. The impact of dust deposition on marine and terrestrial biosphere communities and productivities is poorly constrained	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
3. The impact of dust storms and windblown events on microplastic dispersion, atmospheric microplastic accumulation, transportation, and deposition	3. Correlations between dust deposition and phytoplankton productivity and harmful algal blooms in freshwater and marine ecosystems
	4. Improve monitoring and detection of atmospheric microplastics; Increase public awareness of microplastics as dust hazards and environmental contaminants; enhance the interdisciplinary collaborations for modeling forecast
Safety	
1. Detection of small-scale dust plumes adjacent to highways	1. Improve remote sensing; low-cost sensor deployment; improved data access/use
2. Dust-associated highway accidents improperly recorded in highway crash/public safety data (e.g., listed as "wind")	2. Improve coding of actual weather associated with road accidents
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	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
4. Dust hazard prediction for ground transportation and aviation	4. Improve dust prediction products and routine utilization in safety applications
Dust observations (in-situ and remote sensing)	
1. Lack of routine ground-based measurements near dust sources and along transport pathways away from urban centers and protected areas	1. 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. Lack of high-resolution source maps	2. Regional and global dust source maps with high spatial and temporal resolutions
3. Low density of in-situ dust monitoring in South America	3. Improve dust observation networks and studies in South America

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Table 1
Continued

Gaps/Needs	Recommended future work
4. Missing key remote sensing capabilities, 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	4. Satellite missions to cover peak dust hours, improve night and below cloud dust detection and dust chemistry/mineralogy/optical properties; new sensors and new technologies such as CubeSats for dust detection at much finer spatial scales
5. In situ measurements of particle dynamics (emission, transport, chemical evolution, and in-cloud processes) are very limited	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
6. Dust-associated weather observations improperly coded (e.g., listed as "haze")	6. Invite citizen scientists' active participation in carefully designed and managed dust observing crowdsourcing projects using smartphones and other personal devices
Modeling and Forecasting	
1. Downscaling capability for dust prediction and early warning from global to regional and local scales still lacking for specific regions/areas of the Americas	1. Closer collaboration of NOAA, NCAR, NASA and NRL global modeling facilities with the WMO SDS-WAS Pan-America Node
2. Assimilation of available satellite, lidar/ceilometer and in-situ dust observations not regularly used by dust forecast models	2. Coordinated international efforts to combine ground-based observations with Earth Observation data and dust prediction 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	3. Stochastic models and turbulence-resolving numerical simulations, such as large-eddy simulation to understand the turbulent transport of dust and sand
	4. Explore new methodology such as artificial intelligence and machine learning to address model shortcomings, for example, uncertainties, errors, and computing capacity bottlenecks

highway accidents properly by transportation and public safety agencies. Improved coding is required to better represent weather conditions, such as explicit use of "blowing dust" instead of "wind" if soil dust becomes airborne and impairs visibility. For all associated risks, better coordination and communication are essential to improve public awareness of dust hazards, and to transition research capabilities into health and safety operations.

9. Conclusion

Dust in the Americas has been associated with unique health and safety effects, most notably coccidioidomycosis or Valley fever, that has spread to many parts of the region with an annual health burden on the order of billions of dollars. Dust also affects environmental health: provides nutrients to increase phytoplankton biomass and harmful algae; contaminates water supplies, soil, and food (crops/fruits/vegetables and ready-to-eat meat); spread crop pathogens, pests, and unintended herbicides and pesticides; causes Valley fever among domestic and wild animals and livestock and may cause other diseases; transports heavy metals, radionuclides, microplastics, other contaminant compounds and diseases; and reduces solar power generation and depletes soil fertility. Dust is also a well-documented hazard to road transportation, aviation, and marine navigation, in the southwestern US in particular, 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 Americas, making it critical to develop effective measures and strategic plans to mitigate these harmful effects. Current efforts include regional and international collaborations to enhance dust observations and prediction capability, implement soil conservation measures, design specific dust mitigation and public awareness projects for transportation safety, and conduct Valley fever surveillance. While this work emphasizes the Pan-American region, many of the dust effects found in this region also exist in other parts of the world.

Critical gaps in knowledge remain. Among the most pressing is a lack of process-level understanding of linkages between dust and its health endpoints, including prevalence of Valley fever among humans and animals. Furthermore, operational links between dust observations, dust prediction, and public health/safety advisories are still missing, more so in South America than in North America and the Caribbean. Another significant challenge to mitigate 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 most fatal accidents and attendant societal costs. To address these challenges, it is important to advance dust research through both observations and modeling and to implement mitigation measures that emerge from research. Finally, it is essential to engage in capacity building in affected communities, particularly in regions with fewer resources, through collaborative frameworks such as the WMO SDS-WAS and PAHO. Whether these regional efforts succeed will depend on the successes and failures of local and regional policies and interdisciplinary social and environmental science (e.g., Sprigg & Steinberg, 2016).

Data Availability Statement

The Sand and Dust Storm Index data are obtained from Vukovic (2019) and Vukovic Vimic (2021), and available from the United Nations Convention for Combating Desertification (https://maps.unccd.int/sds/). The spatial distribution of *Coccidioides* fungi is reproduced from Barker et al. (2019). The satellite dust observation is provided by NASA WorldView (available from https://worldview.earthdata.nasa.gov). The prediction of dust melting intensity on aircraft engines is obtained from Nickovic, Cvetkovic, et al. (2019) and Nickovic, Vukovic, et al. (2019).

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