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Dust in the Critical Zone: North American case studies

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ABSTRACT

The dust cycle facilitates the exchange of particles among Earth's major systems, enabling dust to traverse ecosystems, cross geographic boundaries, and even move uphill against the natural flow of gravity. Dust in the atmosphere is composed of a complex and ever-changing mixture that reflects the evolving human footprint on the landscape. The emission, transport, and deposition of dust interacts with and connects Critical Zone processes at all spatial and temporal scales. Landscape properties, land use, and climatic factors influence the wind erosion of soil and nutrient loss, which alters the long-term ecological dynamics at erosional locations. Once in the atmosphere, dust particles influence the amount of solar radiation reaching Earth, and interact with longwave (terrestrial) radiation, with cascading effects on the climate system. Finally, the wet and dry deposition of particles influences ecosystem structure, composition, and function over both short and long-term scales. Tracking dust particles from source to sink relies on monitoring and measurement of the geochemical composition and size distribution of the particles, space-borne and ground-based remote sensing, and dust modeling. Dust is linked to human systems via land use and policies that contribute to dust emissions and the health-related consequences of particulate loads and composition. Despite the significant influence dust has in shaping coupled natural-human systems, it has not been considered a key component of the Critical Zone. Here, we demonstrate that dust particles should be included as a key component of the Critical Zone by outlining how dust interacts with and shapes Earth System processes from generation, through transport, to deposition. We synthesize current

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understanding from global research and identify critical data and knowledge gaps while showcasing case studies from North America.

1. Introduction

Critical Zone science is an interdisciplinary field of study that examines the Earth's near-surface environment aimed at understanding and quantifying life-sustaining resources (Ashley, 1998, National Research Council (NRC) et al., 2001). The Critical Zone is defined as the thin outer veneer of the Earth's surface extending from the top of the vegetation canopy down to the base of active groundwater circulation (White et al., 2015a). This definition excludes atmospheric materials and their interactions with other Earth spheres (e.g. lithosphere, biosphere, hydrosphere…). The Critical Zone plays an integral role in soil formation (Anderson et al., 2007; Dixon, 2015), water storage and filtration (Brooks et al., 2015; Sprenger et al., 2019), nutrient cycling (Chorover et al., 2007; Akob and Küsel, 2011), carbon storage/exchange (Mahowald et al., 2017; Keller, 2019; Wiesmeier et al., 2019), and hazard mitigation (Regmi et al., 2015). This coupled human-natural system spans multiple spatial and temporal scales (Brantley et al., 2007; Sullivan et al., 2022). Anthropogenic land-use alterations (Richter Jr and Mobley, 2009; Kumar et al., 2018) and climate change (Rasouli et al., 2019) are contemporary driving forces. In this review, we present information supporting an extension of this definition to acknowledge the profound impact of dust on global ecosystem processes. This omission currently hinders our understanding, research efforts, data availability, and policy formation related to the dust cycle and anthropogenic dust pollution, especially across ecological, geographic, and political boundaries.

The emission, transport, and deposition of dust is one of the only processes that connects all components of the Critical Zone on local, regional, and intercontinental scales, making dust a key driver of ecosystem and environmental conditions. Dust emissions are generated from the lithosphere, pedosphere, biosphere, and anthroposphere, which together control the physical, biological, and chemical properties of emitted airborne dust particles (Field et al., 2009). Dust emissions are also enhanced or inhibited by the strength and texture of the land surface (Belnap and Gillette, 1998), the distribution of topographic features (Gillette, 1999; Engelstaedter et al., 2003; Pye, 2015), vegetation cover, snow or ice cover, and land use (Lambert, 2020). The hydrosphere and atmosphere also govern dust emissions by regulating soil moisture levels, supporting vegetative growth, and influencing the local and regional meteorological conditions and climate patterns that generate dust (Field et al., 2009).

Once in the atmosphere, dust particles play a key role in Critical Zone processes including climate, the hydrologic cycle, and atmospheric chemistry. Dust optical properties such as scattering, absorption, and extinction influence the Earth's radiation balance by altering the distribution and intensity of both shortwave and longwave radiation (Choobari et al., 2014), which can influence weather patterns, climate, visibility, and atmospheric stability (Dunion and Velden, 2004). Dust also regulates cloud coverage and precipitation by serving as cloud condensation nuclei (CCN) (Karydis et al., 2011) and ice nucleating particles (INP) (Boose et al., 2016a, 2016b). Dust has contributed substantively to the alkalization of precipitation pH, particularly in the western U.S., by substantively neutralizing atmospheric acidic gases, such as nitric and sulfuric acid (Brahney et al., 2013; Grider et al., 2023). When entrained in the atmosphere, dust reduces horizontal visibility and negatively impacts air quality, posing a risk to human health (Pope III et al., 2002; Derbyshire, 2007; Mahowald et al., 2007; Baddock et al., 2014; Tong et al., 2023b).

Dust deposition affects the biosphere through numerous mechanisms (Ravi et al., 2011). Dust composition may alter the pH of surface waters (Rogora et al., 2004; Brahney et al., 2014) and supply key macro- and micronutrients to marine (Duce et al., 1991; Jickells et al., 2005; Meskhidze et al., 2005; Gaston, 2020), freshwater (Morales-Baquero et al., 2006; Brahney et al., 2015a; Scholz and Brahney, 2022), and terrestrial ecosystems (Chadwick et al., 1999; Reynolds et al., 2006b; Aciego et al., 2017; Ponette-González et al., 2018). Dust can also deliver microorganisms (Griffin, 2007; Smith et al., 2013; Dastrup et al., 2018), microfauna (Rivas Jr et al., 2018, 2019), organic material (McTainsh and Strong, 2007; Field et al., 2009), and toxins (Griffin et al., 2002; Fubini and Fenoglio, 2007) to recipient ecosystems. Dust can also be an important contributor to pedogenesis (Yaalon and Ganor, 1973; Munroe et al., 2020, 2024). Lastly, dust deposition can affect the cryosphere by reducing the albedo of snow and both glacial and sea ice, thus accelerating melt. The latter has downstream ecological and anthropogenic consequences through alteration of the resultant hydrographs (Painter et al., 2010; Skiles et al., 2018b).

The term *dust* can be defined differently depending on the disciplinary context. Challenges in defining dust arise because particles in the atmosphere can be both inorganic and organic, can be generated by both anthropogenic and natural processes, and can undergo chemical and physical transformations during atmospheric transport. Some scientists use the term *dust* to refer only to the inorganic mineral fraction of dust because inorganic mineral particles have distinct source regions and emission pathways and behave differently than organic particles in processes such as cloud formation (Creamean et al., 2016; Knopf et al., 2018; Kanji et al., 2019). However, not just mineral material is emitted, transported, and deposited from and to the Earth's terrestrial surface, and minerals are not the only components of soils. Eroded soils and Earth material also contain organic matter, biota, synthetic substances such as fertilizers and microplastics, and adsorbed nutrients and heavy metals. Thus, many scientists and agencies use the term dust to refer collectively to all particles emitted to the atmosphere from the Earth's surface (i.e. primary aerosols), excluding secondary particles formed in the atmosphere like sulfates and nitrates (Okin et al., 2004; Mladenov et al., 2011; Brahney et al., 2021a). This more expansive definition of dust is used particularly when considering the ecological impacts of dust as the labile fractions of nutrients and metals are dominantly found within the organic fractions (Lawrence et al., 2010; Scholz and Brahney, 2022). In addition, teasing apart the mix of particles that are emitted, transported, and deposited is not currently physically or chemically possible.

An individual particle may be a mixture of inorganic and organic compounds, as well as natural and anthropogenic materials. Because biological compounds, microorganisms, pollen, aerosolized salts, and combusted black carbon are all found within the mix of atmospheric aerosols that originate from terrestrial surfaces and may contribute to Critical Zone processes such as fertilization, salinization, and acceleration of snow and ice melt, we include these particles in the definition of dust here. Although secondary aerosols formed in the atmosphere (sulfate and nitrate) can wreak havoc on ecological systems through acid and nutrient deposition (Likens et al., 1972; Galloway et al., 1995; Driscoll et al., 2001), secondary aerosols are not considered in detail in this review due to the abundance of literature on this topic. For clarity, through this review, sections that consider only the mineral fraction use the term "mineral dust", while "dust" refers to all atmospheric aerosols generated from terrestrial dust sources on the surface of the Earth.

Despite the significant influence that dust emissions, transport, and deposition play in shaping ecosystems, dust has not been conventionally considered a key component of the Critical Zone (Giardino and Houser, 2015; Lee et al., 2023). In this review, we follow the dust cycle from generation, through transport, to deposition, making connections to the Critical Zone at each stage. We draw understanding from global research but focus on North American examples. Although most terrestrial dust is generated in and transported from the "Global Dust Belt" stretching across Africa and Asia, we focus on North America because local to regional dust events and small-scale persistent events have a substantial capacity to modify Critical Zone processes. These local to regional dust events are often ignored or absent from reviews that focus on global dust phenomena. In addition, North America has a strong Critical Zone research infrastructure (Minor et al., 2020) and is ideally located for investigations of dust emissions from natural arid, semi-arid, and modified landscapes that range from remote to well-populated. The region also contains a wealth of affected landscape types with substantive research from which to discuss linkages to Critical Zone processes.

We outline some of the key methods that scientists use to track dust from source to sink, and we identify knowledge gaps and important areas for future research. We also aim to spotlight the interplay between human and natural systems across scales – from the predicted future emissions of dust at the continental scale to the chemical composition of an individual dust particle. Each component of the dust cycle is influenced by anthropogenic activities and in turn has consequences for human health and well-being. In many cases, distinguishing between the natural and anthropogenic factors at play is challenging given the current available methods for tracking dust from source to sink. Furthermore, climate, land-use, and policy decisions continue to support the potential for increased dust emissions in many regions of the U.S. (Webb and Pierre, 2018; Ge et al., 2022), making an understanding of the human-natural dust cycle even more pressing. The overall objective of this effort is to review the extensive connections between dust and Critical Zone system components and to provide information that supports inclusion of atmospheric dust as a key component of the Critical Zone (Fig. 1). The review is divided into five key sections that broadly cover the dust life cycle (emission, transport, and deposition), dust composition, and how dusts are measured, tracked, and modeled. Each section provides an overview followed by detailed examples of how dust interacts with Critical Zone processes at each stage of the life cycle. Significant regions of North America discussed throughout the manuscript are depicted in Fig. 2.

2. Dust emissions

The dust cycle begins with dust generation, a process that is controlled by properties of the Critical Zone itself, such as soil grain size, soil moisture, soil cohesion, vegetation, and topography, as well as atmospheric conditions such as wind speed and humidity. The wind erosion of soils can in turn shape vegetation patterns in semi-arid landscapes through the redistribution of soil nutrients (see Section 5.1.2). Over geologic history, dust emissions have varied with glacial climate stages and climate factors such as drought and wind speeds (Muhs, 2013; Arcusa et al., 2019). More recently, anthropogenic activities have increased dust emissions through climate change, activities that alter attributes of and processes in the Critical Zone, and activities that directly emit particles to the atmosphere (e.g., cultivation, grazing, unpaved roads, construction, and industrial drilling) (Zender et al., 2004; Belnap et al., 2009; Brahney et al., 2015a; Webb and Pierre, 2018).

2.1. Dust generation

Dust emissions from the Earth's terrestrial surface arise from a complex interplay of natural and human-driven factors. Four primary mechanisms drive dust emissions: saltation bombardment, aggregate disintegration, direct aerodynamic entrainment, and eolian abrasion (Shao et al., 2011a; Sweeney, 2022). Direct aerodynamic entrainment can be a highly effective mechanism in disturbed soils with unlimited dust supply (Zhang et al., 2016) or in areas accumulating large amounts of unconsolidated sediment, such as river deltas where dust emission occur from wave breaking and bubble burst phenomena (Cornwell et al., 2020; Li et al., 2020a). Saltation bombardment is characterized by large (sand-sized, > 50 μm) saltating particles being lofted and impacting a fine-grained surface, breaking the bonds between the grains and liberating dust particles (Shao et al., 1993). Aggregate disintegration, often

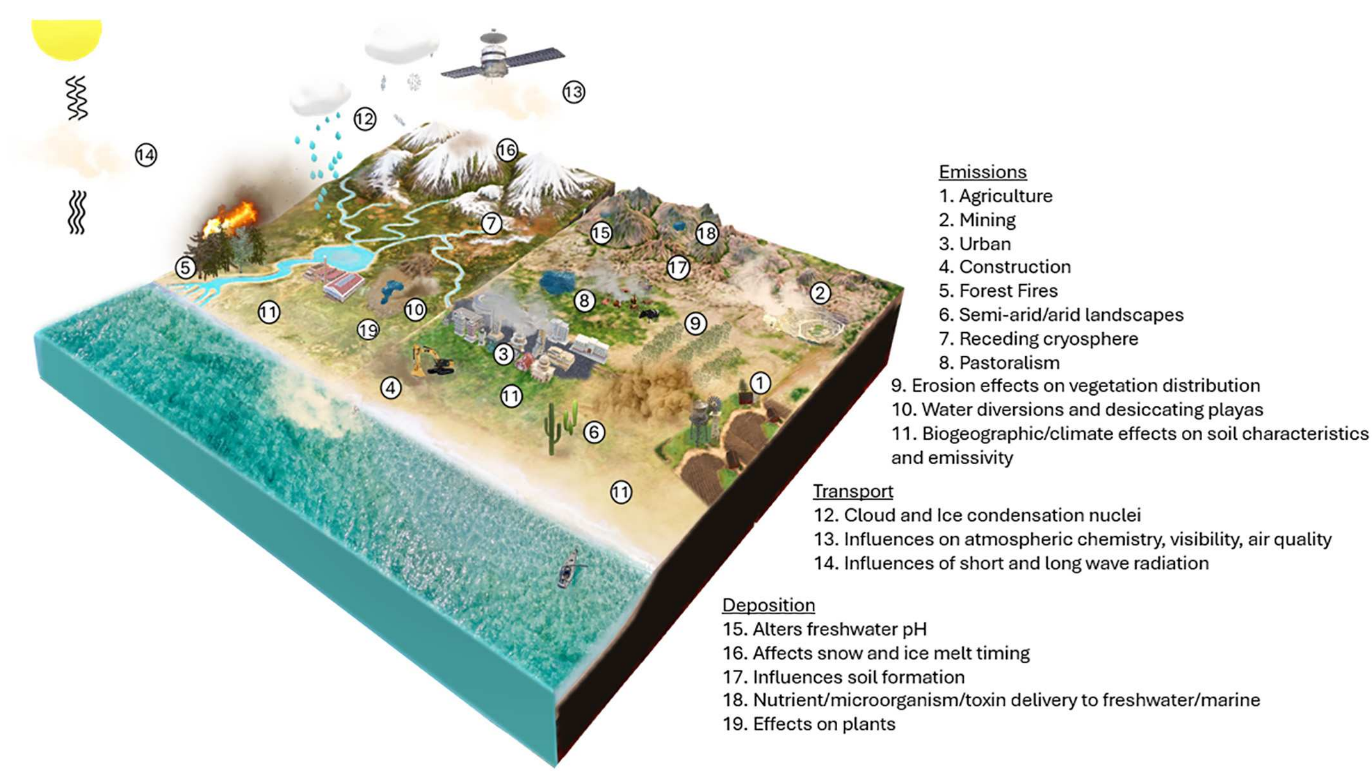

Fig. 1. Dust interactions with the Critical Zone from emissions, through transport, and deposition. Image was created through compositing images obtained using Creative Commons Search Portal and educational stock images, licensing for the base model was obtained 2024.

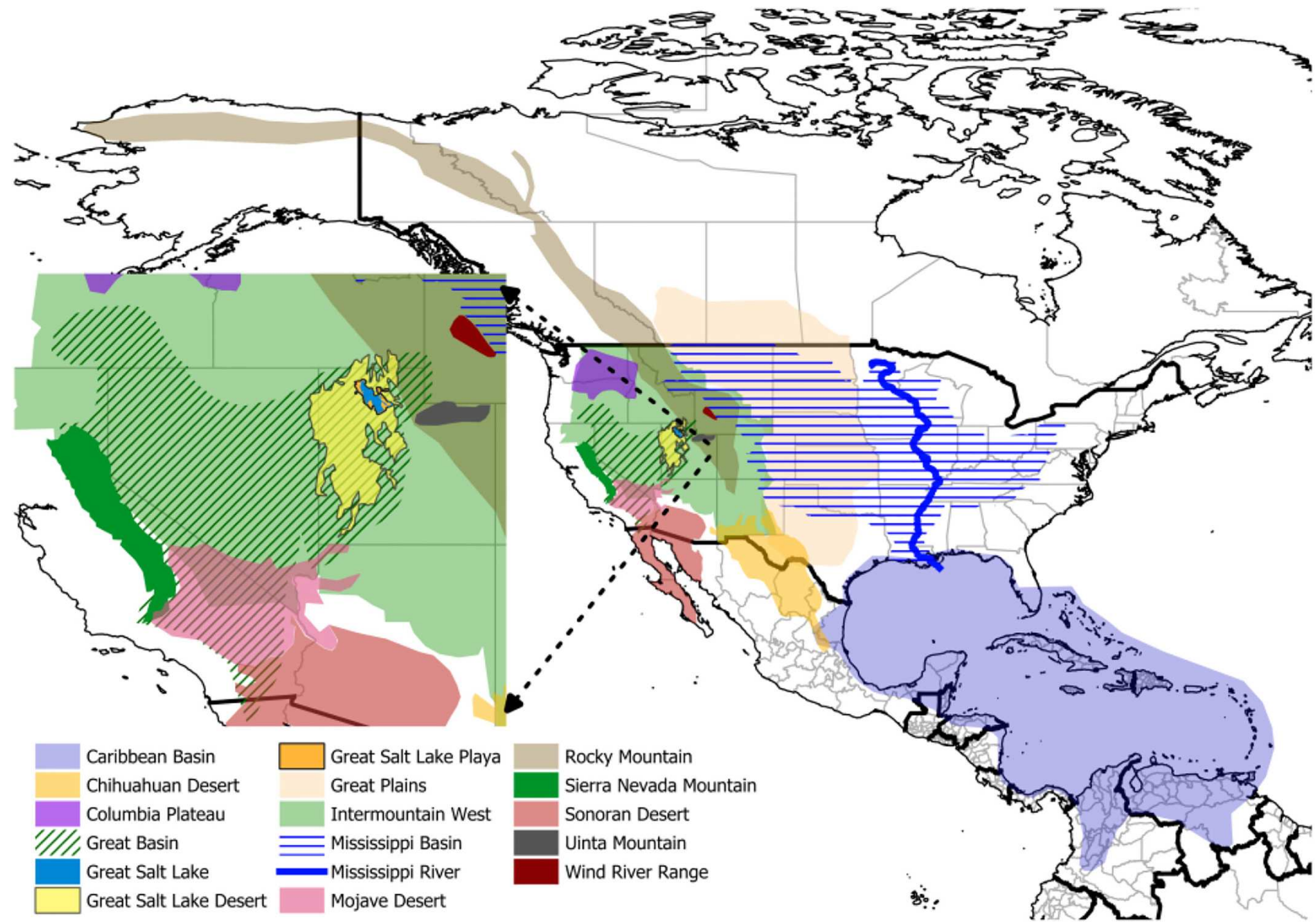

Fig. 2. Major dust producing regions of North America and other significant locations discussed repeatedly throughout the text. The Columbia Plateau and Rocky Mountain regions were adapted from maps created by Encyclopedia Britannica, while the Great Basin and Intermountain West regions come from maps produced by United States Geological Survey (USGS). The Caribbean Basin area was represented based on the map developed by the United States and RED-MEX Long Term Ecological Research (LTER) network (2009). Meanwhile, the boundaries of the Chihuahuan, Sonoran, and Mojave deserts were taken from the Chihuahuan Desert Education Coalition (2022). The Great Salt Lake, Playa, and Desert were extracted from Abbott et al. (2023). The Great Plains were sourced from a map created by the Encyclopedia Britannica (2011), and the Mississippi River and Basin data come from the United States Environmental Protection Agency. The Sierra Nevada and Uinta Mountains regions were drawn from data obtained by Dale (1999) for the US Forest Service and Sprinkel (2014) for the Utah Geological Survey, respectively. Finally, Wind River Range was drawn from Orme et al. (2016).

considered a component of saltation bombardment, occurs when aggregates (compound particles) are lofted and break apart upon impacting a surface or each other, contributing to the dust plume (Kok, 2011). The size of the aggregate or saltating grain able to be lofted is dictated by the wind speed (Chepil and Woodruff, 1957; Wang et al., 2019). Direct aerodynamic entrainment is a dust emission mode in which fine-grained material is entrained in the wind stream in the absence of saltating particles (Sweeney, 2022). Eolian abrasion is the chipping and eroding of saltating grains during eolian transport. This process rounds the larger saltating grains and reduces the overall grain size distribution of the saltators (Whalley et al., 1982, 1987).

The generation of dust particles by saltation bombardment and aggregate disintegration is the principal mechanism for the natural entrainment of dust by wind (Shao et al., 1993; Sweeney, 2022). Direct aerodynamic entrainment and eolian abrasion require high wind speeds and produce low dust fluxes in natural environments due to strong interparticle forces and dust supply limitations (Greeley and Iversen, 1987; Shao et al., 1993; Loosmore and Hunt, 2000; Kok et al., 2012). The relative importance of these four physical properties is largely determined by the soil composition and texture. Soils with a large fraction of fine (clay- and silt-sized) grains are most susceptible to saltation bombardment and aggregate disintegration (Shao, 2008; Swet and Katra, 2016). In contrast, eolian abrasion dominates in sandy soils with active sand dunes (Bullard et al., 2004; Jerolmack et al., 2011; Crouvi et al., 2012; Parajuli et al., 2016; Huang et al., 2019). Lastly, direct entrainment can be the primary mechanism for dust emission mechanism for loess deposits (Sweeney and Mason, 2013) and fine soils without crust (Loosmore and Hunt, 2000). Although eolian abrasion and direct aerodynamic entrainment generate relatively low dust fluxes compared to saltation bombardment and aggregate disintegration, active sand dunes and loess deposits extend over large geographic areas. As a result, direct aerodynamic entrainment and eolian abrasion are likely significant contributors to the global dust budget (Kjelgaard et al., 2004; Sharratt et al., 2007; Crouvi et al., 2008, 2010; Sweeney and Mason, 2013). However, the relative contributions of these four mechanisms to the global dust budget are not fully understood because the existing quality and availability of data are insufficient to validate the dust emission schemes utilized by global dust transport models (Bryant, 2013).

Anthropogenic activities that directly disturb the soil or destroy surface crusts can drastically increase the dust supply and result in dust emissions (Zobeck et al., 2013). Common anthropogenic processes that can accelerate dust emissions (Fig. 3) include cropland agricultural activities (Baker et al., 2005; Sharratt et al., 2010; Faulkner et al., 2011),

Fig. 3. Anthropogenic drivers of dust emission a) dust generated by an ATV (Photograph by David G. Paul, used with permission), b) dust generated off the well pads in Wyoming (Photograph by Dawn Ballou, Pinedale Online!, used with permission), c) Dust emission from the Owens Lake playa (Photography by Brian Russel, Great Basin Unified Air Pollution Control District, used with permission), d) Emissions from agricultural fields in New Mexico (Photograph by Dr. J. Brahney, Associate Professor, Department of Watershed Sciences Utah State University, used with permission).

grazing (Karnieli and Tsoar, 1995; Neff et al., 2005; Vermeire et al., 2005; Belnap et al., 2009), mining (Ghose and Majee, 2000; Petavratzi et al., 2005), construction and cement milling (Abdul-Wahab, 2006), military exercises (Gillies et al., 2010), off-road driving (Goossens and Buck, 2009, 2014), unenclosed storage piles of wind-erodible material (Chalvatzaki et al., 2012), and other human activities, such as water extraction and lake desiccation. In addition, road dust and tire wear particles are emitted to the atmosphere from the mechanical forces generated by the friction of tires on unpaved and paved road surfaces (Grigoratos and Martini, 2014; Evangeliou et al., 2020). This dust may contribute substantively to the total atmospheric dust load. For example, Heindel et al. (2020) detected much larger dust fluxes (23.7 ± 0.5 g m^{-2} yr^{-1}) at collection sites near construction as compared to montane and alpine sites (8.9–9.8 ± 1.4 g m^{-2} yr^{-1}), illustrating the importance of dust fluxes from human land disturbance within built environments. However, dust generated within urban centers may not be transported long distances because buildings disrupt air flows necessary to move particles high into the atmosphere; as a result, dust deposition within urban environments can be an order of magnitude greater compared to locations a few kilometers outside the urban area (Brahney, 2019; Heindel et al., 2020; Grider et al., 2023).

Wildfires, which are exacerbated by human activity (Syphard et al., 2017), contribute to dust production both during burning and through their effect on the landscape. Dust emissions are enhanced in active wildfires and burn scar areas due to the reduction in vegetation, whether through controlled burning or through recent increases in wildfire activity (Zobeck et al., 1989; Wagenbrenner et al., 2017; Wagner et al., 2018, 2021; Treminio et al., 2024). A recently recognized mechanism of dust production is the emission of fine dust by winds associated with pyroconvection at the edge of a burning fire (Wagner et al., 2018). Soil-derived particles on vegetation, particularly grasses, can become mobilized into the atmosphere during wildfire events, though often make up a small proportion of the emitted material (Gaudichet et al., 1995; Li et al., 2003)

The threshold friction velocity, or the wind speed required to liberate particles from the surface, depend on both atmospheric and land surface conditions (Sweeney, 2022). For instance, the type, fractional coverage, and structure of vegetation or built surfaces, their aerodynamic roughness, soil crusting, soil moisture, soil texture, and degree of surface disturbance play a role in determining friction velocities and subsequently the thresholds for dust entrainment (Marticorena et al., 1997; Minvielle et al., 2003; Li et al., 2013; Webb et al., 2014; Sweeney, 2022). These factors are in turn shaped by climate conditions and human land-use practices, highlighting the intricate connections between the biosphere, geosphere, and atmosphere. Additionally, surface crusts, both biological and physical, act to inhibit dust emissions (Belnap, 2001). Thin crusts, in the absence of saltating particles or extremely strong winds, are sufficient to inhibit dust emission (Gillette et al., 1982; Brungard et al., 2015). However, crusts are easily disturbed by human activity, and can take considerable time to reform (Gillette et al., 1982; Belnap, 2003; Belnap et al., 2014; Brungard et al., 2015). The moisture content of the soil also influences the threshold friction velocity, with capillary water in moist soils leading to an increase in the threshold as soil moisture increases (Chen et al., 1996; Fécan et al., 1998; Dong et al., 2002). Conversely, in air-dry soils, where capillary water is negligible, the threshold friction velocity decreases as atmospheric humidity increases (Ravi et al., 2004). Thus, drought and anthropogenic water diversions that lead to the desiccation of wetlands and lakes exacerbate dust emissions (Gill, 1996; Perry et al., 2019; Carling et al., 2020; Zucca et al., 2021).

2.1.1. Dust emissions through time and key knowledge gaps

Dust emissions through recent geologic history (Quaternary; 2.58 Ma - Present) are strongly influenced by climate. During glacial periods, it is estimated that dust fluxes were 2–20 times greater than interglacial periods due to aridity, high wind speeds, reductions in sea-level, and changes in vegetation cover (Jickells et al., 2005). Elevated dust emissions during glacial periods relative to interglacial periods had a strong influence on global biogeochemical cycles. For instance, dust additions to marine environments were 3–5 times higher during glacial periods (3–5 g cm^{-2} kyr^{-1}) compared to interglacial periods (1 g cm^{-2} kyr^{-1}), and dust additions during glacial periods provided key nutrients, in particular Fe, which may have supported increased drawdown of CO_2 from the atmosphere (Maher and Dennis, 2001; Shaffer and Lambert, 2018). The main sources of North American dust in the last glacial period include the Great Plains, western deserts, and the Greater Mississippi Basin (Mahowald et al., 2006a). In the late Pleistocene to early Holocene (12–15 kya), dust emissions increased likely due to the shrinking of the large inland pluvial lakes and the exposition of their playas (Gill, 1995, 1996; Reheis, 2006; Reynolds et al., 2007; Reheis and Urban, 2011). Dust deposition from this period added key nutrients to soils as well as fine particles that increase water-holding capacity and together support present-day ecosystems (Reynolds et al., 2007) (Section 5.1.1).

Dust in the present era is estimated to have increased by 1.3 to 45 times compared to the pre-industrial era (Hooper and Marx, 2018). Dust emissions in North America are controlled by a combination of natural and anthropogenic forcing (Munson et al., 2011; Copeland et al., 2017; Duniway et al., 2019). Currently, the major natural dust sources in the U.S. often arise from landscapes such as alluvial desert lowlands, desiccated playas, and semi-arid agricultural landscapes of the west and Great Plains (Reheis and Kihl, 1995; Prospero et al., 2002; Reheis et al., 2002; Bullard et al., 2011; Ginoux et al., 2012) (Fig. 4). Anthropogenic activities may enhance natural dust production through the destabilization and active disturbance of soils or through the creation of new dust sources. Ginoux et al. (2012) estimated that slightly over 50% of dust emissions per year in North America are anthropogenic in origin. A key example is the 1930s Dust Bowl, where a combination of land use policy and drought led to severe erosion of the topsoil and massive dust storms (Peters et al., 2007; Lee and Gill, 2015). The aftermath was severe because the natural ecosystems were decimated, forcing the migration of 3.5 million people (Worster, 2004).

In recent decades, a combination of climate factors (drought, wind speeds) and human activities have been linked to rising dust emissions in regions of North America (Neff et al., 2008; Brahney et al., 2013; Hand et al., 2016; Tong et al., 2017). For example, through the late Holocene, human activities such as agriculture and livestock grazing led to a 500% increase in dust deposition in the southwestern U.S. (Neff et al., 2008). On shorter time scales, land-use activities such as intense oil and gas activity (Brahney et al., 2015a; Tyree et al., 2024), recreation (Goossens et al., 2012; Nauman et al., 2018), urbanization, and industry (Goodman et al., 2019; Marcy et al., 2024) have been shown to increase dust emissions in the U.S. Western water uses and policies also contribute to dust production through the diversion and appropriation of water that exposes dry lake beds to erosion (Gill, 1996; Reheis, 1997; Jones and Fleck, 2020; Null and Wurtsbaugh, 2020; Zucca et al., 2021), as well as U.S. policies that incentivize fallow agricultural fields (Ge et al., 2022). In northern latitudes, an emerging source of dust is resulting from the retreat of glaciers, shorter duration of snow cover, and drought (Prospero et al., 2012; Bachelder et al., 2020; Meinander et al., 2022; Barr et al., 2023; St. Louis et al., 2024). For example, the retreat of the Kaskawulsh Glacier and the redirection of meltwaters led to the sudden desiccation of the Ä'äy Chù (Slims River), the bed of which contained

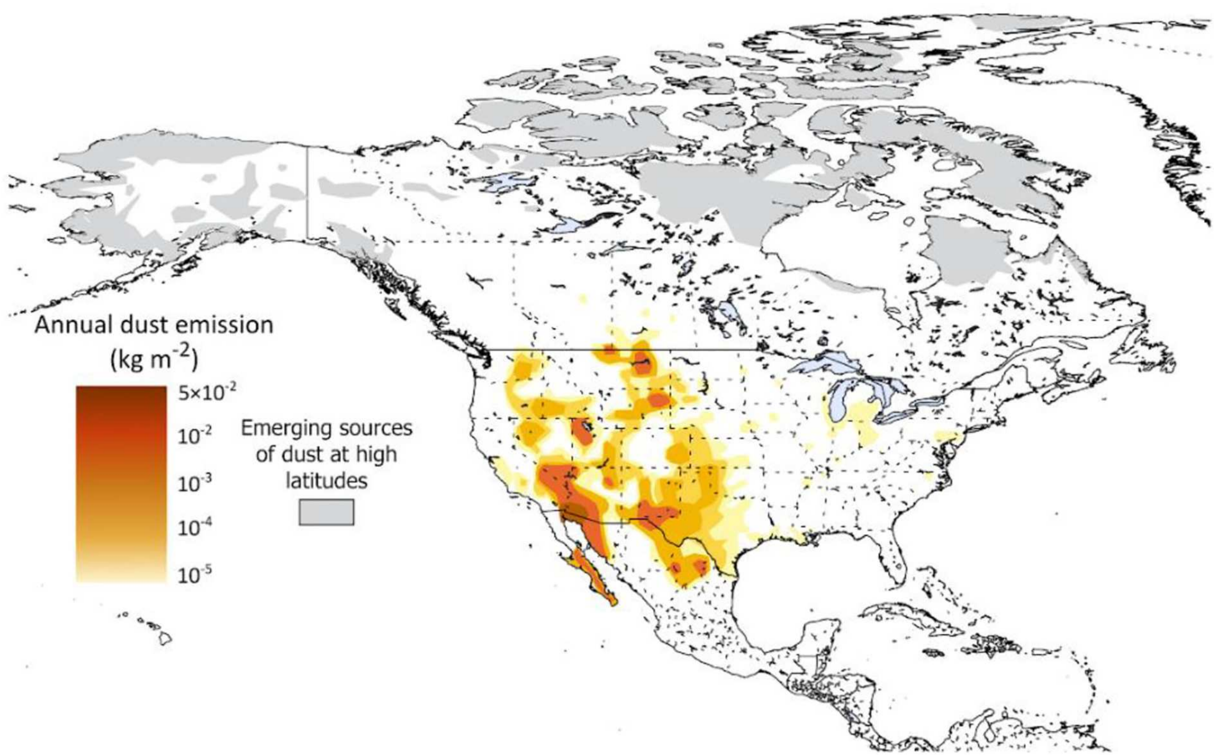

Fig. 4. Soil dust source regions of North America derived from the SILAM (System for Integrated modeling of Atmospheric composition) model represented in Meinander et al., 2022. SILAM is a global atmospheric dispersion and chemistry model in which the dust emission estimate is based on the meteorological IFS model of the European Centre for Medium-Range Weather Forecasts (ECMWF), point- and area- source inventories of sea salt, wind-blown dust, natural pollen, and natural volatile organic compounds, as well as physico-chemical transformation modules that include aerosol dynamics in the air. The emission model was subsequently validated with aerosol optical depth (AOD) data from AERONET (Aerosol Robotic Network). Gray shaded areas represent emerging potential dust sources where data is limited. Figure modified from Meinander et al., 2022.

abundant glacial flour. Measurements of aerosols reached as high as 3950 μg m^{-3} (Bachelder et al., 2020). At present, there is limited detailed information on historical and present-day sources and emission rates at northern locations; however, glacial dust contains some of the highest concentrations of bioavailable micronutrients, and thus the ecological significance of this emerging source is likely underappreciated at present (Koffman et al., 2021).

The future of dust production is highly uncertain, with models suggesting increases, decreases, or no change (Mahowald and Luo, 2003; Mahowald et al., 2006b; Stanelle et al., 2014; Webb and Pierre, 2018). In part, this is due to the uncertainty surrounding the anthropogenic contribution to the atmospheric dust load, with estimates ranging from 5 to 60% (Tegen and Fung, 1994; Mahowald et al., 2010; Shao et al., 2011b; Ginoux et al., 2012; Chen et al., 2023b), as well as novel sources of dust as landscapes change under climate (Meinander et al., 2022; Aryal and Evans, 2023). A study using output from 11 CMIP6 earth system models investigated regionally varying effects on wind erosion (Aryal and Evans, 2023). This study determined that dust emission sensitivity to temperature is strongest in wet climates and that dust emission is most sensitive to precipitation in colder and drier climates. Although increasing temperatures due to climate change will promote global dust emission, changing precipitation patterns will likely alter the hemispheric balance of dust leading to higher dust production in the southern hemisphere and lower dust production in the northern hemisphere.

In the U.S., future projections predict increased dustiness in the Southern Great Plains due to increased aridity, but uncertainties are large, and anthropogenic land use factors were not included (Pu and Ginoux, 2017). Other land use changes over the last decades include increases or conversion from pasture to agricultural lands, increases in developed lands mainly in the western U.S., and increases in fire-impacted landscapes (Homer et al., 2020; Auch et al., 2022). Although all these land-use changes may increase soil emissivity from the Critical Zone, repeated fires can lead to invasive plant encroachment and changes in dust activity, including dust suppression (Treminio et al., 2024). Many studies have found that regional changes in dust emissions will be driven by local variations in vegetative cover, plant community composition, wind speeds, and high-intensity erosive weather events (Lee et al., 2009; Brahney et al., 2013; Csavina et al., 2014; Flagg et al., 2014; Ridley et al., 2014; Edwards et al., 2019; Kandakji et al., 2021; Li et al., 2021), and the role that these combined factors may play in future dust emissions remains unclear.

3. Dust composition

Dust composition is controlled by the parent material of the source region as well as reactions that occur during transport. Dust material may include inorganic (mineral), organic (soil organic matter, bacteria/fungi, pollen, spores, insect and plant fragments, charcoal, and algae), and synthetic components (plastic polymers, tire wear) (Fig. 5). Dust may include any size particle in the atmosphere, although the genesis and composition of different size fractions vary. Few studies have attempted to quantify the relative contributions of all these components within dust, though Brahney et al., 2020a broadly reported that dust deposition from western U.S. protected areas contained 50% organics, 46% inorganics, and 4% polymers by particle.

3.1. Regional sources and transport controls on dust composition

Dust originating from the major deserts tends to be dominated by minerals. For example, dust from the Sahara Desert contains just ~1% organic matter (Eglinton et al., 2002). In contrast, dust originating from some agricultural soils of the southwestern U.S. can have organic contents up to 67% (Dahms and Rawlins, 1996; Malm et al., 2004; Van Pelt and Zobeck, 2009; Lawrence and Neff, 2009). Because the finer grain fractions are more likely to be emitted into the atmosphere, the composition of dust can be distinct from the parent material composition (Van Pelt and Zobeck, 2007; Reheis et al., 2009; Cesari et al., 2012). Relative to the average composition of the upper continental crust, dust is often enriched in key nutrients such as Fe and P because these elements are associated with or adsorbed to the finer grain and organic fractions (Lawrence and Neff, 2009).

Dust particle diameter can range across several orders of magnitude (~100 nm to >100 μm) (Scheuvens and Kandler, 2014; Adebiyi et al., 2023). 'Fine' particulate matter (PM) is defined as the fraction of aerosols with aerodynamic diameters <2.5 μm ($PM_{2.5}$), and this fraction is often dominated by secondary aerosols, particles such as sulfate, nitrate, and organic aerosols that form in the atmosphere from anthropogenic (industrial and combustion) and biogenic emissions. Particulate matter with aerodynamic diameters between 2.5 μm and 10 μm (PM_{10}), is often referred to as 'coarse' aerosol mass and can be a combination of secondary aerosols and primary aerosols (Hand et al., 2017). Super-coarse and giant are defined as 10–62.5 μm, and > 62.5 μm respectively (Adebiyi et al., 2023). Aerosol monitoring is often restricted to particles with aerodynamic diameters <10 μm, leaving large gaps in our understanding of particulate loads in the atmosphere. Even larger particles (i.e., diameters >100 μm) that are entrained and transported may be resistant minerals such as sand-sized quartz grains (Ryder et al., 2019) or particles of non-spherical shapes with low densities and high aerodynamic lift, such as plastic fibers (Brahney et al., 2021a; Xiao et al., 2023), organic particles (Morley and Robert, 2018), microfossils (Barkley et al., 2021), microinvertebrate propagules (Rivas Jr et al.,

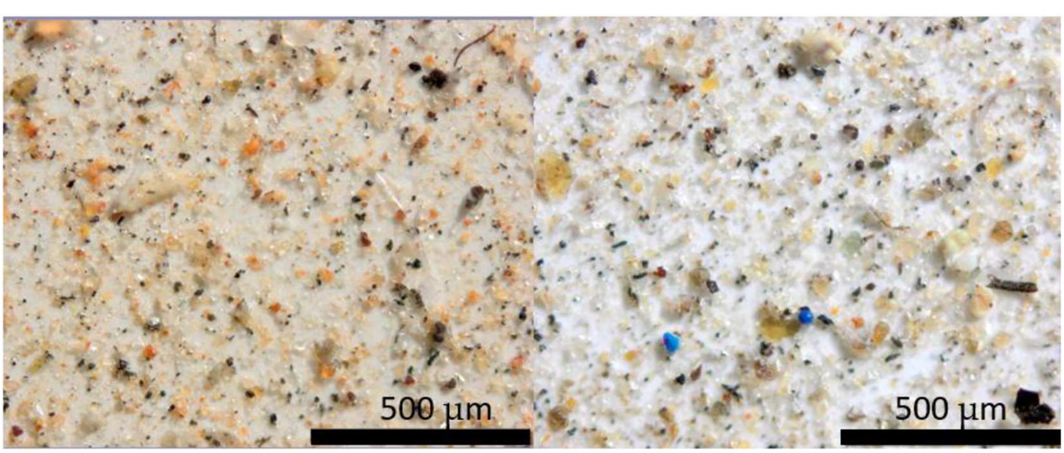

Fig. 5. Examples of dust collected in the United States.. Left dust deposition in Colorado showing a distinct orange hue in contrast to dusts collected in Idaho, where minerals are lighter in color. Photograph by Dr. J. Brahney, Associate Professor, Department of Watershed Sciences Utah State University, used with permission.

2018, 2019), or charcoal (Woodward and Haines, 2020).

Dust that is deposited represents the final stage of its evolution, following the physical and chemical transformations that can occur during atmospheric transport. Transformations during transport include sorting, adsorption, coagulation, photooxidation, and cloud processing, as well as the dissolution and precipitation of minerals (Glaccum and Prospero, 1980; Gieré and Querol, 2010; Hettiarachchi et al., 2019). For example, the concentration of carbonate minerals may decrease through reactions with atmospheric acids (Stockdale et al., 2016). Atmospheric transport affects dust size distributions because large particles generally settle closer to source regions (Maring et al., 2003; Goldstein et al., 2008; Schulz et al., 2012; Scheuvens and Kandler, 2014), although there are reports of giant particles (as large as 450 μm) surviving transport over long distances (>3000 km) (e.g.,Van Der Does et al., 2018).

As urban and industrial emissions have increased and society has created new materials, the composition of dust in the atmosphere has changed. Evaluation of the geochemical makeup of dust within cities relative to upper continental crust and/or likely source areas suggests substantial contributions of particulate pollution from industry to dust within cities. For example, within Salt Lake City, Utah, higher concentrations of Pb, As, La, and Cu, among other elements and nutrients such as P, have been detected (Brahney, 2019; Goodman et al., 2019; Putman et al., 2022). In general, atmospheric deposition of the key nutrient phosphorus is estimated to by 1.4 times greater than the pre-industrial era (Brahney et al., 2015b). Putman et al. (2022) found elevated heavy metals in urban dust with spatial variation in concentration linked to socioeconomic regions in the Great Salt Lake area. In Boulder, Colorado, metals clustered by season, suggesting that metal-heavy particulate matter from Boulder and the surrounding municipalities was transported to the montane and alpine sites seasonally (Heindel et al., 2020). In the southwestern U.S., sediment core and in situ observations have shown that dust has become more enriched in metals through interactions with secondary aerosols and urban emissions. Elevated metal concentrations of As, Cu, Hg, Zn, Cd, Sb, Sn, Pb, Ni and Cr (Moser et al., 2010; Reynolds et al., 2010; Brahney et al., 2014; Gill et al., 2021), have been observed after dust has passed through major urban centers (Marx et al., 2008; Goodman et al., 2019; Heindel et al., 2020) or industrial sites (Van Pelt et al., 2020). In addition, anthropogenic compounds such as pesticides (Richards et al., 2016), polymers, and synthetic rubber from tires have been tracked in dust samples in recent years (Wetherbee et al., 2019; Evangeliou et al., 2020; Brahney et al., 2020a).

3.1.1. *Key data and knowledge gaps*

Because particles with aerodynamic diameters < PM_{10} and $PM_{2.5}$ are regulated in the U.S., aerosol concentration data in these size fractions is available at relatively large spatial and temporal resolution through State and Federal agencies. However, spatial coverage is still insufficient for many epidemiological studies (see Section 4.3), and chemical composition is typically only evaluated on $PM_{2.5}$ samples (Ardon-Dryer et al., 2023a). Our understanding of atmospheric aerosols' composition, particularly within the larger size fraction, is limited. Despite comprising the bulk of dust mass, these larger particles have historically been sampled infrequently at best and over limited spatial scales (Neff et al., 2013; Brahney et al., 2020b). This knowledge gap hinders our understanding of aerosol composition and its role in regulating critical global processes, including biogeochemical cycles, Critical Zone processes, and human and animal health (Ardon-Dryer et al., 2023a). In addition to compositional limitations, spatial gaps in monitoring of dust emissions exist broadly across landscape types including well-known dust-producing regions (e.g., the arid Great Basin; the Dust Bowl region in the Southern High Plains), modified landscapes (desiccated playas, degraded lands, etc.), as well as landscapes undergoing rapid change due to the loss of the cryosphere (e.g., northern landscapes). Gaps in our ability to monitor aerosols in the atmosphere (refer to Section 6.2), and deposition (refer to Section 5) all exist, all of which hinder our ability to predict, model, and understand the role of dust throughout the Critical Zone.

4. Dust in the atmosphere

Once dust is lofted into the atmosphere, it can be transported locally, regionally, or globally (Shao et al., 2011b). In the atmosphere, dust interacts with the climate system by playing a critical role in the formation of clouds and precipitation, precipitation chemistry, and by directly reflecting and absorbing incoming solar radiation as well as terrestrial long-wave radiation (Kok et al., 2023). These, in turn, affect Critical Zone function and processes, such as impacts on hydrology and surface energy balance (Painter et al., 2007). When suspended in the atmosphere, dust also has the potential to directly impact air quality, visibility, as well as human and animal health and well-being in the Critical Zone (Tong et al., 2023b).

4.1. *Atmospheric transport*

Meteorological drivers of local, regional, and transcontinental dust transport are generally separated into two broad categories: synoptic and convective (Novlan et al., 2007; Kelley and Ardon-Dryer, 2021; Ardon-Dryer and Kelley, 2022). Synoptic weather systems are large-scale weather systems that span 100 s–1000s of km and produce strong winds over large areas, while convective weather systems operate on local to mesoscales spanning 1.0 s to 100 s of km (Fig. 6A,B).

Although often less numerous than convective events, synoptic events entrain the greatest amounts of dust (Wigner and Peterson, 1987; Lee and Tchakerian, 1995; Steenburgh et al., 2012; Hahnenberger and Nicoll, 2012; Nicoll et al., 2020) and are responsible for occasional transcontinental dust transport events (Brandli et al., 1977; Park et al., 2007). Synoptic dust events within the U.S. predominantly occur during the cool season (autumn through spring), with a maximum in the spring (March, April, May) (Novlan et al., 2007; Sorooshian et al., 2011; Hahnenberger and Nicoll, 2012). If quantities of dust and atmospheric uplift near the source area are large enough and a vertically stacked upper-level low-pressure area exists in the upper atmosphere, dust can be transported high into the troposphere above the boundary layer. Under favorable meteorological conditions, dust particles may remain suspended for days or in some cases weeks, which allows dust transport across continents and oceans (O'Sullivan et al., 2020). Long-range transport of dust from Africa to North America typically occurs in summer, with lower elevation Critical Zone impacts primarily in the Caribbean Basin and the eastern U.S. (Aldhaif et al., 2020; Hand et al., 2016; Prospero et al., 2012), while transport of Asian dust typically occurs during spring and primarily influences higher elevation Critical Zones in the western U.S. (Creamean et al., 2014; Huang et al., 2022).

Convective weather systems entrain dust when the storm outflow intercepts the ground, generating strong horizontal winds. These winds can at times produce a wall or "front" of dust termed a haboob (Idso et al., 1972; Wigner and Peterson, 1987; Sprigg et al., 2014; Raman et al., 2014; Kelley and Ardon-Dryer, 2021) (Fig. 6C, D). Convective dust events are most prevalent in the warm season, being primarily fueled by moisture inputs from the North American Monsoon in the western U.S. and by the dryline in the Southern Great Plains (Bach et al., 1996; Shafer and Steenburgh, 2008; Jeglum et al., 2010; Wall et al., 2012; Sprigg et al., 2014; Hand et al., 2016; Hyde et al., 2018; Kelley and Ardon-Dryer, 2021).

4.1.1. *Influence of dust on weather*

Dust plays a critical role in the climate system through its role in the formation of clouds and precipitation. The ability of dust to bridge atmospheric and hydrologic cycles hinges on dust particle properties, specifically shape, size, and composition, which influences its potential to nucleate precipitation, acting as CCN or INPs, respectively (McFiggans et al., 2006; Quinn et al., 2008; Koehler et al., 2009; Barahona et al., 2010; Kumar et al., 2011; Murray et al., 2012; Wex et al.,

Fig. 6. A) NASA MODIS true-color image from NASA Earth Observatory, courtesy of Liam Gumley, Space Science and Engineering Center, University of Wisconsin (https://earthobservatory.nasa.gov/images/4054/dust-storm-over-texas). The scene shows a synoptic-scale dust event with numerous regional dust sources in SW North America and Mexico, December 15, 2003. B) NASA true-color image captured by VIIRS on NASA/NOAA Suomi NPP satellite of a Saharan Desert dust plume crossing the Atlantic and blanketing the southern USA, June 24, 2020 (https://climate.nasa.gov/news/2999/nasa-noaa-satellite-analyzes-saharan-dust-plume/). C) A Haboob at Ransom Canyon, Texas. Photography by John Stout, USDA Agricultural Research Service, licensed under the Creative Commons Attribution-Share Alike 3.0 Unported licensed. D) Convective dust in Lubbock Texas, June 5, 2019, Photograph by Dr. Mary Robinson, used with permission.

2014; Kanji et al., 2017; Hiranuma et al., 2021). Playa dust has been shown to be an effective CCN in laboratory experiments (Gaston et al., 2017) and the dominant CCN measured during real-time aircraft observations (Pratt et al., 2010). The hygroscopic behavior of playa dust has been attributed to their internal mixtures with soluble salts, while other components that contain clay minerals can swell and take up water, initiating the formation of cloud droplets (Schuttlefield et al., 2007; Navea et al., 2010; Chen et al., 2020). Coatings composed of other hygroscopic materials such as sulfate or humic-like substances (HULIS) can enhance dust's ability to act as CCN (Hatch et al., 2008; Karydis et al., 2011).

Potassium feldspar and quartz, common mineral components of dust, are important INPs (Chatziparaschos et al., 2023). Agricultural soils have also been shown to be effective INPs in the U.S. (e.g., Knopf et al., 2021). The capability of dust to nucleate ice can either be unaffected by reactions with nitric acid and organic acids (Sullivan et al., 2010) or deactivated depending on the freezing pathway (Möhler et al., 2008; Cziczo et al., 2009; Sullivan et al., 2010; Chen et al., 2023). Nevertheless, uncoated or lightly coated dust aerosols are typically abundant and effective INPs. These are often found originating from agricultural soils (Tobo et al., 2014; Suski et al., 2018), coastal regions (Cornwell et al., 2019), southwestern deserts (DeMott et al., 2003; Richardson et al., 2007; Axson et al., 2016), or distant sources such as Asian and African deserts (Ault et al., 2011; Creamean et al., 2013). Dust containing biological or organic material and bacteria can have enhanced effectiveness as INPs (Hill et al., 2016). For instance, studies by Creamean et al. (2020), Barr et al., 2023, and Barry et al. (2023a, 2023b) found that thawing Alaskan permafrost soil and glacial dust are especially effective ice-nucleating material because of biological and organic components of the dust. These studies suggest that high-latitude dust sources may be underappreciated in the global INP budget. In addition, Froyd et al. (2022) demonstrated that dust aerosol dominates cirrus cloud formation in the Northern Hemisphere (75–93% of clouds seasonally) through global-scale measurements and cirrus formation models.

Given that most precipitation is initiated in the ice phase (Mülmenstädt et al., 2015), dust as INPs and perhaps to a lesser extent, as CCN, may play a key role in modulating rainfall and snowpack, and thus, impacting water resources in various regions of the U.S. (Yin et al., 2002; Solomos et al., 2011; Creamean et al., 2014, 2015, 2016; Fan et al., 2014, 2017; Naeger, 2018; Jha et al., 2021; Mascioli et al., 2021). During transport, atmospheric processing of dust can alter many of the physical and chemical properties that govern atmospheric interactions and determine the direct and indirect climate impacts of dust. Changes to physical properties through atmospheric processing, such as particle shape and size, can affect dust optical and chemical properties during transport and dust hygroscopicity through the coating of dust surfaces with more soluble species (Perry et al., 2004; Hatch et al., 2008; Laskina et al., 2013; Ryder et al., 2013; Alexander et al., 2015; Abdelkader et al., 2017).

The radiative effects of dust — its interaction with longwave and shortwave radiation — can have an impact on the resulting weather. For example, Lerach and Cotton (2018) modeled the effects of large amounts of dust advected out of the Chihuahuan Desert on April 15–16, 2003, on the subsequent severe convective weather outbreak in the Southern Great Plains. Results indicated that increased solar absorption within the dust plume modestly increased pre-storm atmospheric stability at low levels, resulting in weaker convective updrafts and less widespread precipitation.

The radiative properties of dust influenced continued dust emission and large-scale impacts on the Critical Zone over a much longer spatial and temporal scale during the 1930s Dust Bowl in the Great Plains. Modeling by Cook et al. (2008) suggested that the radiative effects of high concentrations of atmospheric dust, centered over the core of the Dust Bowl in the Southern Great Plains, acted as positive feedback to drought and the persistence of Dust Bowl conditions. The increased dust loading in the Dust Bowl core region reduced net radiation at the top of the atmosphere and the land surface. This led to the intensification of the drought over the dustiest region of the Great Plain because anomalous atmospheric subsidence at the time inhibited the inflow of moisture and cloud development (Cook et al., 2009). The physical properties of atmospheric dust combined with human land use mismanagement modified the Critical Zone in the Plains to eventuate North America's greatest dust-related disaster to date (Cook et al., 2009).

4.1.2. Key data and knowledge gaps

Understanding the size distribution of dust in the atmosphere is crucial for evaluating dust impacts on the environment, climate, and human health; however, most studies provide data only over short time periods and narrow spatial extents (Ardon-Dryer et al., 2023a). Studies over longer periods are less common but provide important information regarding climatology and dust size distributions (Marinescu et al., 2019; Ardon-Dryer and Kelley, 2022). Many studies have focused on size spectra of dust emitted and transported from deserts in North Africa and Asia; however, fewer studies report the physicochemical and optical properties of dust emitted from U.S. dust sources (Hand et al., 2002), especially high latitude dust sources that might become increasingly important in a warming climate (Bullard et al., 2016; Meinander et al., 2022). Accurate representation of dust size distributions is needed in regional and global models to estimate the impact of dust on Earth's radiation budget (e.g., Kok, 2011). Additional information is required to understand how hygroscopicity is affected by particle composition, including novel substances like polymers and/or degraded polymers.

Although general meteorological drivers of dust storms are well understood, there remain some key gaps in understanding. Principally, the variation in meteorological conditions that lead to different spatial scales of transport and deposition, such as local (10s km), regional (100 s km), and large-scale (1000s km) dust events. This understanding is limited by a lack of high spatial (horizontal and vertical) resolution wind data and information on the vertical distribution of dust during transport. Moreover, laboratory and in situ studies of threshold wind velocities for erosion are difficult to apply to large spatial-scale dust sources.

4.2. Dust and air quality

Dust influences air quality through increases in PM levels and the associated biological, chemical, and mineralogical components that can adversely impact human health and reduce visibility (Fig. 7). Special attention is paid to $PM_{2.5}$ and PM_{10} due to their established health impacts (see Section 4.3). The current National Ambient Air Quality Standards (NAAQS) prescribed by the U.S. Environmental Protection Agency (EPA) (U.S. EPA, NAAQS) include 24-h average threshold concentrations of 35 and 150 μg m^{-3} for $PM_{2.5}$ and PM_{10}, respectively. In comparison, the World Health Organization (WHO) thresholds for 24-h averages are 25 and 50 μg m^{-3} for $PM_{2.5}$ and PM_{10}, respectively (WHO, 2021).

Fig. 7. Dust and smog blanket Salt Lake City, Nov 5, 2016. Wikimedia Commons, licensed under the Creative Commons Attribution-Share Alike 3.0 Unported licensed.

The myriad local and regional sources of dust within North America, especially in the western U.S. (e.g., Prospero et al., 2002; Ginoux et al., 2012), along with long-range transported Asian and African dust, influence PM levels in the western and eastern U.S., respectively. The "Godzilla" dust event in June 2020 is a notable example of the impact of African dust. This event influenced PM_{10} levels in the Commonwealth of Puerto Rico (increasing up to ~500 μg m^{-3}) and the Gulf states including Texas (TX), Mississippi, Oklahoma, and Florida, with $PM_{10} >$ 100 μg m^{-3} at several sites (Yu et al., 2021). African dust intrusions can put cities such as Houston, TX, beyond regulatory compliance for PM levels (Bozlaker et al., 2019; Das et al., 2022a, 2022b). Dust emitted from dryland critical zones within North America also adversely impacts air quality in the U.S. through PM exceedances of NAAQS. For example, dust storms in the Chihuahuan Desert have led to 24-h-average PM_{10} concentrations exceeding 1000 μg m^{-3} at El Paso, TX (Rivera Rivera et al., 2010), and dust from agricultural lands in the Columbia Plateau has led to 24-h PM_{10} concentrations approaching 500 μg m^{-3} at Spokane, Washington (Chow et al., 1993). The highest outdoor levels of PM_{10} recorded in the U.S. have been in intense dust plumes emitted from playas, with monitored hourly concentrations on the order of 50,000 μg m^{-3} at Mono Lake, California (CA) (Ono et al., 2011) and Owens Lake, CA (Fig. 3C) (Cahill et al., 1996). Because of the presence of fine sediments subject to direct aerodynamic entrainment, such as efflorescent salts and loose silty materials, some playas are particularly prone to emitting extremely high levels of PM (Gill, 1996; Reynolds et al., 2007; Gill et al., 2021). Dust is becoming a more important component of the $PM_{2.5}$ mass budget at certain regions in the U.S., especially as concentrations of other major aerosol species decline due to regulatory activity (e.g., Hand et al., 2020, 2024). In the southwestern U.S., average spring fine mineral dust concentrations contribute over 50% across the region (Hand et al., 2017), and the seasonal mean coarse mass fraction of PM_{10} (PM_{10}-$PM_{2.5}$/PM_{10}) was over 50% across the western U.S. year-round. Contributions of coarse mass (predominantly dust) to PM_{10} were over 70% at regions of the central and southwestern U.S. depending on season (e.g., Hand et al., 2019).

Wildfires in the western U.S. have increased in recent years due to drought related to climate change (Abatzoglou and Williams, 2016; Alizadeh et al., 2021). Whereas the fires themselves present a major hazard to air quality and human health, dust emitted by fires can exacerbate air quality issues presented by the smoke itself (Schlosser et al., 2017), and land disturbance caused by fires increases post-burn dust emission with (Miller et al., 2012) or without subsequent rehabilitation (Yu and Ginoux, 2022). In western rangelands, the prevalence of invasive cheatgrass (*Bromus tectorum*) has increased fire frequency and intensity (Bradley et al., 2018; Molvar et al., 2024), which has also led to positive feedback as cheatgrass can outcompete native seedlings on disturbed sites.

In addition to impacting aerosol loadings directly, mineral dust can indirectly impact air quality via participation in gas-particle reactions. Mineral dust can react with several criteria pollutant gases regulated by the NAAQS including nitrogen oxides (e.g., $NO_x \equiv NO + NO_2$), tropospheric ozone (O_3), and sulfur dioxide (SO_2) (Dentener et al., 1996; Cwiertny et al., 2008; Ma et al., 2013). Mineral dust also reacts with dinitrogen pentoxide (N_2O_5) — a nighttime reservoir of NO_x — to decrease NO_x and O_3 (Seisel et al., 2005; Abbatt et al., 2012; Tang et al., 2016; Gaston, 2020). In general, gas-particle reactions with mineral dust are thought to decrease the burden of pollutant gases; however, recent work has shown that the reaction between playa dust from the U.S. and N_2O_5 can potentially increase ground-level O_3 concentrations by the formation of halogenated gases, most notably, nitryl chloride ($ClNO_2$) (Mitroo et al., 2019; Royer et al., 2021). Dust mineralogy is a key factor in whether $ClNO_2$ formation occurs (Royer et al., 2021). High levels of $ClNO_2$ have been observed in inland regions of the U.S., such as in Colorado, and playa dust likely play a contributing role to these observations (Jordan et al., 2015; Mitroo et al., 2019).

4.2.1. Key data and knowledge gaps

Quantifying the air quality impacts of atmospheric dust in the Critical Zone requires knowledge of dust physical, chemical, and optical properties. Long-term, consistent, and spatially resolved observations of these properties across North America are largely unavailable, resulting in important gaps in our understanding of the impacts and role of atmospheric dust as an air pollutant. In addition, intensive composition and size distribution measurements are typically only available at a small number of sites and for short periods (Ardon-Dryer et al., 2023a), making it difficult to extrapolate these data over other areas. These properties are critical for quantifying the environmental and health impacts of dust as a form of particulate matter. Integrating dust observations from satellite remote sensing, ground-based measurements (such as speciated aerosol observations from the Interagency Monitoring of Protected Visual Environments (IMPROVE), or the Aerosol Robotic Network (AERONET)), and modeling (Section 6) of dust emission would provide additional information that would expand our understanding of both large- and small-scale dust events that influence air quality. Such integrated studies are largely lacking for North American dust events, with one of the only examples being Vukovic et al. (2014).

4.3. Dust and human health

Exposure to airborne dust has been shown to have negative physiological effects on both humans and non-human animals, induce safety risks, and impart negative psychological effects through reduced visibility. Our understanding of dust's physiological health effects in humans are largely based on epidemiological and in vitro studies, supported by animal-model in vivo and toxicological studies. Event scale studies and meta-analyses inform our understanding of the safety hazards associated with dust events.

The first epidemiological study of dust on human health in U.S. populations occurred during the Dust Bowl of the 1930s, when increases in measles, pneumonia, respiratory infections, and mortality were reported in Kansas following dust storms (Brown et al., 1935). Dust storm records (derived from databases, observations, and/or measurements) and hospital and mortality records (e.g., mortality rates, incidences of admission to intensive care units or hospitals) have since been used to link dust exposure from within or outside the U.S. (e.g., dust from Asia and the Saharan Desert) to negative health outcomes. Increased hospital and intensive care unit admittance for respiratory illnesses such as asthma, bronchitis, and chronic obstructive pulmonary disease occur on the day of or days following a dust event (Grineski et al., 2011; Rodopoulou et al., 2014; Gutierrez et al., 2020; Rublee et al., 2020). In western Africa, there may also be a link to meningococcal meningitis (García-Pando et al., 2014), though not all studies found an association (Woringer et al., 2018). Dust events in the U.S. have also been linked to non-respiratory health issues including coronary atherosclerosis, neurodegenerative diseases, other conditions (Herrera-Molina et al., 2021, 2024), and higher probabilities of low birth weights and premature birth (Jones, 2020). The collective load of these health effects may contribute to increased human mortality (up to 7.4%) during and in the days following dust storms (Panikkath et al., 2013; Crooks et al., 2016). However, other U.S.-based studies found no population-level response to dust exposure (Norton and Gunter, 1999; Schwartz et al., 1999; Slaughter et al., 2005).

In vitro experiments examine the direct effect of cell exposure to dust particles. Some studies show that exposure to dust particles causes disruptions to the cell cycle, cell death, release of pro-inflammatory cytokines, and/or other adverse effects (Rodríguez-Cotto et al., 2015; Chang et al., 2016; Ardon-Dryer et al., 2020), while others did not find a statistically robust effect (Hetland et al., 2000; Deng et al., 2007; Schwarze et al., 2007; Freyria et al., 2012).

In vivo investigations have been limited to animal studies and support our understanding of the health risks of dust inhalation to humans (Ghio et al., 2013; Mu et al., 2013; Pal et al., 2015). For example, mice exposed to dust from Asia, Arizona, Nevada, and California showed acute inflammatory responses and impaired lung function like those observed in human epidemiological and in vitro studies (Ichinose et al., 2008; Ghio et al., 2014; Keil et al., 2016a; Leetham et al., 2016; D'Evelyn et al., 2023). The responses were consistent with increased disease susceptibility and immunotoxicity (Keil et al., 2016b; DeWitt et al., 2017), though the toxicity varied with dust source (Ichinose et al., 2008). Biddle et al. (2023) found that exposure to dust from California's drying Salton Sea induced lung inflammatory responses in mice and linked these responses to microbial components entrained in the dust.

Because the chemical, physical, and biological composition of dust is highly variable (Lawrence and Neff, 2009), understanding the toxicological effects of dust composition is challenging. Specifically, bioavailable metals, soluble organics, polymers, synthetic compounds, cyanotoxins, and pathogens may all contribute to the negative health outcomes associated with dust exposure (Chen and Lippmann, 2009, Osornio-Vargas et al., 2011, Dong et al., 2020, Tong et al., 2017, 2023b, Gorris et al., 2023). Studies examining discrete exposure to specific dust constituents are limited to animal or organism models or studies of acute accidental, occupational, or volunteer exposure in humans.

Inconsistent findings at both the epidemiological and in vitro scales, as well as uncertainty about the effects related to dust composition, highlight that the mechanisms leading to health issues are still not fully understood (Deng et al., 2007; Yang et al., 2017). The human lung defense mechanism that helps explain these inconsistent findings is phagocytosis (engulfing particles), which helps the lung deal with high particle loads. However, dust events can lead to such high concentrations of PM that they overwhelm the lung's defense system, either by a large number of particles or by the inherent toxicity of the particles (Salvi and Holgate, 1999). For example, phagocytosis by macrophages is a typical pathway for clearing particles from the lungs, but the ability of macrophages to engulf particles can decline or cease in the presence of large numbers of particles (Bowden, 1987) allowing for more particles to accumulate in the lung. At the single-cell level, Ardon-Dryer et al. (2020) showed that human lung epithelial cells can engulf dust particles, which is atypical for this cell type and could lead to their death (Fig. 8).

Windblown dust is also a psychological and safety hazard. Reduced visibility from dust and other pollution sources can induce stress and depression (Evans and Jacobs, 1981; Evans and Joseph, 1982; Soleimani et al., 2020). Regarding safety, the seriousness of dust-driven visibility impairment was first recognized nationwide in 1991, when a dust storm in California's San Joaquin Valley caused vehicle collisions resulting in 17 people dead and 151 people injured (Pauley et al., 1996). Since then, lack of visibility from dust storms has caused numerous car wrecks (Ashley et al., 2015) with comparable life losses in the U.S. to those from other weather hazards such as hurricanes, thunderstorms, lightning, and wildfires, though the numbers of dust-related traffic deaths are likely underestimated (Tong et al., 2023a). The state transportation departments of Arizona and New Mexico have spent tens of millions of dollars on highway improvements, interactive signage, detours around dust hotspots, mitigation of dust sources, and public awareness campaigns to deal with road hazards presented by blowing dust (Tong et al., 2023a). However, the prevention and mitigation of this hazard will be a continuing challenge because many dust-related traffic fatalities are due to microscale yet intense dust plumes from near-road sources, which are difficult to detect or forecast (Eibedingil et al., 2022; Sprigg et al., 2022).

4.3.1. Key knowledge gaps

Assessing the impact of dust on human and non-human animal health in the United States is hindered by inconsistencies in study design and deficiencies in detecting and evaluating dust events and their compositions. Comparisons between epidemiological studies is hindered by differences in the determination of health endpoints (lag days,

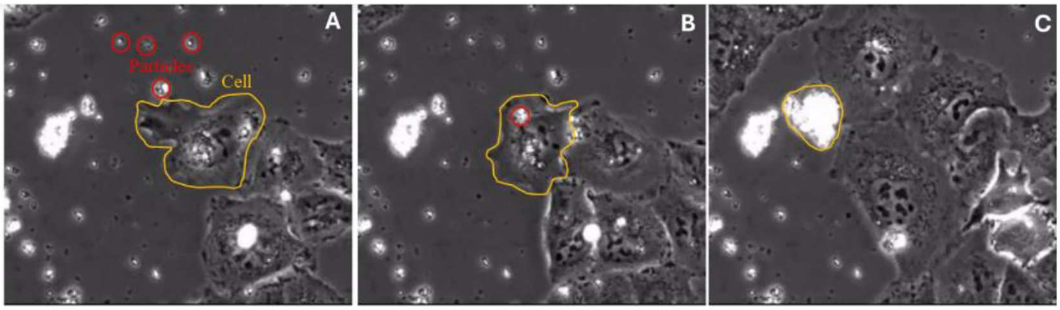

Fig. 8. A549 human lung epithelial cells (in orange) with Montmorillonite dust particles (red) around it (A), the cell engulf the particles (B), and end up dying (C). Cells are approximately 10–15 μm and the clay particles are 2.5 μm. Photograph and annotation by Dr. Karin Ardon-Dryer, Associate Professor, Department of Geosciences, Texas Tech University, used with permission.

hospitalization vs. death, etc.), a focus on different exposure time scales (chronic vs. acute), and the use of different metrics for estimating dust exposure (Ardon-Dryer et al., 2023a). Moreover, dust-prone areas in the U.S. often lack PM_{10} monitoring (United States Environmental Protection Agency, 2022) or report only 24-h averages (United States Environmental Protection Agency, 2022), obscuring short-duration dust events (Ardon-Dryer et al., 2023a). In addition, the spatial and temporal variability of atmospheric particle concentrations tend to increase with increasing particle size (Keet et al., 2018) and particles larger than PM_{10} are seldom monitored (Neff et al., 2013; Brahney et al., 2020b). Even the widely used Storm Events Database from the National Center for Environmental Information has been demonstrated to lack adequate reporting of dust events (Ardon-Dryer et al., 2023b). These monitoring limitations inhibit epidemiological studies (Ardon-Dryer and Kelley, 2022; Ardon-Dryer et al., 2023a, 2023b). A particularly challenging limitation is evaluating risks posed by specific chemical and biological components present in dust due to a lack of composition-specific monitoring. Existing work on pathogens in aerosols has primarily focused on bacteria and fungi, but less work, sometimes with inconclusive results, has been done to evaluate viruses (Gonzalez-Martin et al., 2018). Further, unique geochemical, biologic, and pathogen mixtures present in dust represent a broader suite of compounds than currently captured in existing Regional Screening Levels used to calculate exposure risk and may interact to pose unique health issues (Feron et al., 2001; Dominici et al., 2010; Rückerl et al., 2011; Tan et al., 2021).

Finally, based on a limited set of studies, there may be unrecognized impacts posed by dust on non-human animal health and mortality (Strandberg et al., 2010; Mu et al., 2013; Lauer et al., 2019; Vanderstock et al., 2019; Osborne and Longcore, 2021), behavior, and reproduction, as well as non-human animal access to food resources. Determination of health and behavioral changes related to dust storm activity are challenging to measure in wildlife (e.g., Mu et al., 2013; Strandberg et al., 2010); apart from animal models of dust exposure, information on impacts to non-human animal health relies solely on a handful of incidental observations (e.g. Mu et al., 2013).

5. Dust deposition

Dust exits the atmosphere either through dry deposition (turbulent exchange or the gravitational settling of particles) or wet deposition (scavenging from the atmosphere during precipitation events) (Shao, 2008). Dustfall can supply receiving ecosystems with key macro and micronutrients, acid-neutralizing capacity, heavy metals, microbes and other biota, synthetic materials, and light-absorbing particles (Brahney et al., 2021a). All of the above have the capacity to interact with physical and ecological processes within the Critical Zone such as soil formation, texture, nutrient content, vegetation type and distribution, the timing of snowmelt, water quality, and freshwater ecology (Okin and Gillette, 2001; Painter et al., 2010; Lawrence et al., 2013; Brahney et al., 2015a; Carling et al., 2017; Munroe et al., 2024).

5.1. *Dust in terrestrial systems*

Dust deposition to ground surfaces may be spatially and temporarily non-uniform, particularly when influenced by local convective storms, such as those of the North American monsoon (e.g., Vukovic et al., 2014). However, dust originating from distant locations may exhibit relatively uniform deposition across a landscape on the order of a few to tens km^2. Once deposited, the distribution may not remain uniform, particularly on sloping surfaces where redistribution by wind and water can increase dust concentration in topographic lows (Reynolds et al., 2006a). Similar sorting phenomena can be observed on a smaller scale, where coarse-grained, dust-poor dune crests contrast with fine-grained, dust-rich swales, over distances of meters (Buckley, 1989). This redistribution of dust materials has pedological and ecological implications.

5.1.1. *Dust effect on pedogenesis*

The delivery of dust by eolian processes exerts strong controls on pedogenesis (the origin and formation of soils) over centuries to millennia, potentially altering the physical and chemical properties of soil profiles and driving soil formation. In the classic model, the development of a soil profile is regulated by the influence of five theoretically independent variables: climate, biological activity, topographic relief, parent material, and time (Jenny, 1941; Birkeland et al., 1991). However, deposited dust influences the parent material variable by providing new material that can be converted to soil. In extreme cases, dust comprises the entirety of the soil parent material. For instance, some soils are completely developed by accumulations of mineral dust in the form of silty loess. These loess-derived soils occur, for example, in parts of interior Alaska (Begét and Hawkins, 1989; Muhs and Bettis, 2003; Muhs, 2004), on the Great Plains (Mason, 2001; Mason et al., 2003) or along the Mississippi River corridor (Wascher et al., 1948; Ruhe, 1984; Muhs and Zárate, 2001), originated from environmental conditions that prevailed during the last ice age, when faster rates of eolian deposition resulted in the accumulation of thick deposits of wind-blown silt. Pedogenesis during and after this interval of rapid eolian sedimentation has converted these loess deposits to silt-dominated soils. Additional examples include the extensive Blackwater Draw Formation, composed of eolian sediment that supports productive agricultural soils in eastern New Mexico and western Texas (Holliday, 1990), and some soils of the Channel Islands off the coast of California, which are developed in continental dust delivered by the Santa Ana winds (Muhs et al., 2008). Similarly, many soils in arid landscapes consist of thick layers of eolian silt beneath a surface mantle of coarse gravel (McFadden and Weldon, 1987). Entrapment of dust by the gravel inflates the soil profile over time, with the result that much, if not all, of the soil is derived from eolian deposition (McFadden et al., 1998; Bockheim and Gennadiyev, 2010; McFadden, 2013).

Even in cases where mineral dust mixes with local sediment to form a composite soil parent material, physical and chemical properties of the resulting soil profile or surficial deposits can often be directly connected back to eolian deposition. For instance, rapid rates of dust deposition may produce a physically distinct layer of loess at the top of a soil profile (Fig. 9). Soils containing "loess caps" have been reported from various locations including the Rocky Mountains (Reheis, 1990; Bockheim, 1997; Bockheim et al., 2000; Muhs and Benedict, 2006; Munroe et al., 2015), northern Michigan (Schaetzl, 2008), and river terraces in the southeastern U.S. (Rutledge et al., 1985). The textural discontinuity between the silty loess and the underlying, typically coarser, material has important implications for water percolation in these soil profiles (Fig. 9; Li and Zhang, 2014). In locations where dust deposition rates are slower, and natural processes actively mix soil, dust added to the soil surface may be homogenized throughout the profile. The result is a soil with chemical and physical properties that are directly controlled by allochthonous additions. For instance, most of the fine material in periglacial mountain soils studied in Nevada and Utah is dust mixed downward from the soil surface (Munroe, 2007; Munroe et al., 2020; Munroe et al., 2024). Similarly, in the southeastern U.S., African dust is the primary source of the clay fraction of soil in the Florida Keys (Muhs et al., 2007) and may have some contribution to other soils in the southeastern U.S. (Muhs et al., 2007). Many soil profiles would, therefore, have different textures and thicknesses in the absence of long-term dust deposition (von Suchodoletz et al., 2013). Similarly, in situations where dust deposition and soil formation have alternated over time, sequences of buried soils at shallow depths can influence the relative abundance of shrubs vs. grasses by limiting root growth (Reheis et al., 2018).

Fig. 9. Loess Cap over soils from the alpine Zone of the Uinta Mountains, Utah. The dark dust-rich topsoil (A horizon) contrasts with the light layer dominated by locally derived material (B horizon). Figure reproduced from Munroe et al., 2015, with permission for reuse by authors from Elsevier, Inc.

5.1.2. Dust effects on soil fertility and plant communities

Chemically, dust-derived P can be vital for the long-term maintenance of soil productivity, especially where soils are heavily weathered (Chadwick et al., 1999; Okin et al., 2004; Arvin et al., 2017; Gross et al., 2021). In a few specific examples, dust is responsible for delivering critical plant-available nutrients to terrestrial ecosystems (Ponette-González et al., 2018). In fact, most of the P present in soils of some locations is derived from dust, such as the older Hawaiian Islands (Chadwick et al., 1999; Kurtz et al., 2001), the Sierra Nevada of California (Aciego et al., 2017), the San Juan Mountains of southwestern Colorado (Lawrence et al., 2013), and the wet montane tropical forest of the Commonwealth of Puerto Rico (Pett-Ridge et al., 2009; McClintock et al., 2015). On the Colorado Plateau, dust-derived elements like P and the base cations Ca, Mg, Na, and K are crucial for soil fertility (Reynolds et al., 2001). In the alpine zone of the Front Range in Colorado, the base cations delivered by dust are an important buffer against soil acidification due to chronic nitrogen deposition (Lieb et al., 2011).

The fertility provided by dust can also influence the pattern and diversity of vegetation on the landscape. Wind erosion often removes the fine-grained, nutrient-rich fraction of the soil, which impoverishes the soil environment of key nutrients and influences other soil properties such as water holding capacity and cation exchange capacity (Li et al., 2007, 2008). The loss of these soil resources can lead to a positive feedback loop where seasonal vegetation may struggle to become established, thereby leading to greater wind erosive loss (Larney et al., 1998; Li et al., 2008; Hata et al., 2019). The lost soil nutrients may be transported long distances, enriching downwind areas (refer to Section 5.3 and below), but may also accumulate under shrub canopies in desert regions (Schlesinger et al., 1996). Consequently, elongated areas of bare soil are aligned with the dominant wind direction separated by woody vegetation, highlighting the role that wind erosion plays in determining vegetation cover in semi-arid landscapes (Okin and Gillette, 2001). In addition, these processes can limit plant species diversity by inundating short stature plants and preventing their establishment in favor of larger woody plants (Okin et al., 2001, 2006).

Once deposited, the biological uptake of dust-derived nutrients and contaminants depends on the form and chemical availability. For example, elements loosely adsorbed to the surface of dust particles or within the organic fraction are more readily available to plants than those embedded in the crystalline structure of silicate minerals. Sequential leaching experiments are typically used to assess the environmental mobility and bioavailability of dust-bound constituents (Lawrence et al., 2010; Goodman et al., 2019; Scholz and Brahney, 2022), whereas transfer of nutrients or heavy metals from dust to plants can be examined through field and greenhouse experiments (Schreck et al., 2012; Gross et al., 2021) or using isotope fingerprinting techniques (Miller et al., 2014; Arvin et al., 2017).

In addition to dust composition, the degree to which nutrients and contaminants are transferred from dust to plants can vary based on plant species, plant growth stage, properties of the underlying soil, and meteorological conditions (Shahid et al., 2017). Plants are affected by dust and anthropogenic PM both directly by deposition to leaf surfaces and indirectly by plant root exposure after building up in the soil (Chojnacka et al., 2005; Uzu et al., 2009; Säumel et al., 2012; Schreck et al., 2012, 2013, 2014; Xiong et al., 2014; Mombo et al., 2016; Shahid et al., 2017; Gross et al., 2021; Li et al., 2022). Uptake by foliar surfaces can occur through plant stomata, cuticular cracks, lenticels, ectodesmata, and aqueous pores (Gross et al., 2021; Shahid et al., 2017). Morphological features such as trichomes and leaf surface area tend to increase the efficiency of dust collection by foliar surfaces (Shahid et al., 2017; Gross et al., 2021; Gao et al., 2022; Xu et al., 2022). In soils, plant roots can exude weak acids that enhance the bioavailability of dust-bound nutrients and contaminants, often in symbiosis with fungi and bacteria (Lasat, 1999). These processes enable dust-derived elements to be drawn in from the soil and translocated to aboveground plant parts, facilitating the movement of heavy metals into the food chain. For example, Great Salt Lake wetlands are impacted by the atmospheric deposition of metals contained within fugitive dusts from local industries (Waddell et al., 2009; Naftz et al., 2009); Hammill et al., 2022 quantified the uptake and translocation of these metals into plant parts (buds, seeds, leaves, etc) as well as the accumulation of these metal into primary and secondary consumers.

Though dust may provide critical nutrient resources, in some cases the impacts of dust deposition on plant production are negative. Dust deposition on plants may also affect photosynthesis, respiration, transpiration, and lead to visible injuries (Farmer, 1993). Soheili et al. (2023) reviewed plant injury and other effects caused by dust deposition, including increased leaf temperature, clogging of stomata, changed leaf structure, reduced vegetative growth rates, changes in wood fiber development, reduced gas exchange, decreased chlorophyll concentration, metabolic changes, and other adverse impacts. Zhu and Xu, 2021, and Zhu et al., 2021 found dust-associated decreases in specific leaf area and chlorophyll, while dry matter, tissue density, and leaf thickness increased. Dust enriched in heavy metals can also negatively impact plant growth (Csavina et al., 2012). Epiphytic lichen and sphagnum appear to be the most sensitive species to the negative effects of dust deposition (Farmer, 1993), though there is limited research on this topic, especially with respect to dust composition.

5.1.3. Knowledge gaps

Although much has been learned about the effects of dust deposition on Critical Zone functioning, substantial knowledge gaps remain. Dust clearly plays a role in soil formation (Yaalon and Ganor, 1973), yet some environments (desert, mountain, and low latitudes) are relatively overrepresented by previous studies, and correspondingly less is known about the contribution of dust to soils of high latitudes where dust is increasing (Meinander et al., 2022). Temporal changes in dust delivery to soils are also unresolved in many ecosystems, although dust deposition rates have clearly varied over longer time scales (Neff et al., 2008; Routson et al., 2016; Arcusa et al., 2019; Munroe et al., 2021). As for dust effects on soil fertility and plant communities, there is a need for additional research on the influence of dust on plant functional traits such as leaf area and chlorophyll content (Zhu et al., 2021) as well as plant stoichiometry. The effect of dust deposition on carbon cycling in terrestrial environments is also poorly characterized (Mahowald et al., 2017), although research outside of North America has demonstrated that soil organic carbon loss to wind erosion is an important component of regional carbon cycling (Webb et al., 2012). In general, whether focused on nutrients or contaminants, much of what we know about the transfer of dust-bound constituents to plants has been learned from research conducted outside of North America. In the face of increased land use development and drought in the U.S., there is a need for research on metals content and pathogenic contamination of crops and even backyard gardens from atmospheric dust deposition (Kumar et al., 2018; Li et al., 2022; Brodsky et al., 2023).

5.2. Dust on snow

Darkening of snow cover following episodic dust events is a well-documented process, especially in the Western U.S. (Skiles et al., 2018a; Fig. 10). Dust deposition can accelerate snowmelt by lowering snow albedo directly in the visible wavelengths, where snow is most reflective, and indirectly in the near-infrared wavelengths due to accelerated snow grain growth (Painter et al., 2007). The impact of dust is intensified as snow begins to melt because separate dust layers, previously deposited and then buried, combine at the surface to compound surface darkening (Doherty et al., 2016; Skiles and Painter, 2017). In the spring, this darkening coincides with increasing day length and higher sun angles, which leads to higher radiative forcing and earlier exposure of darker surfaces beneath the snow. The specific impact of dust on radiative forcing and melt dynamics depends on its optical characteristics, such as scattering, absorption, and the single scattering albedo (SSA), which is the ratio of scattering to total extinction. These properties are controlled by dust composition which varies with source region mineralogy, particle size distributions, and mixing with other light-absorbing particles like black carbon.

Dust-on-snow (DOS) processes and impacts have been most well studied at Senator Beck Basin Study Area (SBBSA) in the San Juan Mountains of southwestern Colorado (Painter et al., 2007; Skiles et al., 2012, 2018a; Bryant et al., 2013; Deems et al., 2013; Skiles and Painter, 2017, 2019). The SBBSA has been a focus of study because it is part of the headwaters of the Colorado River, which is primarily snowmelt-fed, and the first high-elevation point of contact for dust emitted from the southern Colorado Plateau. Since SBBSA was established in 2003, dust events have been observed every year, with most events occurring in the spring (March, April, May) (Painter et al., 2012). In this region, deposition rates have increased significantly (5-fold) following modern settlement of the Western U.S., indicating dust emission and loading are elevated by land use change and surface disturbance (Neff et al., 2008; Brahney et al., 2013). Dust radiative forcing has been shown to

Fig. 10. Left: Dust on snow in the San Juan Mountains, Colorado (May 2009), Right: Dust layers form episodic dust events in snow stratigraphy, shown in upper meter of snowpit from Senator Beck Basin, San Juan Mountains, Colorado April 2009. Photograph by Dr. S.M. Skiles, Associate Professor, Department of Geography, University of Utah, used with permission.

accelerate snowmelt by 3–5 weeks (Skiles et al., 2012, 2015), reduce total water yield (Painter et al., 2010), control timing and magnitude of snowmelt (Skiles et al., 2012; Painter et al., 2018), and correlate with errors in operational snowmelt runoff forecasting (Bryant et al., 2013). Modeling studies suggest that when snow melts earlier, annual streamflow yields decrease due to increased evapotranspiration from vegetation and soils (Painter et al., 2010; Deems et al., 2013). As with other processes that influence snowmelt timing, flows shifted to earlier in the year can lead to reduced flows during summer months when demand is high for both ecological and anthropogenic uses.

In general, dust on snow events coincide with high wind speeds, which tend to be pre- or post-frontal (synoptic), and duration of deposition is typically on the scale of hours (Section 4.1). Dust can be dry deposited or entrained in precipitation and wet deposited. Dry deposited events tend to be thin, well-defined layers in the snowpack, whereas wet deposited events tend to be thicker, more diffuse layers (Skiles and Painter, 2017). The amount of dust deposited by each event is variable, and the total amount of dust deposited each snow season, ranging from 1 mg g^{-1} in average years to 4 mg g^{-1} in extreme dust years, does not correlate with the number of dust events (Painter et al., 2012; Skiles et al., 2015). At SBBSA, the physical and chemical properties of deposited dust correspond to the chemical signatures found across arid regions of the Colorado Plateau (Lawrence et al., 2010). Back-trajectory modeling (see Section 6.3) also indicates that events transporting the most dust mass are associated with southwesterly winds that transport dust from source regions in the southern Colorado Plateau (Skiles et al., 2015). Accordingly, remote sensing retrievals show that snow darkening in the Rocky Mountains declines along a northwestern gradient (Painter et al., 2012; Reynolds et al., 2014; Reynolds et al., 2020).

Although less extensively studied, DOS has been documented in other parts of the Western U.S. The Wasatch Range experiences episodic dust deposition from sources in the Great Basin (Steenburgh et al., 2012; Hahnenberger and Nicoll, 2012; Lang et al., 2023), although dust radiative forcing is not as dramatic because dust loading and dust color is lighter relative to the southern Rocky Mountains (Skiles et al., 2018a, 2018b; Lang et al., 2023). Dust deposition contributes minerals, organic matter, and trace elements to Wasatch Range snowpack, dramatically changing snow chemistry (Carling et al., 2012; Reynolds et al., 2014; Goodman et al., 2019) and bacterial communities (Dastrup et al., 2018). Winter dry deposition was also responsible for variable snowpack chemistry across the Rocky Mountains (Clow et al., 2002), with increasing dust loading over the period 1993–2014 inferred from snow chemistry (Clow et al., 2016). In the eastern Sierra Nevada, dust has been shown to dominate snow darkening and radiative forcing, although concentrations are lower than those sampled in the Rocky Mountains (Sterle et al., 2013).

For seasonal snow, the impacts of dust are temporally limited to the time that snow cover is present. For perennial snow cover, darkening impacts may be compounded across multiple years through summer and winter atmospheric deposition. Perennial snow also provides the opportunity to study previously deposited layers maintained within the annual stratigraphy. For example, in the Pacific Northwest, a dark layer associated with forest fire emissions, which had led to faster melt, was sampled by coring down to the layer the following year (Kaspari et al., 2015). The mineral dust concentrations in the layer had a higher radiative impact relative to aerosols more typically associated with fire (black carbon, organic carbon), indicating fire disturbance as a precursor to increased dust emissions (Kaspari et al., 2015). Dust deposition on glaciers may also provide nutrients for algae blooms which, similar to dust, darken snow and ice surfaces (Hotaling et al., 2021) and contribute trace elements to glacial surfaces (Fortner et al., 2009; Aarons et al., 2016) and proglacial streams (Carling et al., 2017; Barkdull et al., 2021). Dust emissions from river systems may be relevant for snowmelt rates locally in northern Alaska (de Boer et al., 2019).

5.2.1. Key data and knowledge gaps

The focused study of DOS at the study plot scale has led to limited understanding of spatiotemporal variability at the watershed to regional scale. Satellite remote sensing of surface albedo is possible but has high uncertainties due to current satellite capabilities (Painter et al., 2012; Warren, 2013) (Section 6.3), although this will likely be addressed with advancing satellite technology. Relatedly, multiple studies have documented high interannual variability in dust event timing and loading at the plot scale (Skiles et al., 2012; Lang et al., 2023), but there is an incomplete understanding of what drives the variability. In addition, fuller comprehension of the types, amounts, sizes, and optical properties of the light-absorbing particles in DOS is needed, especially with respect to interannual variations in compositions of the last-remaining annual dust layers across large watersheds. Such light-absorbing particles include carbonaceous matter (e.g., black carbon) having many origins, dark rock and mineral particles, synthetic materials (e.g. tire wear and plastics), and small ferric oxide minerals embedded in clays. Taking a systems-level approach would support a better representation of source-to-sink processes in earth system models, which currently have limited capabilities with respect to simulating DOS (Oaida et al., 2015). Such an approach could aid in targeting areas for restoration to mitigate the hydrologic impacts of dust-on-snow.

5.3. Dust in freshwater

The dust-mediated transport of elements and organisms significantly influences freshwater systems by delivering essential resources and contaminants like carbonate minerals, key nutrients (P, N, Ca, C), and heavy metals, as well as diverse microbiota (Sickman et al., 2003; Morales-Baquero et al., 2006; Pulido-Villena et al., 2008; Ballantyne et al., 2010; Brahney et al., 2014, 2015b; González-Olalla et al., 2024). Unlike terrestrial environments, where the effects of dust deposition unfold over centuries or millennia, freshwater systems experience impacts on much shorter timescales, ranging from days to decades. Research on the ecological impacts of dust has primarily focused on mountain lake ecosystems. These lakes are critical freshwater resources, possess large airsheds compared to watersheds, are sensitive to environmental changes, and are often less affected by human activity within their catchments (Psenner, 1999; Moser et al., 2019; Brahney et al., 2021b). However, growing evidence suggests that dust also plays a crucial role in larger lake systems by providing vital nutrients and enhancing their acid-neutralizing capacity (ANC) (Jassby et al., 1994; Rogora et al., 2004; Gao et al., 2017; Olsen et al., 2018; Brahney, 2019; Chien et al., 2019).

5.3.1. Dust effects on freshwater chemistry

Dust may be delivered to freshwater systems episodically during dust events (wet or dry) directly to the surface water, and through catchment focussing during rain events or in a pulse during snow melt, (Checketts et al., 2020; Hale et al., 2022) or potentially through the release of dust nutrients that have accumulated within lake sediments (internal loading) (Brahney et al., 2014, 2021b).

Dust plays a crucial role in mitigating the impacts of acid emission and deposition on freshwater resources through the provisioning of base cations, particularly from carbonate minerals such as calcium carbonate ($CaCO_3$) (Psenner, 1999; Rogora et al., 2004; Brahney et al., 2014). This phenomenon is well-illustrated in the Uinta Mountains of Utah. Despite being close to areas with elevated acid emissions and deposition, and the limited buffering capacity of the quartzite bedrock, lakes in the Uinta Mountains have not experienced acidification due to millennia of dust deposition in the region (Messer et al., 1982; Ellis et al., 2015; Munroe et al., 2015). The effect of dust on freshwater pH and ANC can be observed even at annual timescales, which is illustrated using historical data from the granitic lakes of the Wind River Range that reveal clear relationships between dust deposition, the ANC of precipitation, and the ANC of lake waters (Brahney et al., 2014, Fig. 11). Globally, the $CaCO_3$

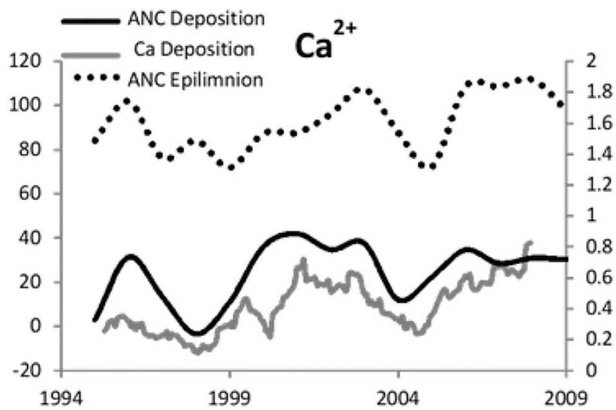

Fig. 11. Ca concentrations and ANC of deposition (solid lines) compared to the ANC of Black Joe Lake, Wind River Range Wyoming. Reproduced from Brahney et al., 2014, Biogeochemistry, with permission from Springer Nature.

content of dust ranges from 0 to 33% (Lawrence and Neff, 2009), and acids in the atmosphere may deplete this fraction through transport (Stockdale et al., 2016) and in snow (Clow et al., 2016; Reynolds et al., 2020). Thus, both the distance traveled, and the source composition may influence the capacity of dust to influence the alkalinity of receiving freshwater systems.

Beyond changes in pH and ANC, dust can deliver key micro and macronutrients. In fact, elevated dust deposition in recent history is believed to be responsible for increasing total phosphorus (TP) concentrations in remote locations of the U. S. (Brahney et al., 2015b; Stoddard et al., 2016), shifting lake-nutrient limitation (Sickman et al., 2003; Vicars et al., 2010; Catalan and Camarero, 2014), and increasing lake trophic status (Brahney et al., 2014). Modeling studies suggest dust-associated increases in P deposition have increased by 40% since pre-industrial times and atmospheric deposition rates are tightly linked to mountain freshwater concentrations (Brahney et al., 2015b). Although phosphorus is often the primary focus of dust-mediated nutrient transport, dust can also transport substantial amounts of water-soluble nitrogen (WSON), rivaling the wet deposition fluxes or inorganic nitrogen (Neff et al., 2002). WSON has been measured at 25% of the total flux in Europe and up to 45% in the Amazon River Basin (Mace et al., 2003; Cornell, 2011). In the U.S., WSON measurements ranged from 18 to 59% (Neff et al., 2002). Dust-derived N is a source of N that is rarely quantified. In Japan, dry deposition contributed 33% of TN deposition (Matsumoto et al., 2019), whereas in the Mediterranean dry deposition of N was 2.5 times higher than wet N deposition (Herut et al., 2002). Dust may also transport substantive quantities of dissolved organic carbon (DOC), which is a substrate for microbial metabolism. For example, Bigelow et al. (2020) used laboratory incubations to demonstrate the capacity for *Pseudomonas fluorescens* to grow using soluble organic carbon substrates provided from dust collected in the Front Range of Colorado. Because DOC has the capacity to absorb harmful UV radiation, dust-derived DOC can potentially influence the chemical, physical, and biotic aspects of lakes (Mladenov et al., 2008, 2011). Finally, micronutrients (Fe, B, Mn, Zn, Cu, Mo, and Ni) from dust deposition may also be important ecological drivers (Lu et al., 2024).

The impact of dust on freshwater chemistry depends on the interplay between catchment properties and lake characteristics, which can either mitigate or exacerbate the delivery of key elements to rivers and lakes (Brahney et al., 2014, 2021b). Dust nutrients can be immobilized through plant and microbial uptake or chemical reactions in soils, or preferentially transported to freshwater if catchments are steep with little vegetation cover and/or contain hydric soils. For example, Brahney et al. (2014) found that catchments in the Wind River Range with higher catchment area to lake area (CA:LA) ratios, shallow soils, steep banks, and little vegetation allowed for a greater flux of dust–derived nutrients into lakes; here, tracers indicated that approximately 30% of the dust delivered to catchment was focused into the lake system. A similar percentage was determined using the Soil Water and Assessment Tool (SWAT) model in Green Lakes of Colorado. Modeled data suggested that the labile portion of dust P and N was partitioned between plants (3 and 8%) and freshwater resources (19 and 1%), with the magnitude dictated by catchment properties (Nielson and Brahney, 2024). Additionally, the bedrock geology may influence the mobility of P since Al- and Fe-oxide minerals in watershed soils limit transport due to the high bonding capacity of these metals with P (Kopáček et al., 2011; Tsugeki et al., 2012; Brahney et al., 2021b). Thus, the CA:LA, geologic composition, vegetation type and cover, soil type, and the slope can influence the amount of dust material received by a lake with respect to a given dust deposition rate.

5.3.2. Dust effects on freshwater ecology

Macro- and micronutrients can occur in both the organic and inorganic fractions of dust, which influences their bioavailability upon deposition (Lawrence et al., 2010; Zhang et al., 2018; O'Day et al., 2020; Scholz and Brahney, 2022). Ions in the exchangeable and water-soluble fraction are readily available in minutes to hours, whereas nutrients bound within organic matter can be released by free enzymes in the water column and microbes over the course of days to weeks (Ziervogel et al., 2010; Song et al., 2019). Other nutrients, such as P, that are bound in minerals like Fe-/Mn- oxides or apatites may not be biologically relevant over seasonal timescales but may become significant over decadal timescales if they are released from lake sediments through redox cycling or through the action of biota (Søndergaard et al., 2003; Cottingham et al., 2015). A recent study demonstrated that the initial pH of lake waters will affect the release and bioavailability of P contained within dust, potentially due to the release of P bound to Ca and the more efficient action of phosphatase enzymes (González-Olalla et al., 2024).

Several observational studies have suggested that dust deposition leads to ecological shifts in lake systems (Reche et al., 2009; Brahney et al., 2014, 2015a). In the Wind River Range, temporal and spatial correlations were observed between dust deposition and both primary and secondary production. A 50-fold increase in dust was accompanied by a two-order-of–magnitude increase in both primary (algal and bacterial) and secondary (zooplankton) production, as well as a relative increase in cyanobacterial abundance (Brahney et al., 2014, 2015a). In a modern observational study, Olson et al. (2023) used remote sensing to temporally link elevated atmospheric nutrients from smoke to cyanobacteria blooms that occurred 2–7 days following the event.

To date, there are limited experimental studies examining the effect of dust amendments on freshwater ecology. González-Olalla et al. (2024) showed a positive effect of dust nutrient amendments on the growth of the model freshwater organism *Scenedesmus acutus* var. *acutus.* Moreover, dust nutrient subsidies expanded the thermal and pH tolerance of *S. obliquus*, raising many further questions on the role of dust in shaping freshwater systems in the past, present, and future. Estimates based on dust emissions and lake characteristics suggest many lake systems in the West and Midwest are particularly sensitive to dust deposition, while much of the U.S. and Canada are moderately sensitive (González-Olalla et al., 2024; Fig. 12). Field studies have shown that dust (or ash) additions to microcosms result in greater growth rates than from N, P or N + P additions alone, suggesting that micronutrients within dust can synergistically enhance the growth of algal communities (Goldman et al., 1990; Wen, 2022).

The role dust deposition may play in freshwater carbon cycling and storage has not yet been resolved. Although increased production can lead to greater accumulation of carbon stores within sediments, the few existing microcosm studies have shown enhanced bacterial activity and respiration. In this way, results from experiments in natural systems have not always been as straightforward. For example, microcosm experiments conducted in several nutrient-limited freshwater mountain lakes in the western U.S. showed that short-term nutrient additions led

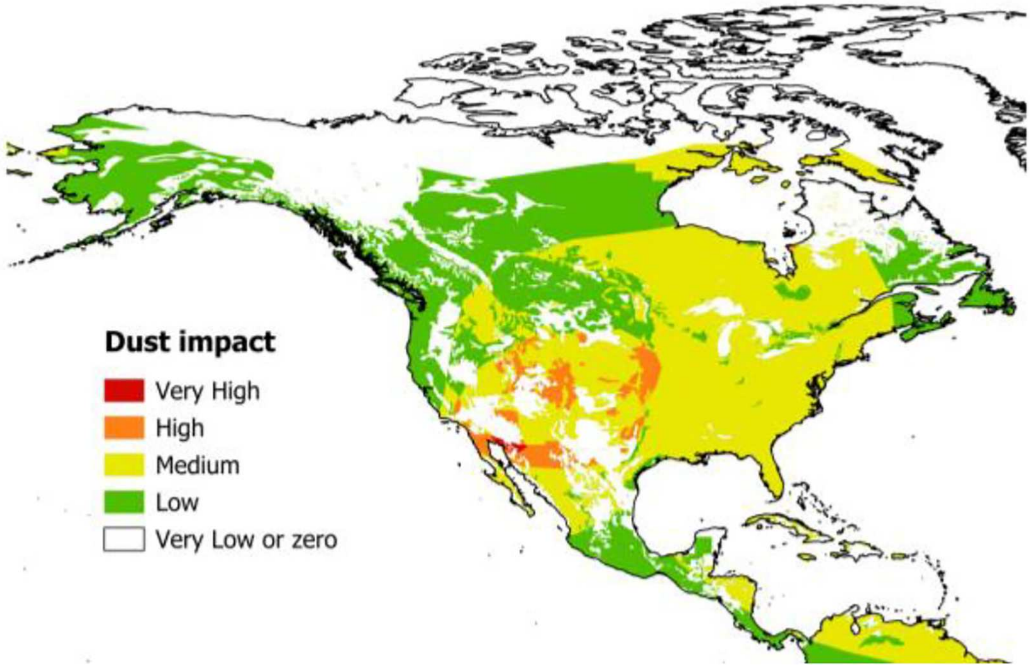

Fig. 12. Projected sensitivity of freshwaters by region in North America based on dust deposition (Kok et al., 2021) and lake properties. Figure reproduced from Gonzales-Olalla et al., 2024, with permission for reuse by authors from John Wiley & Sons, Inc.

to increased chlorophyll-a in all lakes but also decreased primary production in one oligotrophic lake through the stimulation of chemoautotrophic bacteria and the allocation of energy towards nutrient uptake rather than growth (Wen, 2022). A similar study examined how dust with varying Ca and P compositions might influence the community composition of lakes in granitic vs limestone catchments. Regardless of the type of dust used, the lake in the limestone basin became more autotrophic while the lake in the granitic basin became more heterotrophic (González-Olalla et al., 2024). Taken together, these two studies suggest that the ultimate effect of dust nutrient subsidies on carbon cycling and community composition within freshwater systems may depend on the initial characteristics of the lake and the duration of the dust nutrient subsidy.

The effects of dust on community composition extend beyond the provisioning of nutrients for primary producers. Ca is an essential nutrient for freshwater invertebrates because it forms a key component of their shells and carapaces (Tessier and Horwitz, 1990; Wærvågen et al., 2002). In lakes with low Ca abundance, dust-derived Ca may be a critical resource for maintaining healthy zooplankton populations, particularly *Daphnia*, a keystone genus that supports the movement of energy up the food chains (Pulido-Villena et al., 2006; Jeziorski et al., 2008; Jiménez et al., 2018). Thus, dust may have direct effects on community composition by increasing productivity and indirect effects through a greater availability of food resources for higher trophic levels. However, there is evidence to suggest mountain lakes may experience reduced functional diversity and a reduced efficiency of the trophic transfer of energy up the food web due to dust deposition (González-Olalla et al., 2018); thus, the effects of dust on trophic relationships may be locally dependent.

5.3.3. Knowledge gaps

Although recent research has made progress on the ecological consequences of dust amendments to mountain freshwater lake systems, several key questions remain. Specifically, there is a lack of information on how dust may impact freshwater system more broadly. For example, there is a dearth of information on impacts to lakes in more arid and northern environments, especially considering these saline or ephemeral systems receive relatively large dust loads and northern dust is expected to increase. There is still limited information on how differences in dust composition may influence the ecological response to deposition. There are no studies to date that directly examine the influence of dust-derived metals on freshwater functioning, and only a handful of laboratory and in situ experiments examining effects on primary production. Only one observational study exists linking dust Ca additions to the abundance of secondary consumers, though the increased nutrient input and the enhancement of lake productivity is predicted to affect all the trophic levels, as well as the interactions among different trophic compartments (Mehner et al., 2022). Further research should consider how dust deposition influences freshwater carbon cycling (e.g., Mahowald et al., 2017) and other biogeochemical reactions in lake systems. The few studies to date have revealed contrasting results, and it is not yet clear which factors dictate whether dust stimulates production or respiration, or whether short-term experimental effects may differ from long-term real-world dust fertilization. Although several studies have looked at microbes in deposition (Peter et al., 2014; Dastrup et al., 2018; Reche et al., 2018), no studies have yet examined how dust-nutrients and dust-associated microbes may alter microbial functional traits in freshwater systems, and thus how dust may influence nutrient biogeochemical cycling.

Finally, it is not yet clear how catchment or lake characteristics, including lake water composition, area, depth, volume, and fetch may play a significant role in determining the response of lakes to dust deposition. Factors such as dilution and or/rapid sedimentation can limit the biological impact of deposition on lakes. Legacy nutrients from dust may become available from lake sediments under the right conditions; however, these ideas have not yet been tested. In addition, uncertainties of how elevated dust nutrients combined with other stressors of global changes such as longer ice-free seasons, warmer water temperatures, and shifts in water pH may work together to alter freshwater ecosystems. Therefore, information is still scarce about the dust impact on different levels of biological organization, organism types, and systems.

6. Tracking dust from source to sink

Dust emissions, transport, and deposition link the Critical Zone across local, regional, and global scales. Methods to track dust from sources to sinks and to describe atmospheric transport patterns are needed for understanding Critical Zone processes. For contemporary events, dust tracking is performed using field surveys, remote sensing, transport modeling, and physical characterization (e.g., geochemical fingerprinting and grain size analysis) (Tong et al., 2012, Munroe et al., 2020, Baddock et al., 2021, Ardon-Dryer and Kelley, 2022). For paleodust studies, physical characterization is the only method that can be applied for determining dust source depositional locations (soils, lake sediments, loess, and ice cores) (Kohfeld and Harrison, 2001). In this section, we summarize the state-of-the-art for tracking source and transport patterns of North American dust and identify future research opportunities and constraints in each of these areas. These approaches enable a better understanding of Critical Zone interactions by connecting zones of dust emissions with zones of dust deposition and corresponding effects on nutrient and element cycling.

6.1. Dust characterization

6.1.1. Geochemical and biological methods

Physical, mineralogical, and biological characteristics of dust particles have been used to identify sources and transport distances. For example, atmospheric particle concentrations and volumetric size distributions have been used to distinguish between remote continental, marine, and urban sources of aerosols in a single location (Grobéty et al., 2010; Seinfeld and Pandis, 2016). Once deposited, characteristics such as mineralogy can identify dust contributions to ecosystems. For instance, Dahms (1993) used exogenous volcanic minerals to trace dust transport from the Green River Valley source to the Wind River Range, observing higher deposition closer to the source as well as the role of vegetation in dictating deposition patterns. Reynolds et al. (1999) analyzed lake sediments using magnetic techniques complemented by mineralogical and elemental analysis to document historic pulses of dust deposition to the White Rock Lake reservoir in Texas, which was related to upwind land use and drought upwind. More recently, particle characteristics such as quartz defect centers, magnetic properties, and techniques including Mössbauer spectroscopy and Raman spectroscopy have also been used for tracking mineral dust provenance and transport provenance and transport (Reynolds et al., 2014, 2020; Dave et al., 2022; Doughty et al., 2023).

Elemental abundances and ratios are also powerful tracers of mineral dust origin. For example, elemental abundances were used to distinguish between four key dust sources in the southwest U.S. (Reheis et al., 2002). Elemental, mineralogical, and grain-size analyses were used in conjunction to show that dust from the Saharan Desert is often the largest component of aerosols present on the north coast of the Commonwealth of Puerto Rico (Reid et al., 2003). Sometimes, even a single element can indicate a dust source: for example, the concentration of Mn found in aerosols from Barbados and Miami, Florida, over a 20-year period was correlated to African dust concentrations (Trapp et al., 2010). Other times, ratios may be more indicative of source: Al/Ca was used to trace the transport of North African dust to the eastern U.S. (Perry et al., 1997), Sr/Ca ratios tracked transport of gypsum dust in New Mexico from the White Sands into the Sacramento Mountains and beyond (White et al., 2015b), and Brahney et al. (2019) used elemental ratios to distinguish between exogenous dust and ash from local volcanic eruptions.

Traditional isotope systems used in mineral dust provenance studies include the application of radiogenic isotopes of Sr, Nd, Hf, and Pb, which have significantly different values in mantle- versus crust-derived rocks. These differences permit the distinction of dust derived from young volcanic areas and old continental shields, yielding distinct signatures for primary global dust sources (Grousset and Biscaye, 2005). For example, Sr and Nd isotopic compositions of modern dust collected from the Sierra Nevada revealed that Asian sources contributes 18–45% of dust deposition, providing critical nutrients that exceed contributions from freshly weathered bedrock (Aciego et al., 2017). The remaining dust was shown to be sourced from the nearby Central Valley during a prolific drought year, with profound year-to-year variability relating to drought in Asian and regional dust source areas (Aarons et al., 2019). Das et al. (2022a, 2022b) employed Sr-Nd-Hf isotopes to separate the contributions of North African dust and local emissions to Houston air quality. Elsewhere, radiogenic Sr-Nd-Hf isotopes combined with rare earth element (REE) anomalies provided key evidence of the transport of North African dust to the Caribbean (Pourmand et al., 2014) and sources of urban pollution (Marcy et al., 2024).

Traditional radiogenic isotopes have limited utility in distinguishing regional mineral dust sources in places like the southwest U.S. that have overlapping isotopic compositions with global sources. In these instances, novel approaches and combinations of methods can reveal distinct source signatures. For example, Carling et al. (2020) used Sr isotope ratios of the carbonate mineral fraction (as opposed to the more traditional silicate fraction) to trace dust from Utah playas to the Wasatch Front and Uinta Mountains. Munroe et al. (2023) combined mineralogical and elemental evidence with isotopic analysis techniques to show that mountain dust in the southwestern U.S. is primarily derived from surrounding arid lowlands rather than global sources. New isotopic tracers, such as U isotopes, can offer additional insights into sources by distinguishing between source areas based on their geomorphic history (Aciego et al., 2015; Jiao et al., 2022a, 2022b). Other emerging isotopic systems under development include Cu and Zn (Schleicher et al., 2020), Ca (Fantle et al., 2012), Li (Li et al., 2020b), and Fe (Conway et al., 2019), which can be used to distinguish between natural and anthropogenic dust sources. Light elements such as B are also used to differentiate atmospheric dust deposition from dissolved contributions in rainwater (Roux et al., 2017).

The fingerprint of anthropogenic emissions is often distinct enough to parse from natural mineral dust sources. For example, Bozlaker et al. (2019) used elemental ratios of African dust to separate its contribution to Houston air quality from local anthropogenic emissions, which is important from a NAAQS regulatory standpoint. Similarly, Goodman et al. (2019) showed that dust in the Great Basin originated from regional playas as well as urban aerosols. The latter were specifically enriched in Cu, Sb, Se, Mo, Cd, and Cr, many of which were shown to be readily mobile within receiving ecosystems. These findings highlight the complex interplay between natural and anthropogenic factors in shaping dust composition and its potential impacts on receiving ecosystems.

Lake sediment and ice core archives have also been ‘unmixed’ to evaluate changes in dust loads, dust sources, and climatic or anthropogenic drivers of emissions through time. Neff et al. (2008) used isotopes in sediment records to demarcate a 5-fold increase in dust loads to the southwestern U.S. through the late Holocene (11.7 Kya – Present). The strong increase was followed by a substantive reduction in the early 1900s (though not Early Holocene rates). The timing of these events suggested that the increased deposition was associated with the expansion of livestock grazing in the western U.S. and the subsequent decrease a direct result of the Taylor Grazing Act (Hurlburt, 1935), aimed to prevent overgrazing and soil degradation. In the Wind River Range of Wyoming, Sr—Nd isotopes combined with geochemistry and grain size measurements showed increasing dust inputs related to anthropogenic activity (mining) in the western U.S. in both sediment cores and ice (Brahney et al., 2015a; Aarons et al., 2016). In the Uinta Mountains of Utah, elevated metal concentrations in lake sediments were linked to dust from historical mining in upwind areas (Reynolds et al., 2010). These studies illustrate the potential for using geochemical characteristics in natural archives to understand drivers of mineral dust emissions and transport.

Direct, or in situ, measurement of dust using molecular-level spectroscopic techniques such as Fourier transform infrared (FTIR), nuclear magnetic resonance (NMR), and synchrotron-based X-ray absorption spectroscopy (XAS) can provide information on the bonding environment, crystallinity, oxidation state, and/or spatial distribution of elements at the micron-scale (Sparks et al., 2022). This information is valuable in determining the bioavailability, toxicity, and chemical fate of dust and its constituents (Kiem et al., 2003, Barrett et al., 2010, Rasmussen et al., 2011, Ono et al., 2016, Zhang et al., 2018, Root and Chorover, 2023). Global-scale measurements of mineral dust particles from aircraft platforms by single particle mass spectrometry can be used to identify sources, such as incursions of dust plumes from Asia and the Saharan Desert over the US (Froyd et al., 2019, 2022). These techniques can also be used to help determine dust provenance for those species that are not chemically altered during atmospheric transport.

Dust microbiology offers exciting new opportunities to trace to dust sources. Entrained dust harbors thousands of bacterial species in unique combinations reflecting the ecology, land use history, seasonal signature, and disturbance regimes of the originating soil (Barberán et al., 2015; Grantham et al., 2015; Maltz et al., 2022). Dust collected from the snow surface in northern Utah contained bacterial species unique to a given airshed, reflecting distinct sources from playas and urban areas (Dastrup et al., 2018). In another example, dust from dryland soils in Arizona were largely traceable to proximal agricultural practices like cotton and livestock farming based on taxa within the Microbacteriaceae, Micrococcaceae, and Deinococci taxonomic groups and from plant and soil sources associated with *Sphingomonas, Streptomyces,* and *Acinetobacter* species (Finn et al., 2021). In another example, propagules of microinvertebrates of ephemeral wetlands were recovered from dust falling in El Paso, Texas, suggesting transport to the urban area from distant playa and floodplain sources (Rivas Jr et al., 2018, 2019).

6.1.2. Challenges and knowledge gaps

The aforementioned studies highlight the utility of geochemical, isotopic, and biologic dust tracers. However, challenges associated with these techniques including differentiating mixed dust sources, quantifying chemical changes and atmospheric mixing during transport, and characterizing post-depositional changes to the geochemical signature of mineral dust for mobile elements. A current challenge with isotopic tracing studies is a lack of dust source characterization. In places where dust source libraries exist, there is often a lack of a consistent sample preparation technique used by researchers. Most geochemical compositions will vary with grain size, mineralogical fraction, and leaching methods. However, new emerging tracers that can be used in conjunction with traditional techniques offer great promise for both tracking emission sources and deconvoluting mixed dust samples. Some examples of emerging tracers and technologies include more detailed measurements of microorganisms, sophisticated mineralogical properties, novel isotopes, Raman spectroscopy, magnetism, and contaminants (polymers, pesticides, tire wear etc.).

6.2. Dust remote sensing

Remote sensing has long been used to track dust storm activity. One of the first known remote sensing images of dust was a photo of multiple dust plumes taken from an aircraft in eastern Colorado during the Dust Bowl in 1936 (Fig. 13). Since then, technological advancements have helped shape remote sensing of dust sources in the Critical Zone and transport through the atmosphere (Jiao et al., 2021; Wei et al., 2019). Both ground-based optical monitoring and satellite platforms are used to trace sources, transport, and properties of dust.

6.2.1. Orbital (spaceborne) remote sensing

The Moderate-Resolution Imaging Spectroradiometers (MODIS), launched aboard the Terra satellite in 1999 and Aqua in 2002, with 36 spectral bands and spatial resolution as low as ~250 m, spurred rapid advancement in dust remote sensing and Critical Zone research. MODIS has offered global coverage- with its swaths covering the Earth in one to two days- consistently for more than two decades. Data from MODIS were used almost as soon as they became available by researchers and air quality agencies in detect long-distance transport of dust to Texas (Hutchison, 2003), and to assess model performance of dust transport from the Sahara Desert to the Commonwealth of Puerto Rico (Colarco et al., 2003). Especially through use of its aerosol optical depth products (Wei et al., 2020), MODIS was also just as quickly used to assess the radiative impact of airborne dust (Costa et al., 2003; Zhang and Christopher, 2003), and has been widely used since to assess climate and radiative effects of dust, such as evaluating modeled impact of dust on the North American Monsoon (Zhao et al., 2012). MODIS optical depth products have been widely used for investigating aerosol loadings, size distributions, spatiotemporal variations and changes (Wei et al., 2020), intercomparison with ground-based and other measurements of aerosol properties (Drury et al., 2010), and for understanding changing aerosol loadings and properties over time over North America (Mao et al.,

Fig. 13. Aerial photo of dust plume development in eastern Colorado, 1936 (NOAA). Looking roughly west-southwest, linear distance at front of image approx. 15 km. (USDA Archives: https://infosys.ars.usda.gov/WindErosion/multimedia/dustbowl/big/wea01409.jpg).

2014). MODIS vegetation index products can be used to discern land cover change in North American dryland Critical Zones, which are closely tied to dust emission (Finch et al., 2016) and have been used in modeling land cover change effects on wind erosion in the Chihuahuan Desert (Galloza et al., 2018).

MODIS has been utilized to identify soil dust point sources at local scales as related to land cover/use or geomorphology- i.e., Critical Zone characteristics (Lee et al., 2009; Hahnenberger and Nicoll, 2012). This ability was used to develop geomorphic 'preferential dust source' categorizations and create regional-scale maps of soil dust emission potential (Bullard et al., 2011). Baddock et al. (2011a, 2011b), Lee et al. (2012) and Hahnenberger and Nicoll (2014) further clarified the regional dominance of certain land surfaces in the U.S. as dust source types- specifically, playas in the Great Basin and Chihuahuan Desert, and sandy agricultural lands in the Southern High Plains. The fundamental linkages between geomorphology (i.e., Critical Zone characteristics) and dust emissions were confirmed by correlating the remote-sensing-based record of dust above Southwest North America with land surface properties (Baddock et al., 2016). MODIS dust source data also provided insights into the nuances of the relationship between dust and drought in different ecoregions of the Southwest (Eibedingil et al., 2024; Kandakji et al., 2021). The MODIS Deep Blue algorithm, along with the derived dust optical depth, enabled Ginoux et al. (2012) to accurately assess the frequency and spatial distribution of dust over land, and allowed for the correlation of dust with land use and ephemeral water bodies. An analysis by Ginoux et al. (2012) indicated the Southern High Plains as a dominant source of dust in North America, where dust events were predominantly associated with cropland and rangeland- thus, largely anthropogenic. MODIS was largely succeeded by the Visible Infrared Imaging Radiometer Suite (VIIRS) launched on board the Suomi NPP satellite in 2011; VIIRS data proved helpful for improving short-term forecasts and warnings of dust events in the Southwest U.S. (Fuell et al., 2016) and assessing the impacts of dust from the Sahara Desert on the Commonwealth of Puerto Rico (Morales-Medina et al., 2024).

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, which was launched in 2006 and retired in 2023, carried the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar system which detected the vertical distribution of aerosols in the atmosphere and optical and physical properties of aerosols and clouds. CALIOP's vertically resolved data could be used to provide a three-dimensional view of atmospheric dust and aerosols, aiding investigations of the dynamics of dust storms and concentrations of dust at different altitudes (Raman et al., 2014; Kumar et al., 2015; Joshi, 2021). CALIOP data on aerosol depolarization allow for the identification of mineral dust and its separation from other types of aerosol, due to dust's generally large size and nonsphericity (Yu et al., 2015). This property has, for example, been used to estimate the transport and flux of African dust across the Atlantic Ocean to the Caribbean (Yu et al., 2015), and helped in discerning the vertical structure of African and Asian dust transported to the east and west coasts of the Continental U.S., respectively (Chen et al., 2018). However, CALIOP, as an active sensor, has a much smaller field of view (narrower footprint) than passive sensors, observing only a fraction of a MODIS scene, 5-km spatial resolution, and a much longer (16 days) repeat cycle, which provides limitations in aerosol studies (Pashayi et al., 2023; Tesche et al., 2016).

Remote sensing instruments, platforms, tools, and techniques are continuing to improve our ability to track the origin, transport, and impacts of dust across the Critical Zone. The Atmospheric Infrared Sounder (AIRS), launched on Aqua, has provided useful data in understanding global distribution, transport, and radiative forcing of atmospheric dust (Pagano et al., 2010). Since 2017, NASA's and NOAA's Geostationary Operational Environmental Satellites (GOES)-R over North America combine 5-min temporal and ~ 2 km spatial resolution for the continental U.S. with improved dust detection algorithms and sensors (Kondragunta et al., 2020). The atmospheric lidar (ATLID) aboard the EarthCARE satellite (van Zadelhoff et al., 2023), launched in 2024, should provide continuity to CALIOP's observations. New satellite sensors with very high spatial resolution (10 m or less), such as Sentinel-2 and PlanetScope, allow detection of the properties of dust source areas within the Critical Zone and the dynamics of dust events down to the field scale (Baddock et al., 2021; Cheng et al., 2022). NASA's Earth Mineral dust source InvesTigation (EMIT) is its first dust-dedicated mission, mapping the mineralogy of key dust source areas (Connelly et al., 2021), and the Multi-Angle Imager for Aerosols (MAIA) instrument in development promises improved sensitivity to airborne particle composition for health effects studies by incorporating polarimetry and expanded spectral range (Diner et al., 2018). The Tropospheric Emissions: Monitoring of POllution (TEMPO) mission on board a geostationary satellite will continuously monitor air quality, including aerosol properties, over North America with a UV–visible spectrometer, with publicly available hourly measurements at a footprint size of ~10 km^2 (Chance, 2024; Zoogman et al., 2017).

6.2.2. *Ground-based remote sensing*

Ground-based columnar atmospheric optical monitoring with sun/sky photometers can be used for long-term records of significant aerosol events, such as long-distance dust transport from the Sahara Desert into Texas (Mims III, 2022), or as part of short-term field campaigns to monitor optical properties of dust at source areas, such as the playa of Owens Lake, California (Niemeyer et al., 1999). The Aerosol Robotic Network (AERONET) program of photometers across the globe collect data on aerosol optical characteristics at local, regional, and global scales with applications to transport and radiation budget studies, validation of satellite aerosol retrievals (Holben et al., 1998), and validation of numerical models of dust storms including the role of remotely-sensed Critical Zone parameters (e.g., Lee et al., 2024). For example, Chauhan et al. (2018) used AERONET data in combination with ground-based and satellite data to study the characteristics of aerosols and the influence of dust storms at Bakersfield, California. The authors used particle size distribution, refractive index, and single scattering albedo to contrast between dusty and non-dusty days and between dust and smoke.

Lidar tools deployed in dust source areas have been used to understand dust emission processes: for example, Gunn et al. (2021) used a Doppler lidar in conjunction with other sensors to identify a daily "circadian rhythm" of dust and sand transport within the White Sands, New Mexico, dune field critical zone arising from nonequilibrium atmospheric boundary layer convection. Evan et al. (2022a) used a lidar ceilometer to reveal the structure of a dusty density current (haboob) near the Salton Sea, California, showing how dust concentration and wind speed fluctuations were related to those structural features. Guzman-Gonzalez et al. (2024) also used a lidar ceilometer to probe dust storms from the ground, showing atmospheric boundary layer collapses at the time of peak dust concentrations in synoptic dust events in El Paso, Texas.

Ground-based and spaceborne remote sensing data can be combined with other observations and techniques to characterize dust events more comprehensively. For example, Yu et al. (2021) used a set of satellite and ground-based observations (including MODIS, CALIOP, and AERONET remote sensing data, alongside EPA Air Quality Network monitoring data) and the NASA GOES global aerosol transport model to investigate the "Godzilla" African dust intrusion to the Caribbean and continental U.S. in 2020.

6.2.3. *Constraints and knowledge gaps*

Although remote sensing has been a key tool in dust tracing, challenges have always constrained its use. Clear skies are required for the detection of dust plumes from most spaceborne sensors: many dust events, especially those associated with convective weather, remain hidden under clouds. Diffuse dust, localized dust plumes remaining within the atmospheric boundary layer, dust events at night, and North American haboobs generally are not detected by satellite (Urban et al., 2018; Sprigg et al., 2022). Polar-orbiting satellites provide data over a site at most once a day; thus, many dust storms and sources are missed (Lee et al., 2009; Urban et al., 2018). Cloud-screening algorithms for remote sensing systems may also screen out dust events (Evan et al., 2022b). Human identification of dust sources from satellite imagery is subjective and subject to error (Sinclair and LeGrand, 2019). Ground-based automatic camera systems operating within the Critical Zone can fill dust detection gaps in some areas, remotely detecting dust events missed or incompletely detected by other platforms (Evan et al., 2022a). An example of ground-based dust-emission monitoring and its comparison to spaceborne remote sensing is provided by Urban et al. (2018) who used continuous remote camera recording of dust-emitting settings on and around Soda Lake (Mojave Desert) every 15 min during daylight between 10 November 2011 through 31 December 2016. Dust emission during nearly 20% of all days was never observed in satellite retrievals. Extrapolation to similar settings within the Mojave and worldwide led Urban et al. (2018) to conclude that global dust budgets are currently underestimated. Over North America, geostationary sensors such as GOES provide continuous monitoring, but their spatial resolution (~ 2 km) may be too coarse for local-scale air quality studies (Sowden et al., 2018). Lidar networks for aerosol monitoring with relatively dense spacing exist in Europe and Asia, but coverage is sparse in North America (Welton, 2020). Similarly, AERONET has strong global coverage, but lacks sites in some of the key dust source regions and transport pathways in the United States such as Utah and the Southern High Plains. AERONET has also been shown to underestimate very coarse dust particles (Zheng et al., 2024), which are now realized to be more abundant in the atmosphere than previously generally thought.

Ground-based and space-based measurements require confirmation with each other as well as intercalibration of sensors to resolve aerosol properties (Jethva et al., 2019). Inferring intrinsic dust properties and aerosol concentrations remotely from sensor signals is complicated and requires assumptions to be made on aerosol physical and optical properties as well as land surface properties such as albedo and emissivity (Castellanos et al., 2024; Chiapello, 2014; Sowden et al., 2018). Many of these challenges were quantified by the field study of Huck et al. (2023), pointing out how data gaps in remote sensing impact the effective calibration and validation of climate and dust models. Additionally, Castellanos et al. (2024) pointed out how remote sensing retrievals and numerical model algorithms often use different assumptions regarding aerosol properties, complicating interpretations and comparisons of model outputs to remote sensing data. Though gaps in monitoring and data still exist, refinement of algorithms and the promise of new sensors such as EMIT and TEMPO should reduce them. Combined with rapidly evolving artificial intelligence techniques for interpretation of remote sensing data (e.g., Rafi and Rivas, 2024), dust in and being transported between Critical Zones will be able to be sensed remotely with ever more detail and fidelity.

6.3. Dust transport modeling

Traditionally, dust aerosol modeling has focused on either the global dust budget using large-scale climate models or episodic events using regional-scale weather models. Although the former approach provides a global perspective, it often relies on simplified dust schemes and misses sub-grid scale Critical Zone relevant phenomena such as turbulence, clouds, convection, and soil and vegetation spatial heterogeneity. Conversely, regional models suffer from errors and mismatches in boundary conditions and are unable to provide a comprehensive picture of global dust emissions or transport. Dust emission fluxes are inputs for atmospheric transport models such as Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Stein et al., 2015) (Fig. 14), Community Multiscale Air Quality model (CMAQ) (Byun and Schere, 2006) and Weather Research and Forecasting (WRF-Chem; Grell et al., 2005), which can utilize either Eulerian or Lagrangian approaches (Draxler et al., 2010; Fu et al., 2014; Dong et al., 2016; Mallia et al., 2017; Skiles et al., 2018b; Lang et al., 2023), which can be used independently or together to understand the linkages between dust and Critical Zone processes.

Eulerian models, like CMAQ, track dust emissions from all source cells to all grid locations within a 3-dimensional computational domain using prevailing meteorological conditions (Foroutan et al., 2017). This approach allows for "filling in" dust data between measurement locations and provides valuable insights into the linkages between emission sources, air quality, and deposition in critical regions (e.g., snowpack/watershed areas, transportation corridors, business zones, residential

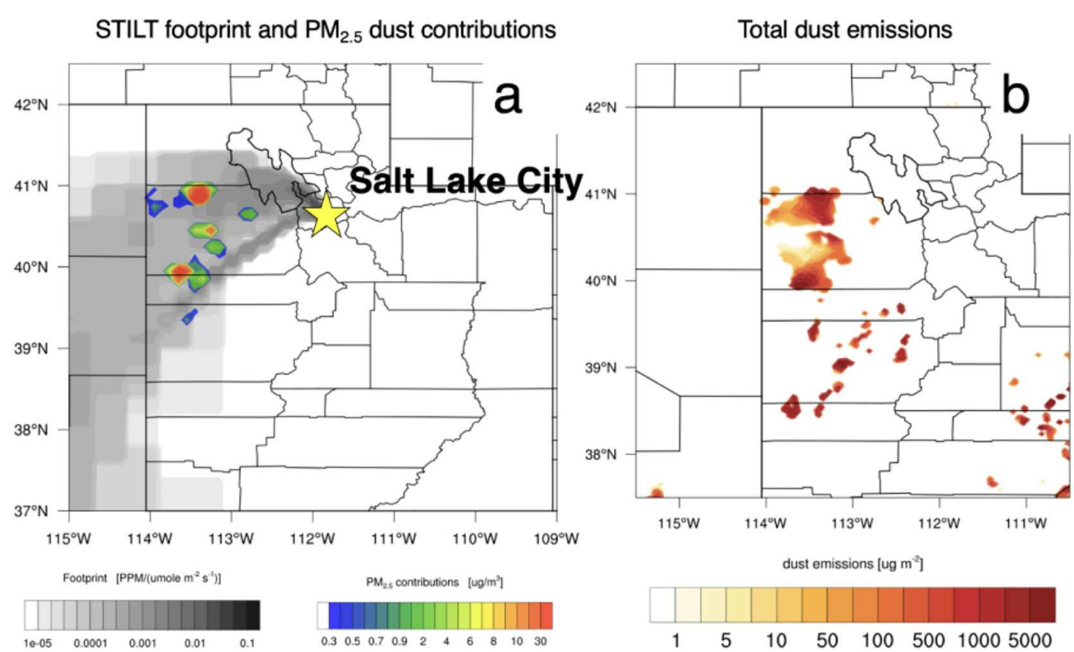

Fig. 14. STILT model simulation of a dust event for Salt Lake City, Utah, on March 30, 2010. Panel (a) shows the STILT footprints (gray-filled contours) mapped with dust contributions towards Salt Lake City (colored-filled contours). Panel (b) shows dust emissions (μg m^{-2}) across northern Utah. Figure created by Dr. Derek Mallia, Research Assistant Professor, University of Utah, using the NCL software.

neighborhoods). For instance, models that track speciated soil nutrients in dust can identify transport impacts on local water quality (Ran et al., 2019). Dust is also included in global climate models to project how changes in climate will influence the emission, transport, and deposition of dust, track sources of dust, and influence ecosystem processes (Mahowald et al., 2006a, 2007, 2017; Zhao et al., 2022; Aryal and Evans, 2021). Recently, Eulerian models have been used to estimate how microplastics in dust samples are generated from Earth's surface soils, roads, and aquatic environments (Brahney et al., 2021b).

Lagrangian models employ a moving frame of reference and trace dust movement either forward or backwards in time. For such models, a 3-dimensional meteorological analysis, typically obtained from a numerical weather prediction (NWP) model, is used to calculate the trajectory of dust following the wind field. The direction of the simulation, forward or backward, depends on the specific application (Lin et al., 2013). For example, an air quality manager might be interested in determining the source regions and/or land uses that contributed to a soil dust event observed at a major city center. An example of a backward trajectory simulation can be seen in Fig. 14, where HYSPLIT was updated with a new turbulence parameterization and vertical Lagrangian time scale (Stochastic Time-Inverted Lagrangian Transport (STILT); Lin et al., 2003; Loughner et al., 2021) to simulate the origin of soil dust for a dust storm in Salt Lake City, Utah. Here, backward trajectories are used to derive an atmospheric footprint (gray shading; Fig. 14a), which is then mapped with soil dust emissions to identify areas of upwind contributions of dust (Fig. 14). Recently, Lagrangian approaches have been used to identify the Great Salt Lake as a dust source to the Wasatch Front, Utah (Grineski et al., 2024), and the influence of the Great Salt Lake on snowmelt timing (Skiles et al., 2018b, Lang et al., 2023). Alternatively, a forward trajectory simulation may be more appropriate when the dust source region is known and the modeler is trying to determine the impacts that a dust source might have on a large downwind geographic region.

6.3.1. Constraints and knowledge gaps

Modeling wind-blown dust carries inherent challenges due to the complex interactions of various processes that control dust emissions, transport, and deposition. Critical Zone processes play a crucial role in modulating many of these processes. For example, the characteristics of the soil and vegetation simultaneously determine the near-surface wind speeds needed to emit soil from the surface into the atmosphere, the amount of soil available to be eroded, and the amount of dust deposited back to the surface. In practice, dust transport models rely on an emission parameterization that describes the relationship between dust fluxes and near-surface wind speeds, land characteristics like soil type and moisture, erodibility, and vegetation cover (Marticorena and Bergametti, 1995; Shao et al., 2011a; Kok et al., 2014a, 2014b; Foroutan et al., 2017). However, accurately measuring these quantities is often difficult due to the poorly understood nature of these underlying processes, which ultimately introduce large uncertainties into soil dust emission models (Okin et al., 2011). In addition, the literature is overwhelmed with case studies concluding that convective dust storms, also known as haboobs, are largely underestimated (or even absent) in models (Marsham et al., 2011; Garcia-Carreras et al., 2013; Heinold et al., 2013; Foroutan and Pleim, 2017; Roberts et al., 2018). This shortcoming may be attributed to the necessary parameterized representation of convection in regional- to-global models with lower resolution, as well as to dust parametrization representing dust emissions as a uniform and continuous process under a deterministic wind shear rather than a turbulent and intermittent process under a stochastic shear stress. Finally, a key uncertainty in dust models is the size of the suspended dust particles, which has different implications for weather, climate, and human health. Models often make assumptions about dust particle size range and, as several recent studies have shown, often underestimate coarse mode ($PM_{2.5}$-PM_{10}) and larger dust aerosols (Adebiyi and Kok, 2020; Meng et al., 2020; Zhao et al., 2022; Adebiyi et al., 2023). To confirm modeling results, additional studies are needed to combine physical measurements, remote sensing, and transport models for specific dust events.

7. Concluding remarks

This review has provided evidence of how the dust cycle connects disparate environments and ecosystems, from dust sources in drylands and modified landscapes, through atmospheric transport and transformation, to dust deposition in diverse receiving ecosystems. Using knowledge gained globally, we have synthesized current knowledge about the generation and composition of dust, the transport of dust through the atmosphere and subsequent deposition, the human health and environmental impacts of the dust cycle, and how the trajectory of dust is tracked from source to sink. By focusing on local and regional dust events that occur within the U.S., we have highlighted new discoveries related to the role of dust in the Critical Zone, such as its ability to impact surface chemistry, hydrology, vegetation, biogeography, community composition, water and air quality, and weather and climate. Dust is one of the key threads that links the natural and human components of the Critical Zone and is also modulated by them. For example, anthropogenic soil disturbance and drawdown of lakes lead to dust emissions, for which society pays the price in altered snowpack and hydrologic cycle, impacts on water quality, and direct human health consequences. This growing body of knowledge demonstrates that dust should be considered a key component of the Critical Zone.

Although our understanding of the dust cycle has improved dramatically over the past decades, there are still several key areas for future research that we have identified throughout this review. First, better knowledge of the total atmospheric burden of particulates and the physical, chemical, optical, and biological properties of dust particles across space and through time would enhance our understanding of dust's role in climate, air quality, human health, and ecosystems. Second, a clearer understanding is needed of how climate change affects the role of dust emissions and deposition on terrestrial and aquatic elements, including carbon cycling, as well as the growing dust sources from retreating ice and melting permafrost. Third, additional information is needed about how specific components of dust – pathogens, microbiota, metals, microplastics, etc. – affect human health, crop health, and ecosystems. Additional research is needed to determine howdust interacts with other Critical Zone processes. For example, the co-location of eddy covariance and dust monitoring stations and the quantification of dust nutrient contributions to terrestrial landscapes (soils, vegetation) can assist with the understanding of dust-carbon cycle interactions. Broader monitoring could also improve our understanding landscape-water quality interactions with dust deposition. The integration of ground-based observations with remote sensing and modeling approaches could help address persistent issues with the remote sensing and modeling of the dust cycle, such as identifying diffuse atmospheric dust and accurately representing larger grain sizes. This integration would also allow the scaling-up of from field-based studies to more accurately represent coupling between the dust cycle and Critical Zone processes (e.g., water, energy, and carbon cycles) in Earth Systems Models. A combination of methods, approaches, and disciplines could be used to address the critical knowledge gap of future projections of dust emissions and impacts to Earth Systems. Given the complex human-natural system of the dust cycle, these projections depend on a fundamental understanding of dust cycle processes and on anthropogenic land use changes, climate change, and policy decisions. We hope that integrating atmospheric dust into the conceptual framework of the Critical Zone can facilitate the type of interdisciplinary research that is needed To fully understand and characterize the role of dust in the global environment.

Declaration of competing interest

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

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