Dust and Fog Effects on Inland Waters*

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Glossary

Acid neutralizing capacity (ANC) A measure of the overall buffering capacity of a solution against acidification.
Aerosols A suspension of solid, liquid, or gas particles in the atmosphere.
Dry deposition The deposition of dust and other aerosols by gravity.
Orographic Relating to the topographical relief of mountains. Orographic precipitation occurs when an air mass is forced to higher altitudes due to the presence of mountains, leading to condensation.
Persistent organic pollutants Toxic organic compounds that are resistant to degradation within the environment.
Wet deposition The deposition of chemicals via precipitation (rain, snow).
Xenobiotics Synthetic chemicals that is foreign to the body or to ecological systems.

Introduction

The atmospheric deposition of aerosols can occur in sufficient quantities to influence the water chemistry and aquatic communities of receiving inland waters. Although both dust and fog are natural phenomena, human activities have greatly influenced the production, composition, and distribution of these aerosols. For example, any activity that destabilizes soils can increase dust entrainment and influence dust composition. Some examples of land use activities that exacerbate soil erosion include agriculture, animal husbandry, and construction (e.g., Fig. 1). The chemical and aerosol composition of clouds and fog (hereafter fog) is usually more concentrated than rain and is influenced by urbanization and other sources of combustion products. Therefore, fog can play a role in the transportation to or removal of aerosols and soluble gasses from ecosystems.

The composition of dust and fog is influenced by both the composition of the generating source (e.g., the soil or water body composition) as well as chemical reactions that may occur along the transport path including sorting, adsorption, coagulation, nucleation, dissolution, precipitation, and in the case of fog, photochemical reactions. These atmospheric vectors have the potential to transport or export other constituents that may influence aquatic ecology, including metals, microorganisms, pathogens, plastics, and persistent organic pollutants. Both dust and fog can effectively transport nutrients but are likely to differ in their influence on aquatic chemistry. Because dust constituents are frequently alkaline, dust deposition will tend to increase the pH of receiving ecosystems. When downwind of pollution sources, fog can transport significant concentrations of airborne acids, which are

Fig. 1 Dust plumes arising from a tractor in Cache Valley, UT, US. Photo Credit: Patrick Strong.

Fig. 2 Fog in the Bitterroot Mountains, US. Fog can deposit nutrients and other constituents onto catchment surfaces. Source: Flickr.

deposited on surfaces within a catchment and can be subsequently transported to lake systems (Fig. 2). In the case of fog, water droplets generated from a lake surface can also be a vector for moving constituents out of the waterbody and into atmospheric systems.

Defining the minimum deposition rate of dust or other aerosols that could negatively influence an aquatic ecosystem, often described as a 'critical load', would be useful for land managers wishing to identify targets and/or predict whether a system may be affected by upwind activities. However, deposition rates of particulate aerosols onto catchments or lake surfaces may not be sufficient to predict the aquatic response. This is because catchment properties and antecedent lake conditions will also play a role in how an aquatic system responds. Catchment properties can either exacerbate or mollify the effect of deposition by either taking up the deposited nutrients/constituents or facilitating the transport to its aquatic systems. The antecedent lake conditions will also dictate the biological and/or chemical response to changes in atmospheric deposition.

Though the importance of dust in fertilizing soils and oceans over millennial times scales is well understood, only recently have scientists become aware that dust can meaningfully impact freshwater aquatic systems over annual to decadal time scales. This new awareness is in part due to the more recent decadal increases in regional dust emissions associated with land use. Globally, there are comprehensive networks aimed at measuring and monitoring atmospheric concentrations of particulates smaller than 10 μm as these are the sizes that influence human health. However, the bulk of the mass of particulates in local to regional dust sources is found in large size classes. Thus, we still know very little about the composition of atmospheric materials and their influence on receiving aquatic waterbodies. Below, we describe how dust and fog are generated, the controls on composition, the influence to aquatic systems, the role of catchment properties using the special case of mountain lakes, and we point to current knowledge gaps.

Dust generation and sampling

Atmospheric or eolian dust generally refers to mineral particulates that have been eroded from the Earth's surface and subsequently transported through the atmosphere. In contrast, particulate aerosols may refer to both dust and particulates that have formed within the atmosphere itself (e.g., photochemical smog). Dust particles are generated from a number of natural and human sources including soil erosion, industrial emissions (e.g., mining, fossil fuel burning, cement production), transportation, construction sites, biomass burning, residential heating sources, plant products (e.g., pollen), volcanic emissions, and synthetic particles like plastics (Piketh et al., 1999; Mahowald et al., 2008; Gesierich and Rott, 2012; Langmann, 2013; Allen et al., 2019; Brahney et al., 2020a) (Fig. 3). Because dust generated from such sources is transported through the atmosphere to aquatic ecosystems, for the purpose of this chapter, all particulate aerosols will be considered as atmospheric dust, regardless of source.

The production of dust from arid and semi-arid landscapes is a natural phenomenon and is controlled by two primary factors (Field et al., 2010). First, the soil surface must be exposed to erosive forces such as wind. Factors that limit soil exposure to wind include vegetation cover or other surface protectors such as cryptobiotic crust (Belnap and Gillette, 1998; Leys and Eldridge, 1998). Second, there must be sufficient wind energy for soil erosion and subsequent entrainment (Fig. 4). These biogeoclimatic drivers of dust production can be influenced by year to year variation in rainfall, storm tracks, and decadal drought (Prospero and Nees, 1986; Goudie and Middleton, 1992; Qian et al., 2002; Flagg et al., 2014). For example, in the semi-arid regions of the southwestern US, La Niña years lead to decreased precipitation, which suppresses the growth of grasses during the growing season. The loss of the stabilizing vegetation causes the soil to be more susceptible to erosion the following spring when storms and strong winds travel through the region (Okin and Reheis, 2002).

Human activities can exacerbate natural dust production in dust-producing regions and create new dust source areas by removing vegetation cover, water, and/or destabilizing surface soils (Neff et al., 2008; Mulitza et al., 2010; Munson et al., 2011;

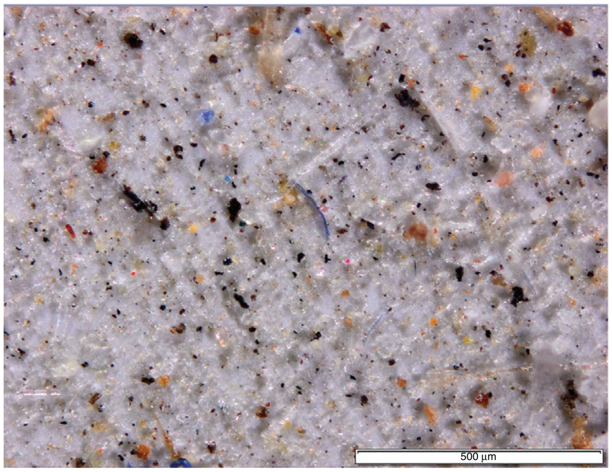

Fig. 3 Dust samples collected by Janice Brahney through the National Atmospheric Deposition Program (NADP http://nadp.slh.wisc.edu/). Visible particles are composed of minerals, amorphous organic matter, charcoal, pollen, car tires, and plastic. Photo Credit: Janice Brahney.

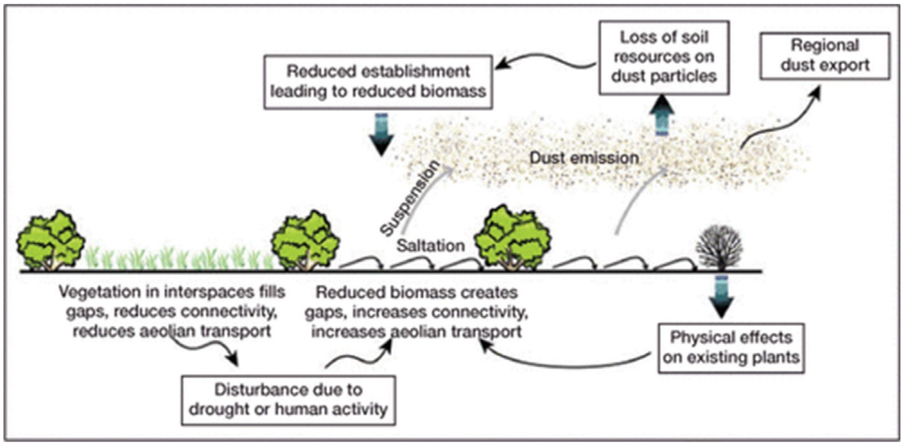

Fig. 4 The role of surface protectors and landscape disturbance on dust generated. Reproduced from Field JP, Belnap J, Breshears DD, Neff JC, Okin GS, Whicker JJ, . . . and Reynolds RL (2010) The ecology of dust. *Frontiers in Ecology and the Environment* **8** (8): 423–430.

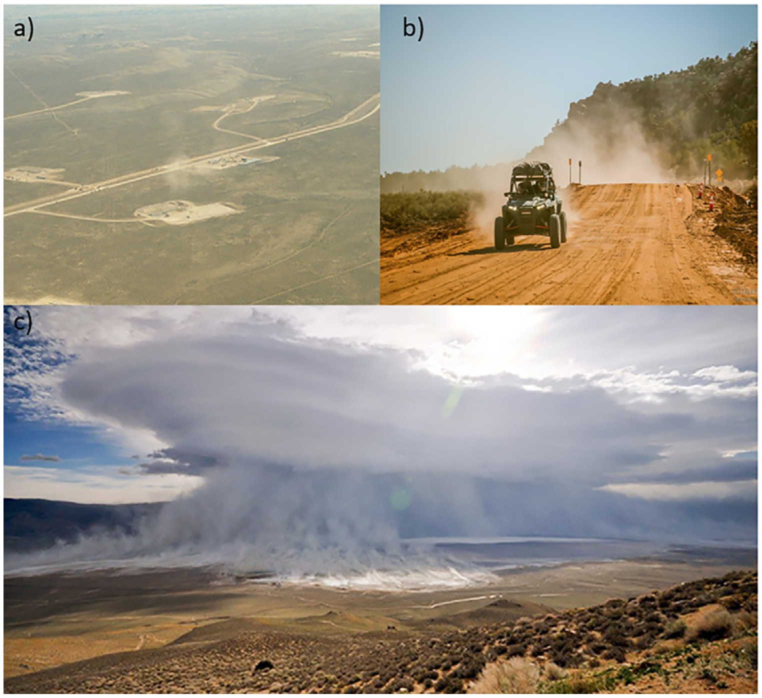

Fig. 5 Human activities and dust production (A) dust generated from well pads in WY, US, (B) dust generated from an ATV, (C) dust from the dry lake bed of Owens Lake, CA, US. (A) Photo: Dawn Ballou, (B) photo David G. Paul, (C) photo: Brian Russell, Great Basin Unified Air Pollution Control District.

Duniway et al., 2019; Brahney et al., 2019). Recent centennial and decadal increases in dust deposition have been linked to both drought and human activities (Neff et al., 2008; Brahney et al., 2013; Aarons et al., 2019; Arcusa et al., 2020). Human land-use activities that can aggravate dust production include agriculture and pastoralism (Neff et al., 2008; Lee et al., 2012; Brahney et al., 2019), water diversions (Saint-Armand et al., 1986; AghaKouchak et al., 2015; Indoitu et al., 2015), industry, roads, and construction (Morishita et al., 2006; Neitlich et al., 2017), oil and gas operations (Brahney et al., 2015a), biomass burning (Andreae et al., 1988), and recreation (Goossens and Buck, 2009) (Fig. 5).

The extent of the human fingerprint on Earth is enormous as more than 95% of the Earth's surface has been appropriated for the variety of land-uses listed above (Kennedy et al., 2019). Impacts of this human fingerprint are highlighted by a 50% diversion of the global runoff (Abbott et al., 2019). These diversions can lead to desertification and the complete or near-complete loss of large lake ecosystems whose lakebeds are then susceptible to wind erosion (Reheis, 1997; Larsen, 2014; Wurtsbaugh et al., 2017). Approximately 40% of the Earth's surface has been appropriated for pasture and crop production (Foley et al., 2005), which can exacerbate soil erosion through tillage or by reducing the threshold wind velocity required for soil entrainment (Leys and Eldridge, 1998; Goossens, 2004; Neff et al., 2005). The widespread fingerprint of human activity on the Earth's surface, combined with persistent and intensified droughts, led to an increase in global atmospheric dust generation in the 20th century (Mahowald et al., 2010). It is estimated that human sources make up 25% of the global 21st century dust production (Ginoux et al., 2012). This increase in the movement of material through the atmosphere has the capacity to significantly alter the natural biogeochemistry of receiving aquatic ecosystems.

Although dust emissions caused by humans have increased in recent centuries and decades, natural dust generation events are episodic and controlled by stochastic and climatic factors (Moulin et al., 1997; Prospero and Lamb, 2003). As a result, dust deposition rates in inland aquatic ecosystems are highly variable across space and time, which poses challenges to sampling efforts. To illustrate, 15 years of dust on snow data from the intermountain west has shown as few as three to as many as 12 dust events during the winter season with corresponding mass deposition rates ranging from 1.65 to 64.3 g m^{-2} $year^{-1}$ (CODOS, 2019). At a global scale, dust deposition rates range from 0 to 450 g m^{-2} $year^{-1}$ with the highest deposition rates influenced by proximal ($<$10 km) sources (Lawrence and Neff, 2009).

Dust sources are divided into three broad categories based on their proximity to dust deposition sites, namely "Local" dust sources originating from 0 to 10 km away, "Regional" from 10 to 1000 km, and "Global" from greater than 1000 km (Lawrence and Neff, 2009). Dust source distance influences the deposition rate and the spatial heterogeneity in deposition, the chemical composition, and the particle size distribution. Whether or not a researcher is interested in quantifying the effect of local, regional, or globally sourced dust will influence the types of samplers used and where they are placed on the landscape. Dust derived from local sources tends to have larger particles sizes and is likely transported closer to the ground surface than aerosols sourced from long distances. For example, Asian dust over North America is typically less than 2.5 μm in size and found between 500 and 3000 m asl (VanCuren and Cahill, 2002).

Fig. 6 Field deployed active (left) and passive deposition samplers. Photo credits: Jeff Perala-Dewey and Molly Blakowski.

Methods for sampling dust fall into two categories, namely passive and active sampling (Fig. 6). Passive sampling techniques rely on the gravitational deposition of particulates into the sampling apparatus (e.g., Reheis and Kihl, 1995). Bulk passive samplers collect particulates deposited both dry and with rain, whereas some samplers are designed to capture dry and wet deposition separately (Reche et al., 2018; Brahney et al., 2020b). Active sampling techniques use a vacuum to draw air through a filter and/or foam to capture gasses, aerosols, and dust (Hart et al., 1992). One advantage of active sampling techniques is that it allows for the separation of aerosols by their size (Büttner, 1988). A disadvantage is that active sampling methods provide atmospheric concentrations, not deposition rates. Concentrations may be more important for understanding atmospheric chemistry and the impacts to human health, but deposition is more relevant for quantifying and understanding the ecological implications of dust deposition.

Fog formation and sampling

Fog, or ground-based cloud, is comprised of water droplets whose size usually ranges from a micron to ~50 μm. These droplets, which are suspended in the atmosphere (Gultepe et al., 2007), are often referred to as occult precipitation (Weathers, 1999; Weathers et al., 2020). Occult precipitation is an apt description of fog behavior—fog hangs in the atmosphere—and also an indication of the complexities inherent to quantifying its deposition since it does not fall vertically like rain. Fog is formed via radiative cooling of moist air either as a result of advection over land from large water bodies or adiabatic expansion (e.g., upslope fog formation).

Of the three primary forms of atmospheric deposition—wet (rain, snow), dry (aerosols and gasses) and fog—fog sits between wet and dry: it is liquid, but because its droplets are suspended, its deposition is governed by meteorological conditions (e.g., windspeed) and receptor surface (i.e., vegetation) (Weathers and Ponette-González, 2011). Because of this, it is unlikely that direct deposition of fog to inland water surfaces is significant. Collection of fog water is usually accomplished via passive or active collection devices (Fig. 7). Passive collectors rely on wind to drive droplets onto collection surfaces, which are often inert strands or mesh, after which the droplets run down the surface into a collection bottle. Active collectors pull air into an opening and across a collection surface at constant speed. Advantages of using an active collector include that high windspeeds are not necessary to collect a sample of sufficient volume, and liquid water content of the sample can be calculated easily.

Dust and fog composition

Dust and fog composition are determined by the biophysical environment of the source region as well as other factors that alter its reactivity during transportation to deposition sites. The primary controls on dust composition are the parent geology and degree of soil development of the source region, as well as human land use activities. To illustrate, dust from arid regions such as the Sahara are typically poor in organic content comprising less than 1% of the dry mass (Eglinton et al., 2002), while dust generated from agricultural regions can contain much larger fractions of organic and nutrient-rich material, up to 67% (Malm et al., 2004). Dust may also change appreciably in composition during travel through the atmosphere due to sorting, scavenging, and chemical

Fig. 7 Passive (top) and active sampling of fog. Photo credit: Kathleen Weathers (top), Collett research group (bottom).

reactions. For example, the progressive loss of the larger size fractions due to sorting may lead to a loss of heavier and larger minerals such as zircons and silicates. Various gaseous and particulate emissions may also be scavenged by dust during transport through adsorption, coagulation, nucleation, dissolution, and precipitation reactions. As a result, dust produced in or passing through urban centers will have a composition influenced by combustion sources (fossil fuels, incinerators), volatile metals, and organic contaminants (Han et al., 2004; Marx et al., 2008; Xiong et al., 2017; Goodman et al., 2019) (Fig. 8). The chemical and biological composition of fog is often reflective of its regional environment (Weathers et al., 1988, 2020; Evans et al., 2019; Gultepe et al., 2007). Fog has been recorded to have up to a 100-fold higher chemical concentration than rain collected from the same location (Kimball et al., 1988; Weathers et al., 2020) (Fig. 9). Dust and fog can also contain synthetic compounds such as pesticides, fertilizers, or even plastics (Glotfelty et al., 1987; Allen et al., 2019; Brahney et al., 2020a). Finally, dust and fog can act as a vector for the transport of microorganisms including pathogens that can affect human and ecosystem health and functioning (Hervàs et al., 2009; Metcalf et al., 2012; CDC, 2013; Reche et al., 2018).

Dust and fog influences on aquatic system pH

The acid neutralizing capacity (ANC) references the ability of water body to resist, or buffer, changes in pH. Most natural waterbodies have pH ranges between 6.0 and 9.0 pH units and deviations higher or lower can fundamentally alter the ecology and chemistry of the waterbodies. Lakes with low natural ANC are sensitive to external inputs, like acid rain. Because dust is often, but not always, generated from sedimentary basins, dust often includes carbonate minerals and can therefor affect receiving water ANC.

Carbonate minerals such as $CaCO_3$ are readily soluble in even slightly acidic waters contributing ANC to both precipitation (Loye-Pilot et al., 1986; Rogora et al., 2004, 2016; Brahney et al., 2013; Kopáček et al., 2016) and aquatic ecosystems through the addition of the bicarbonate ion (Psenner, 1999; Tait and Thaler, 2000; Rogora et al., 2004). Fig. 10A shows a tight correlation

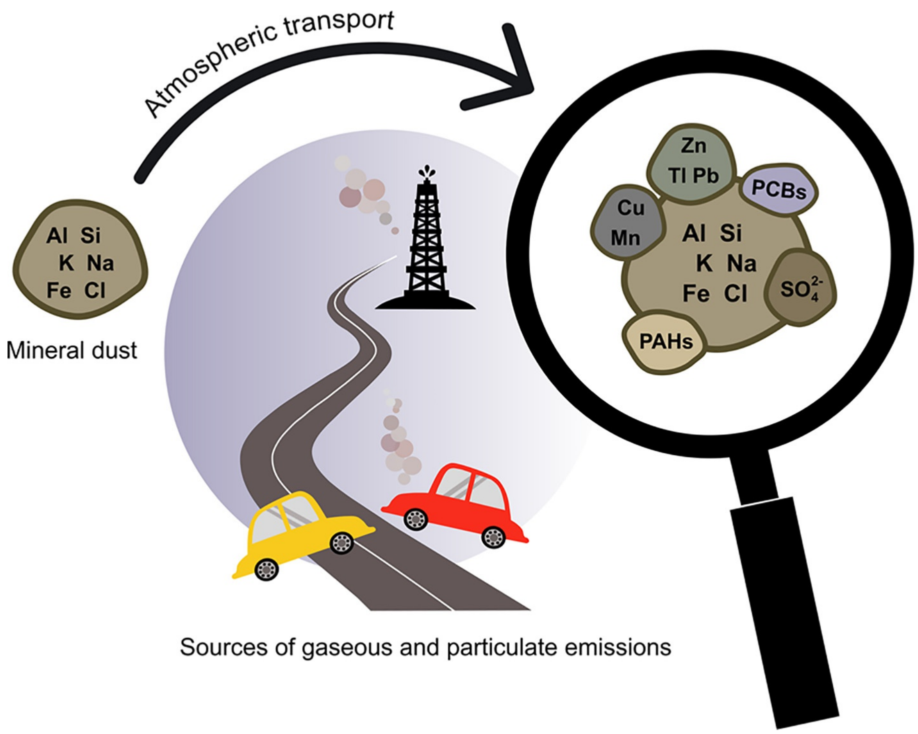

Fig. 8 During atmospheric transport, the reactive surfaces of dust can be modified by elements and compounds introduced to the atmosphere by human activities. Image credit: Molly Blakowski.

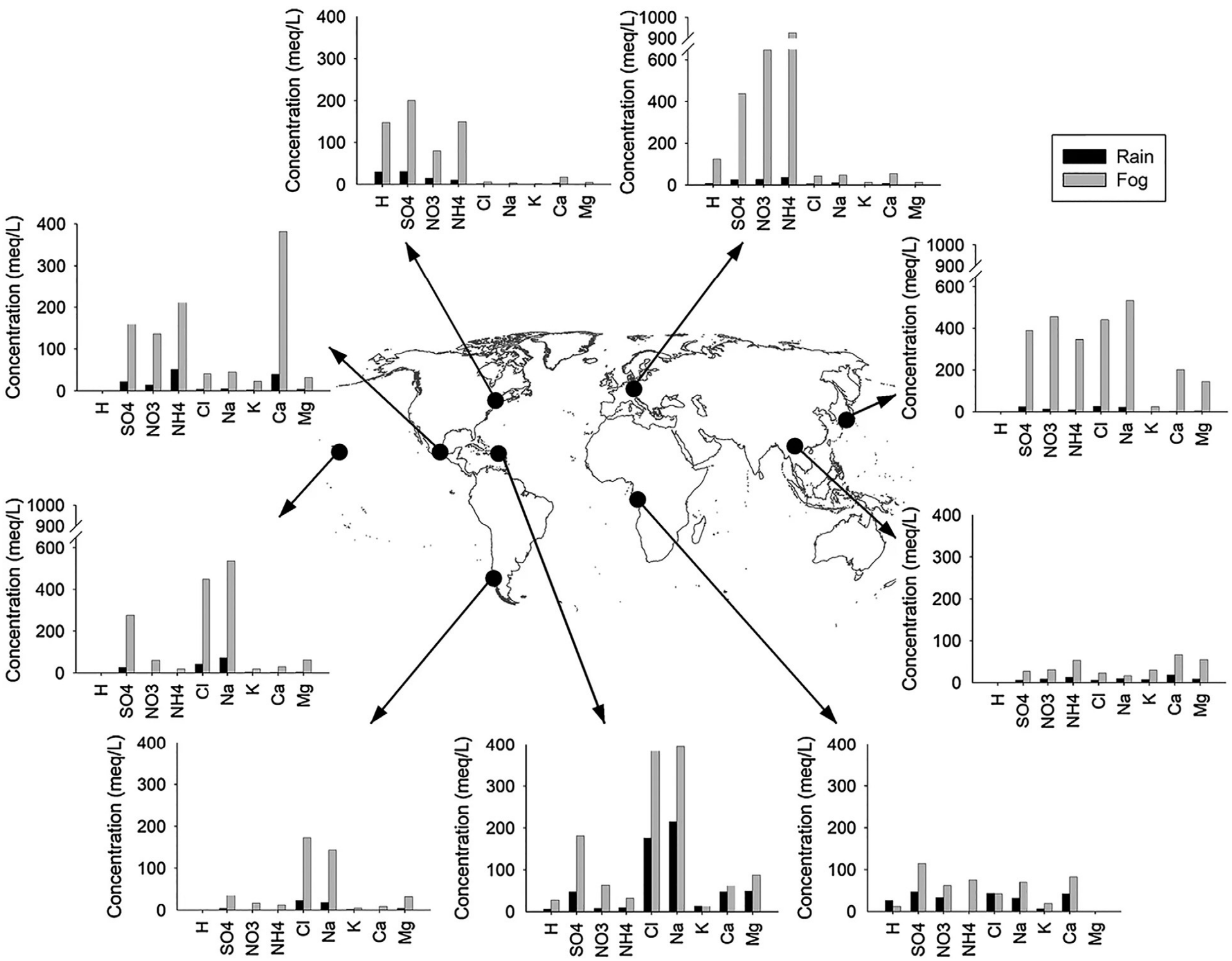

Fig. 9 The concentration of major ions in fog is considerably greater than concentrations found in rain water, even in arid regions. Image reproduced from Weathers KC, Ponette-González AG and Dawson TE (2020) Medium, vector, and connector: Fog and the maintenance of ecosystems. *Ecosystems* 23:217–229.

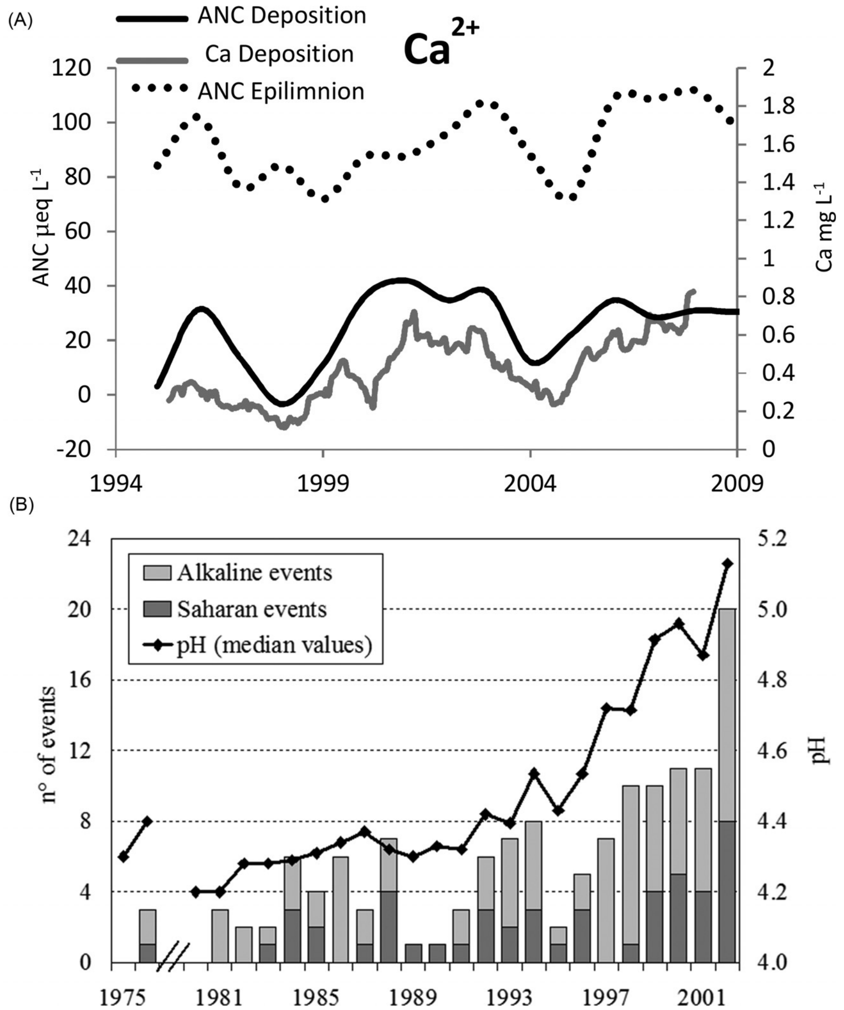

Fig. 10 (A) Temporal correlation between the Acid Neutralizing Capacity (ANC) in the Epilimnion of Blake Joe Lake, Wyoming with the dust (Ca^{2+}) and ANC in deposition (Brahney et al., 2014). (B) Temporal trends in Saharan dust events and the pH and alkalinity of precipitation in the Lake Maggiore region of Italy and Switzerland (Rogora et al., 2004).

between dust deposition, precipitation ANC, and the ANC of Black Joe Lake, Wyoming, illustrating the relationship between dust contributions and the buffer capacity of lake systems. Alkalinity contributions from dust may counteract acid deposition from other human activities. For example, the quartzite bedrock of the Uinta Mountains is naturally poor in ANC, yet these mountain waters have not experienced acidification despite their proximity to acid emissions. It has been speculated that dust contributions have buffered these aquatic systems that remain neutral to alkaline (Messer et al., 1982; Ellis et al., 2015). The effect of dust on lake recovery from acidification is illustrated in Fig. 10B. Elevated Saharan dust deposition from the 1990s onward is thought to have aided in the recovery of Lake Maggiore from acidification (Rogora et al., 2004).

The calcium carbonate content of dust ranges from 0% to 33% worldwide (Lawrence and Neff, 2009). However, due to its high solubility in water in some regions, the calcite content may rapidly disappear during transport, particularly if airborne acid concentrations are high (Jacobson and Holmden, 2006). Thus, the dust source composition, the distance traveled, and the presence of acid precursors in the atmosphere will influence the extent to which dust may neutralize acids in freshwater systems.

Dust and fog delivery of nutrients and metals to aquatic ecosystems

The transport of the key limiting nutrients such as nitrogen (in dust and fog) and phosphorus, carbon, and calcium to ecosystems may occur in both the organic and inorganic forms. Dust and fog may also be vectors for metals to ecosystems, some of which may be necessary micronutrients while others are considered toxins. Because it is aqueous, fog can effectively transport ions such as nitrates (NO_3^-) and ammonium (NH_4^+), and can trap and move particulates such as pollen, or particulate organic carbon from atmosphere to ecosystem (e.g., Fuzzi et al., 1997; Fenn et al., 2000). The bioavailability of nutrients, and thus their capacity to influence inland waters, will vary with the composition of the particulate aerosols. For example, the water-soluble fractions of nutrients are immediately available for biological uptake whereas the organic or mineral bound fractions may become available over longer time periods. Dust can directly deposit nutrient and metals onto lake surfaces and some portion of the dust deposited within the catchment will be mobilized to the lake basin (Brahney et al., 2015a). Though fog is often enriched in elements (N, P, Ca, C) relative to rain (Fig. 9), direct deposition to lake surfaces is unlikely and it is not clear how efficiently fog deposition is transported into lake systems.

At present, a critical unknown is how the antecedent lake conditions will influence the response and bioavailability of deposited dust. Both pH and nutrient limitation can theoretically influence the efficiency of nutrient acquisition from dust particulates based on enzyme production and activation. Regardless, the atmospheric deposition of bioavailable nutrients will not only increase primary production but can also influence community composition through the alteration of N:P ratios (Elser et al., 2009a,b, Camarero and Catalán, 2012). For example, there is a strong linear relationship between the stoichiometry of nutrient deposition and that found in mountain lake systems (Fig. 11). These data suggest that direct atmospheric deposition is a primary control on mountain lake nutrient availability, which in turn influences production and species composition.

Nitrogen

Nitrogen deposition via rain and gaseous aerosols is well monitored and modeled around most areas of the world (Holland et al., 2005; Lü and Tian, 2007; NADP, 2019). Less is known about the contributions of nitrogen to receiving ecosystems from dry dust material as this fraction is rarely analyzed, although it is often modeled (Jia et al., 2016; TDep, 2019). Likewise, while fog has been shown to deliver proportionally large quantities of nitrogen to fog-dominated terrestrial ecosystems (e.g., Weathers et al., 2000a,b, 2020), little sustained, coordinated fog monitoring has been conducted. Furthermore, as noted earlier, while fog is chemically concentrated when compared to rain, direct deposition to inland waters is likely to be very limited.

In some areas, the dry fraction could potentially be an underappreciated component of the atmospheric nitrogen deposition (Neff et al., 2002; Cornell, 2011). The water-soluble organic nitrogen fraction has been shown to contribute approximately 25% of the flux of total nitrogen to Europe (Mace et al., 2003b; Cornell, 2011), 66% of the flux to North America (Neff et al., 2002), and up to 45% of the total nitrogen flux in the Amazon basin (Mace et al., 2003a; Cornell, 2011). Morales-Baquero et al. (2013) quantified wet and dry deposition of nitrogen associated with Saharan dust events, and found that wet deposition accounted for a larger fraction, with a Dry:Wet ratio of NO_3^--N at 0.56 and TN at 0.78. The bioavailability of particulate nitrogen is likely to vary according to dust composition, which is largely influenced by the climate and human land use patterns of the source area. For example, biomass burning and agriculture may contribute to the particulate nitrogen flux in areas where these practices occur, whereas, in the Mediterranean region, the organic nitrogen fraction has been linked to soil and dust sources (Mace et al., 2003b). Because dry deposition rates of nitrogen are generally modeled rather than measured and the spatial variability in deposition is high, overall uncertainties in the deposition rate of organic nitrogen and its waters soluble fraction can be large (Cornell et al., 2003).

Phosphorus

In contrast to atmospheric nitrogen, phosphorus has no stable gaseous form and thus atmospheric transport largely occurs as particulates. Important sources of atmospheric phosphorus include soils, biomass burning, and industrial emissions (Mahowald et al., 2008). Owing to the erodibility of the fine-grained, nutrient-rich fractions of soil, on average, dusts are enriched in

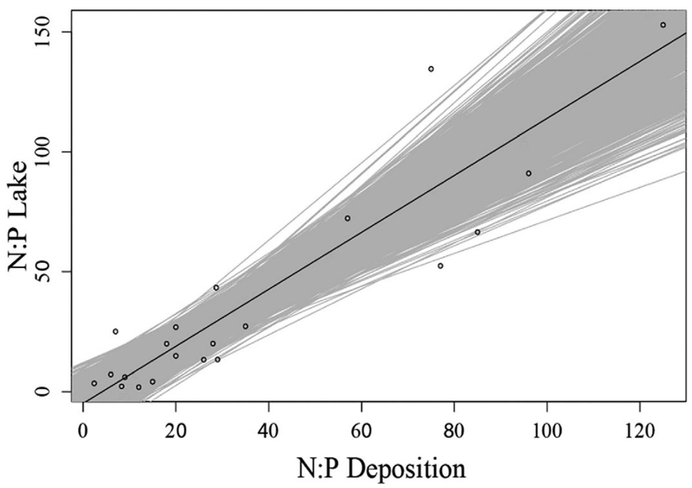

Fig. 11 The global relationship between the N:P ratio in atmospheric deposition and the N:P ratio in co-located mountain lakes. Each point represents the average within a mountain region spanning four continents (Brahney et al., 2015b).

phosphorus over average crustal concentrations by a factor of 1.6 (Lawrence and Neff, 2009). Thus, dust generally has the capacity to fertilize receiving ecosystems. Because fog can effectively scavenge and transport particles, total phosphorus concentrations measured in fog can be enriched compared to rain, and account for a sizeable portion of the mass flux of the nutrient to leaf surfaces in some areas (Vandecar et al., 2015).

Phosphorus concentrations in dust range from <1 mg g^{-1} to 5 mg g^{-1} (Tipping et al., 2014; Brahney et al., 2015b) but the form of particulate phosphorus will greatly influence the bioavailability of deposited phosphorus. Exchangeable and water-soluble phosphorus are the most bioavailable, while phosphorus bound in organic matter can be released in the water column when broken down by free enzymes and microbes. Phosphate bound to Iron (Fe) or Aluminum (Al) oxides or phosphorus locked up in the mineral apatite may not be biologically relevant over seasonal timescales but may become available through longer time scales.

The source of atmospheric particulates influences the forms of particulate phosphorus. For example, dust originating from the Sahara are dominantly minerogenic, with the organic fraction making up just 1% of the dry mass (Eglinton et al., 2002). Much of the phosphorus in this dust is tied up in apatite and iron minerals (Clausnitzer and Singer, 1996; Eijsink et al., 2000). Nevertheless, studies have shown that approximately 10% of the phosphorus in the Saharan dust becomes available within one hour, and an additional 30–40% within just 16 hours (Herut et al., 1999; Ridame and Guieu, 2002). Dust originating from agricultural or semi-arid soils, in contrast, can have organic concentrations that range from 15% to 67% by weight of dry mass (Dahms and Rawlins, 1996; Malm et al., 2004; Lawrence and Neff, 2009). Particulates from biomass burning may also be enriched in phosphorus (Newman, 1995; Boy et al., 2008; Ponette-Gonzalez et al., 2016). However, the concentration of P in emitted ash may vary with both the type of vegetation burning and the intensity of the fire (Maenhaut et al., 1996; Vicars et al., 2010; Vicars and Sickman, 2011).

Because phosphorus is a key limiting nutrient in aquatic ecosystems, the atmospheric deposition of this nutrient to remote sensitive aquatic ecosystems is of concern. The capacity for dust to affect phosphorus nutrient subsidies in mountain lake systems was first identified in the Austrian Alps (Psenner, 1999). Since then, other studies elsewhere in mountain regions of Europe, Asia, and the US have shown the effects of dust associated phosphorus deposition on controlling lake water nutrient chemistry, productivity, and species composition (Sickman and Melack, 2003; Morales-Baquero et al., 2006; Pulido-Villena et al., 2008; Tsugeki et al., 2012; Brahney et al., 2014). A 2016 study showed that oligotrophic (low phosphorus) lakes and streams in the continental US may be becoming higher in nutrients and the sites most affected were the most remote with the least amount of human influence within the catchment (Stoddard et al., 2016). This result suggests that phosphorus is likely entering these catchments via the atmosphere, potentially as dust. Lowland lakes are not exempt from the influence. For example, in regions with intense burning, even large lakes have been enriched in nutrients due to large atmospheric contributions (Tamatamah et al., 2005; Boy et al., 2008).

Research in the Wind River Range of Wyoming, US has provided strong correlational evidence that even at low deposition rates (e.g., <4 g m^{-2} $year^{-2}$), dust can transport phosphorus in sufficient quantities to affect lake systems. Because the dominant dust source to the Wind River Range is the nearby Green River Valley, a gradient in dust deposition across the range exists (Dahms, 1993; Dahms and Rawlins, 1996; Brahney et al., 2014). Dust affected lakes in the range had higher total phosphorus (TP) concentrations and up to two orders of magnitude greater primary and secondary production than nearby non-dust affected lakes (Brahney et al., 2014). Sediment core analyzes corroborated the spatial analyzes and showed temporal relationships between dust deposition and the diatom-inferred phosphorus concentrations in lakes (Fig. 12). This research highlights that while large dust storms or haboobs may generate public interest, smaller chronic emissions, which may not be visible via satellite, may lead to significant cumulative consequence in receiving water bodies.

There is a growing body of evidence that dust phosphorus can have measurable consequences in lake ecosystems Sickman and Melack, 2003; Reche et al., 2009; Vicars et al., 2010; Ballantyne et al., 2011; Camarero and Catalán, 2012; Brahney et al., 2014, 2015a,b). However, all but one of these studies (Reche et al., 2009) relied on correlational rather than experimental analyzes. Therefore, more research on the role of dust phosphorus is required to fully understand ecosystem impacts.

Calcium

Calcium is an important nutrient for many organisms in lake systems, but in particular for invertebrates, where the element makes up a key component of their shells and carapaces (Tessier and Horwitz, 1990; Wærvågen et al., 2002). Calcium leached from dusts into aquatic systems may be derived from a variety of minerals including feldspars, phyllosilicates, gypsum, dolomite, and calcium carbonate ($CaCO_3$). The dissolution of calcium carbonate and other dust minerals either in precipitation or in depositional water bodies can provide readily available calcium ions (Ca^{2+}) to remote mountain lakes (Pulido-Villena et al., 2006). For regions with catchments having low natural calcium abundance, this contribution may be a critical source of calcium to aquatic organisms with relatively high calcium requirements. Measured calcium carbonate concentrations from Chinese dust sources have ranged from 2% to 10% (Jacobson and Holmden, 2006), African sources from 2% to 20% (Guieu et al., 2002), U.S. sources from 1% to 25%, and up to 33% in parts of the Middle East (Singer et al., 2003). For example, in the Sierra Nevada Mountains in Spain, paleolimnological research showed that in the last ~50 years there has been an intensification of dust and Ca^{2+} inputs from the Sahara (Jiménez et al., 2018). This, combined with the effects of climate change, resulted in increased Ca^{2+} concentrations, which in turn, led to an increase in *Daphnia*, a Cladocera taxon, whose growth and reproduction can be impaired by low Ca^{2+} (Jeziorski et al., 2008). *Daphnia* is a keystone genus, and the expansion of their populations is an indication of significant environmental changes in this region, illustrating the role dusts may have in shaping community composition.

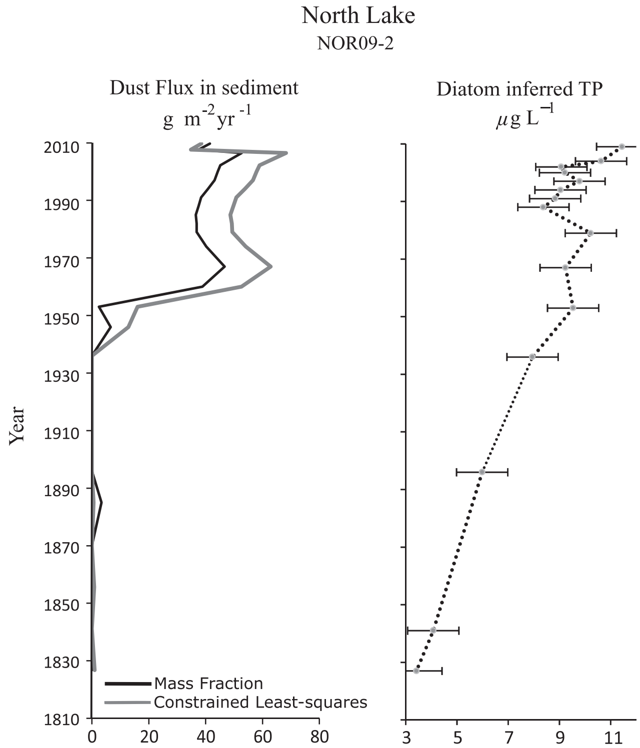

Fig. 12 Historical dust deposition rates to North Lake in Wyoming paired with diatom-inferred total dissolved phosphorus (TDP) concentrations.

Carbon

Dissolved organic carbon (DOC) concentrations in high-elevation lakes has been associated with the water-soluble organic carbon fraction of dust (Reche et al., 2009; Mladenov et al., 2011). Because alpine lakes are above tree line, terrestrial production and export of dissolved organic matter (DOM) is generally low and alpine lake transparency high. DOC not only serves as a substrate for microbial metabolism, but also adsorbs harmful ultraviolet radiation (UVR) that would otherwise act to suppress production. Thus, the dust-mediated transport of water soluble organic carbon (WSOC) can have both physical and biotic implications. A study in the Mediterranean reservoirs showed that dust transport of DOC into waterbodies reduced transparency and (UVR) penetration, and was associated with shallower mixing depths (de Vicente et al., 2012). Nutrient and DOC inputs from dust likely also support microbial growth in receiving water bodies (Pulido-Villena et al., 2008; Reche et al., 2009; de Vicente et al., 2012).

Metals

Along with macro nutrients (N, P, C, Ca) dust can transport trace elements that can act as either nutrients or toxins, depending on the concentration. Although several studies have quantified the metal concentrations within dust and the role of dust in transporting heavy metals such as As, Cd, Cr, Cu, Fe, Ni, Pb, Sb, Se, and Zn to aquatic systems (Sweet et al., 1998; Reynolds et al., 2014; Brahney et al., 2015a), there are no studies to date that directly examine the influence of dust-metal deposition on the ecology of lake systems. However, Goldman et al. (1990) attributed an increase in Lake Tahoe production during forest fires to nutrient and trace metal additions via ash deposition. Iron is critical for biological processes, including photosynthesis and nitrogen fixation, and may be limiting in some oligotrophic lakes systems (Vrede and Tranvik, 2006; North et al., 2007). Bhattachan et al. (2016) showed that dust iron (Fe) is more soluble than soil Fe and provided evidence that Fe in dust becomes more soluble through atmospheric processing, thus atmospheric processes may increase the bioavailability of soil macro and micronutrients. Future work might focus on quantifying the bioavailability of dust metal deposition to inland, oligotrophic systems, and the role of multi-element nutrient limitation on community composition and production.

Microorganism deposition to and export from inland waters

Dust and fog transport may represent a significant mechanism for the dispersal of microbes ranging from viruses to fungi across ecosystems, which have the potential to alter the function of resident communities (Kellogg and Griffin, 2006; Lindström and Östman, 2011; Yamaguchi et al., 2012; Reche et al., 2018). Microhabitats within dust and in situ sediment particles have been shown to enhance the survival of pathogens extending their range of influence (LaBelle and Gerba, 1982; Rao et al., 1984; Reche et al., 2018). Further, microbes in coastal fog have been shown to resemble aquatic and terrestrial genera (Dueker et al., 2012; Evans et al., 2019), demonstrating that fog can be a vector of microbes from aquatic to adjacent terrestrial ecosystems.

Experiments in the Sierra Nevada and Pyrenees Mountains of Spain demonstrated the viability of transported taxa in laboratory experiments (Hervàs et al., 2009; Reche et al., 2009). However, the likelihood of establishment in a recipient habitat will relate to seeding pressure and the resident community composition (Jones et al., 2017). This microbe seeding may be particularly influential in mountain regions where the losses of perennial snowpack and glaciers have exposed new terrain and established new terrestrial and aquatic systems. Although atmospheric deposition of dust is likely to result in dispersal of microbes to inland waters (Peter et al. 2014), recent research suggests that fog may be a vector for microbial export from inland waters to adjacent terrestrial systems (e.g., Dueker et al., 2012; Weathers et al., 2020). Aerosols generated from lake surfaces have also been shown to contain cyanobacteria and associated toxins (Cheng et al., 2007; Banack et al., 2015; Olsen et al., 2018). The export and import of microbes to lakes and the ecological relevance of these processes are currently not well understood.

Aerosol effects on solar radiation

Dust and fog also have the ability to affect photosynthetically active radiation (PAR) in aquatic ecosystems. In fact, the greatest impact of fog on inland waters is likely to be indirect through its effect on PAR. Fog has been shown to reduce PAR and affect photosynthesis in terrestrial systems (Weathers et al., 2020). However, in terrestrial systems that are enveloped in fog, there is a counterbalancing effect on plant productivity through hydrologic modulation by fog: trees transpire less. In a similar way, dust can absorb PAR and it is likely that during periods of intense biomass burning, lakes experience diminished solar irradiance to a point where primary production is altered (Scordo et al., 2021) (Fig. 13).

Dust and fog effects vary by lake and catchment characteristics

The effect of dust and fog on water chemistry and biology in aquatic ecosystems will vary with catchment and lake characteristics. Geology, aspect, slope, catchment morphometry, and vegetation type and cover can all act to either mollify or exacerbate the influence of atmospheric deposition on receiving water bodies (Morales-Baquero et al., 1999). Steep, rocky slopes with poor vegetation cover can be very effective at delivering atmospherically deposited nutrients to waterbodies, whereas vegetation and soils can take up nutrients either effectively delaying the transport to the waterbody or preventing it altogether.

In steep mountain catchments, dust material can be mechanically focused into lake basins by either wind redistribution, or overland flow. However, catchment geology will play a role in the transport of phosphate as it binds tightly to available Al and Fe-oxide minerals, even when vegetation is poor. An abundance of these minerals within catchments may effectively immobilize phosphorus on the landscape (Vicars et al., 2010; Kopáček et al., 2011, 2015). Conversely, watersheds with poor soil development and a low abundance of Aluminum (Al) and Fe bearing minerals may allow for the effective transport of dust–phosphorus to lake basins (Tsugeki et al., 2012; Brahney et al., 2014).

Lake morphometry, including area, depth, volume, and fetch can influence whether lakes are more or less susceptible to the effects of atmospheric deposition. The addition of nutrients and other compounds can be diluted if the volume of the upper mixed layer of a lake (epilimnion) is relatively large, for example. Pre-existing lake conditions are also likely to influence the role of atmospheric nutrient deposition. Acidified lakes are likely to respond to a greater degree to dust alkalinity contributions and phosphorus limited lakes may see a greater increase in production than lakes that are predominantly nitrogen limited. Those hypotheses have yet to be explicitly tested.

Fig. 13 A lake enshrouded in fog to the extent that solar radiation reaching the lake surface is diminished. Similar effects may occur with excessive particulates in the air from smoke or inversions. Peter Dasilva/EPA, via Shutterstock.

A special case: Mountain lakes

Mountain lakes and their catchments are highly varied in their composition (Fig. 14). Thus, the response of any one lake to similar dust composition and deposition rates are likely to vary. Mountain ranges act as natural barriers to the atmospheric transport of material and orographic precipitation on windward slopes that may produce fog and effectively scrub the atmosphere of particulates. Mountain lakes tend to be particularly sensitive to atmospheric deposition due to their small, steep, and poorly vegetated catchments. These types of lakes are also excellent recorders of dust deposition due to enhanced mechanical transport of dust to lake basins. Further, a uniform and simplified geology of small catchments allows for the geochemical tracking of dust deposition rates in sediment core studies (Neff et al., 2008; Reynolds et al., 2010; Brahney et al., 2015a; Routson et al., 2016). Researchers can use the geochemical composition of dust and catchment bedrock as fingerprints and the relative amount of bedrock versus dust material that accumulates in a lake's sediment can be used to reconstruct historical dust loading. As such, mountain lakes provide an excellent context for studying changes in dust deposition and any associated effects on mountain lake chemistry and biology. Contemporary and paleolimnological analyzes in mountain lakes worldwide have shed light on long- and short-term dust histories as well as the variation in chemical composition, and influence on aquatic ecosystems through the atmospheric addition of alkalinity, nutrients, trace elements, contaminants, and organisms.

Research on the dust-mediated transfer of phosphorus to aquatic systems has primarily focused on oligotrophic mountain lake systems as they have few alternative watershed sources of nutrients (Morales-Baquero et al., 2006; Vicars and Sickman, 2011; Camarero and Catalán, 2012; Brahney et al., 2014). Similarly, the atmospheric deposition of N and its effect on aquatic systems is pronounced in mountain watersheds where natural concentrations are low and abatement through catchment uptake is limited (Baron et al., 2000, 2011; Wolfe et al., 2001; Nydick et al., 2003; Elser et al., 2009a). Thus, in mountain systems, a small change in atmospheric loads can result in a large change in absolute nutrient concentrations, causing mountain lakes to be more susceptible to the influence of atmospheric deposition than lowland lakes and those with large watersheds (Moser et al., 2019). For example, in the Sierra-Nevada Mountains of Spain, dust associated P deposition ranged from 24 to 38 $\mu g\ P\ m^{-2}\ day^{-1}$, a seemingly small contribution, yet this deposition rate had measurable effects on productivity, nutrient ratios, bacterial abundance, and plankton diversity (Morales-Baquero et al., 2006; Pulido-Villena et al., 2008; Reche et al., 2009). In fact, there is evidence suggesting mountain lakes may experience reduced functional diversity and a diminished efficiency in the trophic transfer of energy up the food web as a consequence of dust deposition (González-Olalla et al., 2018). Because mountain lakes are sensitive to such perturbations, a warmer dustier future may fundamentally alter mountain lake community composition.

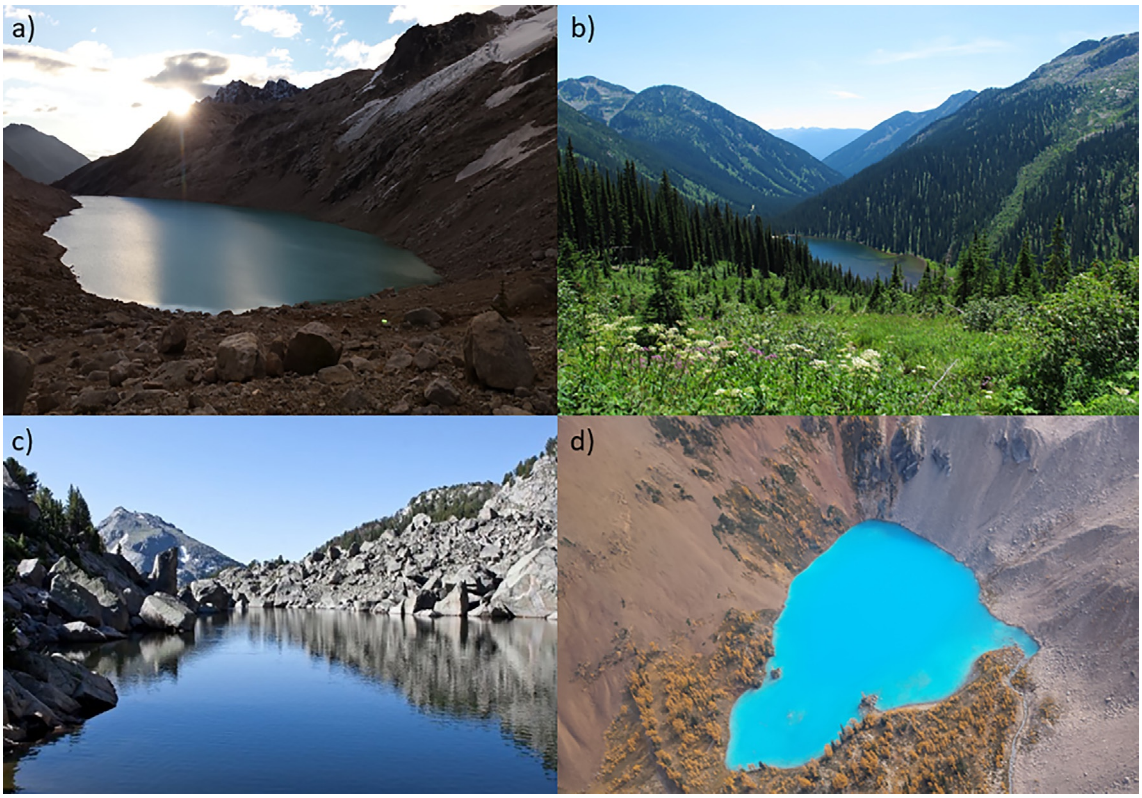

Fig. 14 Mountain catchments and their lake chemistries are highly varied. (A) No name lake, British Columbia, (B) Gibson Lake, British Columbia, (C) North Lake, Wyoming, (D) Buster Lake, British Columbia. Photos: Janice Brahney.

Summary

Dust and fog have the capacity to influence the physical, biogeochemical, and biotic components of inland waters both directly and indirectly. Paleolimnological, modeling, and monitoring studies have shown that soil and biomass emissions have increased across large regions of the globe (Neff et al., 2008; Mulitza et al., 2010) and the resulting deposition has led to ecosystem shifts, such as elevated production, changes in pH, and associated changes in community composition. Because particulate emissions are tied to human land-use changes from pastoralism, food production, biomass burning, and the frequency and severity of drought, it is reasonable to conclude that with human population growth and climate change, eolian dust may become more important to aquatic ecosystems in the near future (Foley et al., 2005; Hudson, 2011; Trenberth et al., 2014). Fog is more likely to have indirect impacts on inland waters through scattering and absorption of incoming light, and hydrologic and biogeochemical impacts to adjacent catchments. However, in some systems and under certain conditions, inland waters may be a source of condensation nuclei for fog and thus result in an export of biotic or abiotic materials from inland waters to surrounding terrestrial systems.

Knowledge gaps

There are many knowledge gaps in our understanding of dust and fog deposition and subsequent direct and indirect effects on inland water ecology and ecosystem processes. Here we outline a few. While we know that what goes up into the atmosphere must come down, we know less about what is emitted, transported, and deposited when it comes to dust and fog. For example, there are few studies that have examined novel pollutants, pesticides (xenobiotics), nanoplastic, metals, or ash in either dust or fog, or what quantities of these chemicals make their way into aquatic ecosystems. Whether the aerosols and chemicals that are transported are also bioavailable to aquatic systems is also a major question. We know that dust can contain relatively high concentrations of nutrients, like phosphorus. However, phosphorus in dust can be found at mineral or organic exchange sites, bound within organic matter, or locked up in minerals. The ability for an aquatic organism to acquire dust-derived nutrients may also vary with antecedent lake properties, like pH and nutrient limitation. At present, the variability in dust composition and thus the bioavailability of dust-nutrients is not well quantified and there are limited studies evaluating how aquatic organisms respond directly to dust deposition in either controlled or in-lake experiments.

In recent years there has been an increasing interest in understanding to what extent materials move from inland waters to adjacent ecosystems via atmospheric transport. Of particular interest and concern is the transport of potentially toxic substances such as cyanotoxins. Further, several studies have shown that dust, and sometimes fog, can transport viable microbes to distal locations, and that the composite microbial community reflects the particle source area. However, whether or not the deposited microbes influence or shape the resident microbial community has not yet been addressed in the literature.

Finally, along with climate warming, dust on snow can change albedo and accelerate snowmelt (Skiles et al., 2018) leading to shifts in the pulse of water and nutrients to receiving water bodies. Changes in the timing snowmelt has led to shifts in periphyton communities in river systems. It is possible that dust-induced earlier runoff and nutrient delivery could impact lake ecosystems as well, but to date we are unaware of any research targeting this specific question.

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