A COLLABORATIVE NETWORK TO UNDERSTAND HOW WILDLAND FIRE EMISSIONS INFLUENCE LAKE ECOSYSTEMS

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Wildland fires are increasing in frequency, size, and severity globally (Cunningham et al. 2024), releasing large quantities of a complex mixture of airborne particles that can be transported thousands of kilometers through the atmosphere. Fire emissions include smoke aerosols (particles ≤10 μm), pyrometeors (medium-sized particles or agglomerates of smaller particles 10–2000 μm), and firebrands (large burning embers >2000 μm). Lakes are increasingly exposed to emissions from wildland fires (Farruggia et al. 2024; Smits et al. 2024), with observations indicating that these emissions alter water chemistry and biology, nutrient availability, light penetration, and thermal conditions (Fig. 1). These effects occur through two main pathways that are theorized to vary with distance from the fire. Near the fire (<100 km), large pyrometeors can deposit directly into lakes, delivering particulate material, nutrients, contaminants, and microorganisms (Ardyna et al. 2022; Hickenbottom et al. 2023; Bonfantine et al. 2024) while also influencing light conditions (Scordo et al. 2021, 2022). At greater distances (>100 km), smaller smoke aerosol particles remain suspended in the atmosphere and primarily affect lakes by altering solar radiation (Fig. 1b). Although these particles can enter waterbodies through wet deposition, their total mass is much lower than that of pyrometeors.

The effects of wildland fire emissions on waterbodies are expected to depend on their characteristics, properties of the downwind ecosystem, and the timing of deposition (Fig. 1a). These emissions vary in total mass, particle size distribution, and chemical and biological composition. These properties are determined by the type of material burned (e.g., forest, grassland, organic soils, or urban fuels), fuel characteristics (e.g., load and moisture), fire behavior (e.g., heat release and combustion efficiency), and weather conditions, which govern atmospheric transport and particle settling. During atmospheric transport, as smoke plumes age and travel, the chemical and biological characteristics of emissions can change through processes such as oxidation, photochemical reactions, and particle coagulation. During this time, particles may also accumulate volatile heavy metals and microbes or lose carbonate content depending on pH conditions (Stockdale et al. 2016; Goodman et al. 2019; Heindel et al. 2020). In addition, the ecological response of lakes to wildland fire emissions have been conceptualized to be dependent on lake characteristics (e.g., productivity, stoichiometry, morphometry, underlying geology) and on the timing of deposition relative to seasonal ecosystem dynamics (Scordo et al. 2021, 2022; Farruggia et al. 2024; Smits et al. 2024). Depositing nutrients to a nutrient-limited waterbody may stimulate primary productivity when light is not limiting, whereas the same nutrient input may have little detectable effect in systems with high background nutrient concentrations or where phytoplankton communities are light limited (Farruggia et al. 2024). Consequently, the ecological response to wildland fire emissions depends on the timing of deposition relative to seasonal ecosystem dynamics (Smits et al. 2024). If wildland fire emissions deliver nutrients while simultaneously reducing radiative inputs near the end of the productive season (late summer or autumn), the ecological impact may be limited. In contrast, similar inputs occurring during the middle of the growing season, when biological activity and primary production are at their peak, may produce stronger ecosystem responses.

Despite their potential importance, the pathways through which wildland fire emissions affect aquatic ecosystems remain poorly understood due to limited monitoring and insufficient modeling capability, particularly for larger particles (>10 μm) and the microscopic living component of smoke (Kobziar et al. 2022). Atmospheric modeling frameworks often focus on the smallest particle-size fractions (<10 μm) and typically represent particle mass concentrations without detailed information on chemical composition or biological content (Brahney et al. 2024; Kobziar et al. 2024). In addition, atmospheric transport models often underestimate the transport of coarse wildfire particles, because they tend to deposit large particles out of the atmosphere too quickly (Adebiyi and Kok 2020). Moreover, research on wildland fire impacts on aquatic ecosystems has largely focused on watershed burning, with atmospheric pathways linking fires to aquatic ecosystems largely understudied.

To address these knowledge gaps, we launched a collaborative research network entitled "Wildfire Airborne Particles: Emissions, Transport, Fate, and Their Influence on Lake Ecosystems," supported by the U.S. National Science Foundation FIRE-NET program. This network brings together an interdisciplinary group of scientists to examine wildfire airborne particle transport, deposition, and ecosystem responses. The network focuses on improving modeling approaches, refining conceptual frameworks, and developing coordinated monitoring protocols to advance understanding wildland fire emission impacts on freshwater systems in an increasingly fire prone world.

BUILDING AN INTERDISCIPLINARY COMMUNITY

Our network was established to connect researchers working at the intersection of wildland fire science, atmospheric science, and aquatic ecology. The group brings together 30 scientists representing a range of career stages, from early career researchers to senior investigators, with expertise spanning atmospheric modeling, fire, aquatic, and soil ecology, environmental chemistry, microbiology, and engineering. At the February 23, 2026, kickoff meeting, participants identified key knowledge gaps, opportunities for collaboration, and four major research tasks to guide future activities which are described here.

Task 1. Define methods for better quantifying how wildland fire emissions spread through the atmosphere and deposit on the landscape

Task 1 focuses on improving methods for modeling and quantifying how wildland fire-emitted airborne particles move through the atmosphere and deposit across landscapes. Lakes within the landscape and their airsheds receive different amounts and types of particles depending on

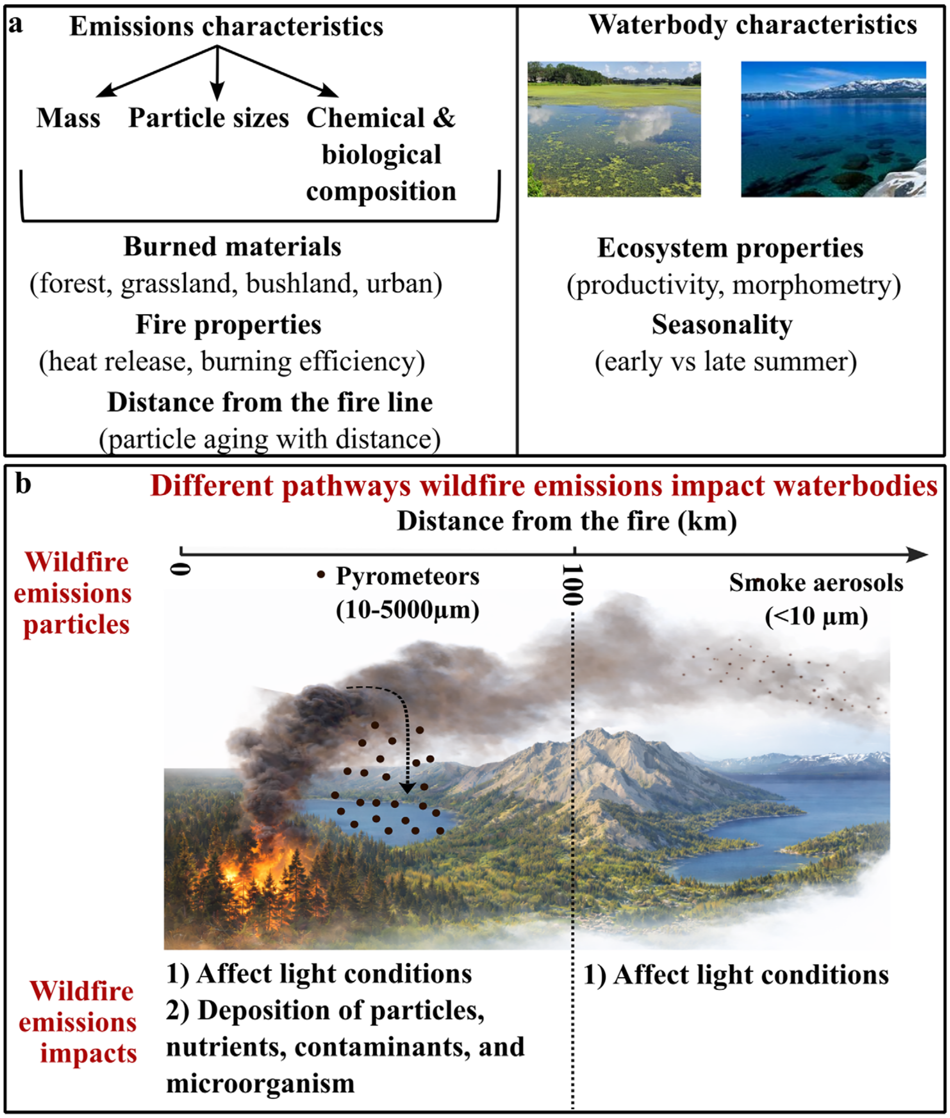

FIG. 1. Conceptual pathways linking wildfire emissions and lake ecosystem responses. Wildland fires emit a wide range of airborne particles, including coarse pyrometeors and fine smoke aerosols, that can be transported through the atmosphere across regional to continental scales. (a) The effects of wildland fire emissions on waterbodies depend on emission characteristics, properties of the receiving ecosystem, and the timing of deposition. Emission characteristics (including total mass, particle size distribution, and chemical and biological composition) vary with the type of material burned, fire characteristics and behavior (e.g., heat release and combustion efficiency), weather, and the distance from the fire where particles are deposited. Lake responses are further mediated by ecosystem properties (e.g., productivity and morphometry) and seasonal conditions. (b) Larger particles (pyrometeors; 10–5000 μm) typically deposit near the fire and can affect lakes through multiple pathways, including the delivery of nutrients, contaminants, and microorganisms, as well as changes in light availability. In contrast, smaller smoke particles (<10 μm) can travel long distances before deposition and primarily influence lakes by altering the underwater light environment. Although these particles can enter water bodies through wet deposition, their total mass is much lower than that of pyrometeors, making their deposition potentially less significant.

their distance from fires, the fire characteristics, weather, and burned material. Particle size strongly influences atmospheric transport, deposition rates, and ecological impacts. We will evaluate ways to integrate physical modeling of the convective fire-plume process with particle lofting, transport, and deposition, using existing datasets and field measurements. Emerging tools, including remote sensing, low-cost sensor networks, and atmospheric models, may help quantify particle transport across landscapes. Understanding how meteorological processes influence transport will be critical for predicting where emissions ultimately deposit.

Task 2. Assess the chemical and biological composition of wildland fire emissions as they are transported from the source of combustion and deposited in the landscape

Task 2 focuses on understanding the chemical and biological composition of wildland fire airborne particles and how that composition evolves during atmospheric transport. Wildland fire emissions contain a complex mixture of materials, including organic carbon, nutrients, trace metals, and microbial communities originating from soils and vegetation. Atmospheric processes such as oxidation, photochemical reactions, and particle coagulation can alter particle composition as smoke plumes age and travel through the atmosphere (Gieré and Querol 2010). This task complements Task 1 by bringing together experts to link modeled and observed particle transport and deposition to composition, improving understanding of how fire characteristics shape the distribution and ecological impacts of pyro-emitted materials.

Task 3. Refine a conceptual framework linking wildland fire emissions and lake ecosystems

In Task 3, we will refine and advance a conceptual framework linking wildland fire emissions to ecological responses in lakes by addressing key knowledge gaps. Existing conceptual models focus primarily on autotrophic or whole-ecosystem responses to atmospheric deposition, altered light climate, and watershed-mediated transport pathways. Research is less well developed regarding how emissions from different fire types (e.g., grassland versus forest fires) affect aquatic ecosystems and the duration of their impacts. Likewise, existing models do not address mechanisms through which changes in incident radiation or deposition of materials may restructure microbial or autotrophic communities, reshape biogeochemical cycling, or generate feedback among microbes, phytoplankton, and broader aquatic community structure. As a result, current models remain limited in their ability to predict how fire emissions reorganize lake ecosystem processes or the timescales over which such reorganization may occur, limiting our ability to incorporate these dynamics into existing regulatory and water-quality management frameworks. Collectively such factors will determine the resilience of lakes to change and timescales associated with recovery. FIRE-NET will address these linkages by integrating emissions characteristics, watershed hydrology, lake biogeochemistry, and aquatic community ecology to better understand the magnitude, timing, and persistence of fire-related impacts across lake types.

Task 4. Propose protocols to improve the monitoring of wildland fire emissions during active fires

Current monitoring of wildland fire emissions and their impacts on aquatic systems is often fragmented and opportunistic, lacking consistent metrics and systematic sampling. In Task 4, we aim to establish a repeatable approach applicable across diverse ecoregions (e.g., grasslands to forests) and fire scenarios. We seek to integrate and advance field and remote sensing methods, key biological and chemical indicators, and data management practices into standardized protocols, enabling managers and scientists to better understand wildfire emissions impacts on lakes and surrounding landscapes. Participants identified opportunities to improve observations, including deposition collectors, high frequency sensor networks, rapid response protocols, and coordinated atmospheric measurements. Integrating these observations with remote sensing can help target sampling and detect short term ecosystem responses that might otherwise go unresolved. Developing shared monitoring and reporting protocols will also enable coordinated studies across regions and fires.

To move beyond opportunistic sampling, we also emphasize the importance of establishing partnerships with fire management agencies conducting prescribed burns and national atmospheric monitoring programs. These coordinated efforts create opportunities for more structured and hypothesis-driven monitoring designs, improving our ability to directly link fire emissions with changes in water quality and ecosystem processes.

LOOKING FORWARD

FIRE-NET will continue through 2026 and 2027 with collaborative activities, including virtual meetings and a three-day in-person workshop at the University of Nevada, Reno Lake Tahoe campus. The network will produce synthesis papers on wildland fire particle transport and deposition, a conceptual framework for freshwater impacts, and recommendations for modeling and monitoring, including protocols for coordinated research during future wildfire events. By bringing together diverse disciplines, the network seeks to advance understanding of how wildfire emissions affect aquatic ecosystems and to improve capabilities for monitoring and predicting these impacts in an increasingly fire-prone world.

We invite members of the Association for the Sciences of Limnology and Oceanography community to engage with FIRE-NET by contributing data, participating in collaborative analyses, and helping refine emerging research priorities and monitoring approaches. Opportunities for involvement include joining working groups, contributing to synthesis efforts, and coordinating observations during future wildfire events. We also welcome input on key knowledge gaps, particularly regarding how wildfire-driven changes in aquatic systems can be integrated into long-term monitoring programs and management frameworks. Researchers interested in participating in or receiving updates are encouraged to connect with the PIs of the network (F. Scordo, S. Chandra, J. Brahney, or D. Mallia) as we work to build a more coordinated and interdisciplinary understanding of wildfire impacts on inland waters.

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CONFLICT OF INTEREST

MJF declares they are an Associate Editor of L&O Bulletin.

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