Workshop Report, “Bioaerosols in the Earth System”

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Directorate / Division	Program
GEO/AGS	Atmospheric Chemistry
GEO/AGS	Physical and Dynamic Meteorology
BIO/DEB	Population and Community Ecology Cluster
BIO/DEB	Ecology and Evolution of Infectious Diseases
BIO/DEB	Ecosystem Science
BIO/IOS	Symbiosis, Infection, and Immunity
ENG/CBET	Nanoscale Interactions Program
ENG/CBET	Environmental Engineering Program
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Executive Summary

The interdisciplinary workshop on Bioaerosols in the Earth System, held in early 2025, brought together experts from biology, ecology, microbiology, aerosol science, engineering, and geoscience to address key gaps in understanding the structure, function, and impacts of bioaerosols. The 1.5-day workshop highlighted major scientific challenges, technological barriers, and opportunities for advancing the field. This summary outlines the workshop findings, including emerging themes, future directions, and strategies to foster continued interdisciplinary collaboration.

In this report, we use the term "bioaerosols" to include airborne particles of biological origin, such as viruses, bacteria, fungi, and pollen. The "aerobiome" refers to the community of airborne microorganisms, whether viable or not, and their fragments.

Key Workshop Findings

1. **Structure and Function of the Aerobiome**
   - **Gaps**: A major challenge in bioaerosol research is the lack of comprehensive observational data on the spatial and temporal dynamics of bioaerosols. Studies to date are typically short-term and local. Long-term, high-resolution datasets are needed to advance our understanding of emissions, viability, and atmospheric transport.
   - **Key Insights**: Emphasis was placed on understanding the biogeochemical mechanisms that allow bioaerosols to survive atmospheric conditions, such as desiccation, nutrient acquisition, and UV exposure. Notably, atmospheric viability and interactions with cloud processes are underexplored.
   - **Actions**: Advancements require the development of low-cost, viability-preserving samplers, standardized monitoring networks, and new lab facilities to simulate atmospheric conditions.

2. **The Aerobiome as an Earth System**
   - **Gaps**: Bioaerosols play significant roles in cloud formation, ecological processes, and public health, yet the mechanisms of bioaerosol emission, transport, distribution in the atmosphere, deposition, and transformation remain poorly understood.
   - **Key Insights**: The workshop underscored the importance of integrating bioaerosol research into broader Earth system models and understanding their ecological and health impacts, with specific attention to emissions variability, deposition dynamics, and modification while airborne..
   - **Actions**: Enhancing models that predict bioaerosol emissions, transport, deposition, and impacts, leveraging interdisciplinary frameworks (e.g., GeoHealth), and designing collaborative experimental and monitoring systems are critical steps forward.

3. **Methods, Standards, and Monitoring**
   - **Gaps**: A lack of standardized methods for sampling, sequencing, and characterizing bioaerosols creates significant challenges in comparing data across studies. The ultra-low biomass of air samples complicates DNA/RNA extraction and analysis, making reproducibility difficult.
   - **Key Insights**: Participants emphasized the need for standardized protocols, reference materials, and improved data-sharing practices to ensure consistency and comparability in bioaerosol research. There is also an urgent need for more interdisciplinary training and accessible resources, especially for early-career researchers.

- **Actions**: Development of best-practice guidance, centralized, open source data repositories, and AI-powered data analysis tools will be essential for advancing the field and enhancing research efficiency.

Future Directions: Enabling Breakthroughs

1. **Enabling Interoperable Datasets**: A fundamental need and therefore a primary recommendation is the development of improved metadata protocols and centralized, open-source repositories for bioaerosol data. These databases would underpin and facilitate cross-study comparisons and enable researchers to leverage existing datasets, such as those collected for health surveillance or weather forecasting.
2. **Accelerating Progress with AI and Automation**: The integration of AI-based tools into bioaerosol research promises to advance predictive modeling and address current bottlenecks in data processing and sequencing. Machine learning algorithms and automated pipelines could enhance data reproducibility and scalability, accelerating scientific progress.
3. **Building Community Infrastructure**: Expanding bioaerosol monitoring capabilities and creating shared-use facilities for bioaerosol research and training will be key to building community capacity. Integrating bioaerosol monitoring into existing atmospheric and environmental networks will broaden the scope and impact of research.
4. **Coordinating Field Campaigns**: Large-scale, interdisciplinary field campaigns are essential for generating interoperable datasets, generating and testing hypotheses, and fostering collaboration. These campaigns would provide critical insights into bioaerosol emissions, transport, transformation, and health impacts.
5. **Applying and Adapting Ecological Theory for the Atmosphere**: Existing microbial biodiversity and ecosystem functioning models have not been developed for atmospheric systems. Testing existing ecological theory and/or developing a new theoretical framework for the aerobiome is key to understanding its structure and function in a changing world.
6. **Advancing Predictive Models**: The development of predictive models for bioaerosol emission, transport, atmospheric processing and deposition will be transformative for forecasting health and ecological impacts. These models will benefit from better observational data and integration with climate and weather forecasting systems.
7. **Expanding Training Opportunities**: To ensure continued innovation in bioaerosol science, participants emphasized the importance of interdisciplinary training programs. Summer schools, fellowships, and building interdisciplinary cohorts to ask and answer fundamental questions can be employed to empower early-career researchers to lead integrative studies.

Frontiers: Mapping Microbial Transport and Forecasting Disease

The aerobiome, while an invisible and often overlooked component of Earth systems, has significant implications for global health, agriculture, and biosecurity. The atmospheric transport of pathogens, allergens, and invasive species presents new challenges for public health and national security. The creation of a national bioaerosol forecasting system would integrate existing monitoring platforms with bioaerosol-specific detection tools, expanding observations from the surface into the vertical. This system could not only be used to test and validate models of bioaerosol dynamics, but also to predict the movement of plant pathogens, antibiotic-resistant microbes, and airborne diseases, enabling early warnings and more effective responses.

To realize these breakthroughs, significant investment in infrastructure, data collection, and cross-disciplinary collaboration is required. A coordinated, interdisciplinary bioaerosol research community can unlock critical insights into the role of the atmosphere in shaping life on Earth, protecting human health, and securing global ecosystems.

Contents

Executive Summary ii

1. Introduction and Motivation 1

2. Workshop Format. 2

3. Pre-Workshop Input 3

4. Workshop Findings 6

- **4a. Structure and Function, including Viability** 6
- **4b. The Aerobiome as a System** 8
- **4c. Methods, Standards, and Monitoring** 10
- **4d. Future Directions: Enabling Breakthroughs** 12

5. Workshop Follow-Up 14

References 15

Appendices 17

1. Introduction and Motivation

With recent advances in microbiome science, the essential role of microbes and microbial community dynamics in the Earth system is gaining increasing recognition (*Tastassa et al*., 2024; *Huang et al.,* 2024; *Amato et al*., 2023; *Zhou et al.,* 2022; *Šantl-Temkiv et al*., 2022; *Tignat-Perrier et al*., 2020). While the airborne dispersal of some microbes—such as plant pathogens and allergens—has been studied for decades due to their relevance to human health and food systems, only in recent years has broader attention turned to bioaerosols' role as integral components of atmospheric processes. This includes growing efforts to model their sources, transport, transformations, interactions, and impacts across local to global scales. Here, we use the term "bioaerosol" to include airborne particles of biological origin, such as viruses, bacteria, fungi, and pollen.

Interest in bioaerosols has expanded significantly, as seen in a surge of review articles over the past decade. Much of this momentum has come from the atmospheric science community, particularly in connection with bioaerosols' role in ice nucleating particles (INPs), which influence cloud formation. Early research in the 1970s identified certain plant-associated bacteria as active INPs at relatively warm temperatures (*Schnell and Vali*, 1973; *Lindow et al*., 1978). Since then, additional species—including fungi and pollen—have also been found to nucleate ice (*Huang et al*., 2021), prompting further investigation into their atmospheric roles and health implications. These discoveries have motivated continued efforts to improve detection and quantify the abundance of bioaerosols in both natural and built environments (*Huffman et al*., 2020; *Šantl-Temkiv et al.,* 2020; *Mainelis*, 2020).

The COVID-19 pandemic further accelerated interest in bioaerosols by highlighting critical gaps in our understanding of aerosol emissions, pathogen viability during atmospheric transport, and environmental virus abundance (*Marr*, 2025; *Oswin et al*., 2022; *Marr et al.,* 2019). It also underscored the importance of aerosol physics and chemistry in advancing understanding of behavior and functioning of bioaerosols. At the same time, improvements in sequencing technologies, especially for ultra-low biomass samples, have enabled deeper exploration of airborne microbial communities across a wide range of environments—including remote oceans, polar regions, and high-altitude locations—leading to a growing body of taxonomic data.

This increase in observational capacity has facilitated new efforts to incorporate bioaerosols into regional and global Earth system models (e.g., *Hummel et al*., 2015; *Janssen et al.,* 2021). These models aim to improve understanding of microbial sources, sinks, and atmospheric distributions, contributing to a more complete picture of their ecological and climatological significance.

Despite these advances, interdisciplinary collaboration across atmospheric science, microbiology, biology, chemistry, and engineering remains limited. Few opportunities have existed to bring together researchers across these domains to jointly address the complexity of environmental bioaerosols. This workshop was designed to do just that—convening experts to review progress, identify persistent gaps, and explore opportunities for innovation. By synthesizing recent findings and fostering collaboration, the workshop aimed to chart a path toward transformative scientific discovery and high-impact advancements in this evolving field.

2. Workshop Format

The idea for the workshop was developed in early Spring 2024 by the co-leads. A proposal was prepared, submitted, and reviewed, with funding awarded in late Summer 2024. A potential attendee list was prepared Summer-Fall 2024. A preliminary agenda and invitations were sent in Fall 2024. A pre-workshop survey was sent to each person who accepted the invitation, and the responses were used to develop the full agenda (Appendix 2). Brief biographies of each participant are in Appendix 1. Copies of the questions and the full set of responses are in Appendix 3, with summaries in the next section.

The workshop began with an evening reception and icebreaker the night before the first full day. During the icebreaker, each participant was asked to introduce themselves, and to place a sticker with their name and face on an element in a bioaerosol Earth system cycle with which they most identified (after *Weathers et al.*, 2014; *Piso, O'Rourke and Weathers*, 2016). The diagram was adapted from the Graphical Abstract of *Tastassa et al.* (2024) and printed on an oversized poster. Each participant was also offered a Sharpie to draw in any system component they identified that was missing, which resulted in some creative additions. The activity was well received and helped introduce the broad range of disciplines that were represented. An image of the resulting poster is shown in Appendix 4.

Discussions were organized into four themed sessions, held in person over the following 1.5 days. Each session started with a plenary talk, followed by ~5 lightning talks and a summary from one of the organizers on survey responses that related to the theme. Participants then were organized into three breakout groups and asked to discuss and summarize recent progress, remaining gaps, and opportunities for advancing knowledge in that area. Each group added notes to a Google Drive that was set up with full access to all participants, before, during, and after the workshop, and that also contained slide decks for the plenaries and lightning talks. Each breakout group was asked to appoint a reporter who would summarize the group's discussions around (1) frontiers; (2) "big ideas"; and (3) additional gaps and barriers not identified in the pre-workshop inputs. An additional plenary talk was delivered over dinner on the first full workshop day. This talk focused on how an interdisciplinary group came together in a decade-long coordinated center effort to successfully tackle longstanding "big picture" questions around the nature and role of marine aerosols. A recent application of center findings to identify and remediate a community health crisis was described.

Location: CIRA Commons Building, Foothills Campus, Colorado State University, Ft. Collins, CO

Dates: February 4-6, 2025

Invitees: Approximately 30 researchers with expertise spanning the breadth of research represented in participating NSF programs (e.g., microbiology, genomics, ecology of infectious disease, microbial ecology, ecosystem science, atmospheric science, aerosol science and technology, indoor air quality, data science, and modeling). Efforts were made to identify participants at different career stages and from across the U.S., with one international participant.

Anticipated Outcomes: Workshop report; peer-reviewed manuscript exploring research frontiers; launching of ongoing activities to build community, for example, virtual seminar series and online discussion groups.

Other: Participation by invitation only, and in person (two invited participants joined online, due to illness and unavoidable schedule conflicts). No recordings. Invitees were asked to commit to attending the entire meeting and to contribute to the report and manuscript.

3. Pre-Workshop Input

The co-leads aimed to include themes and participants from across relevant fields of biology, ecology, engineering, and geosciences. A short survey was sent to all confirmed participants, that included the following three open-ended questions and achieved 100% participation. Respondents were invited to "provide a narrative or bullet points, however you prefer. We will share these insights with the group ahead of time, so please be succinct (max ~ 150 words)."

- **Key Research Needs:** *What are current limitations on progress in Earth System bioaerosol research? What do you view as the (**up to 3**) most urgent science questions and/or knowledge gaps for interdisciplinary bioaerosol research scientists to explore and overcome in the coming decade?*

- **Barriers to Progress:** *What are current limitations on progress in Earth System bioaerosol research? What do you view as the (**up to 3**) most important barriers to filling/bridging the questions / gaps you listed above? What information, data, tools, or equipment do you most need from another discipline in order to move your bioaerosol research forward?*

- (OPTIONAL) **Bioaerosols as an Emerging Research Theme:** *What interested you in participating in this workshop? What are your expectations / hopes for workshop outcomes? What are your impressions of the "aerobiome" as an emerging theme?*
  - *Within your discipline*
  - *Outside of your discipline*

The responses to the first two questions were organized into major thematic areas that were used to establish the themes of the sessions in the workshop. Consideration of the 1.5-day format and the desire for ample discussion time in breakouts led to the decision to group topics into four overarching sessions. As seen in the agenda, these sessions were as follows. Brief summaries of the key needs and barriers that were sorted into each are listed below.

Session 1: Structure and Function of the Aerobiome System

Gaps: There is a fundamental lack of observational data that impedes our understanding of the aerobiome system. Emissions inventories, both natural and anthropogenic, remain incomplete, and long-term studies or monitoring networks capable of capturing spatial and temporal trends are sparse. This has left the sources and distribution of bioaerosols largely unknown. Key scientific questions remain unanswered, such as the degree to which bioaerosols contribute across rural–urban gradients, what their vertical profiles look like in the lower atmosphere, and whether microbes remain metabolically active once airborne. Further, the biochemical strategies used by microbes and pollen to endure atmospheric stressors, such as proteins and polysaccharides that protect against desiccation, are not well characterized.

Barriers: A lack of consensus on measurement standards, best practices, and research priorities hampers progress in this field. Infrastructure to support routine, widespread measurement is inadequate. There is also a need for portable and lightweight samplers that can preserve the viability of collected microbes while providing high-resolution data. Interdisciplinary collaboration remains limited, and the development of experimental designs that can replicate tropospheric and stratospheric conditions in laboratory settings is still in its infancy.

Session 2: Pathogens in the System

Gaps: One of the central challenges is determining the biological composition of airborne pathogens—understanding what is present, when, and where, especially in the context of climate change and co-occurring atmospheric particles. It remains unclear how long and which pathogens can survive in the atmosphere, what factors influence their viability as they move across environmental systems, and how biological constraints shape their survival. There is limited insight into the interactions within microbial communities aloft, including their implications for human health and ecological functions. Existing spatio-temporal monitoring efforts are insufficient, and the relative contributions of pathogens across terrestrial, freshwater, and marine gradients are poorly understood. Additionally, the environmental controls that govern the abundance and persistence of these pathogens remain largely speculative.

Barriers: Progress is constrained by the absence of standardized tools for measurement and analysis, and lack of experimental approaches needed to bridge divides between bioaerosol and medical research methodologies. Infrastructure for regular, repeatable sampling and assessment is lacking, and researchers face challenges in synthesizing diverse datasets. There is a critical need for advanced tools, including AI and statistical models, to integrate and interpret complex biological and environmental data.

Session 3: Atmospheric Processes and Viability

Gaps: Major gaps exist in our understanding of microbial viability in the atmosphere. We do not yet know whether airborne microbes remain metabolically active, nor how their activity might be influenced by the presence of water in clouds or fog. The nature of interactions among airborne microbes—whether synergistic, antagonistic, or neutral—and with other atmospheric particles remains poorly characterized. There is also limited knowledge about the functional roles that bioaerosols play in atmospheric processes such as ice nucleation, cloud chemistry, and biogeochemical cycling.

Barriers: The aerobiome is inherently dynamic and characterized by extremely low concentrations of microorganisms, making reliable statistical analysis challenging. We lack a detailed understanding of the biological drivers of aerosol release, such as pollen emission, and how these drivers respond to environmental change. Instruments capable of detecting real-time emissions and analyzing microbes in-flight without compromising their viability are not yet fully developed. Laboratory infrastructure that can simulate atmospheric conditions for controlled studies is scarce as key parameters are not well understood. Additionally, measurement campaigns are resource-intensive, requiring specialized equipment and interdisciplinary expertise.

Session 4: Methods and Standards

Gaps, Methods: Methodological limitations begin with challenges in sampling, particularly for viral particles and environments with ultra-low biomass. Efficient amplification techniques for DNA and RNA in collected samples, crucial for metagenomic sequencing, should be further developed, especially when considering co-extraction and co-amplification of DNA and RNA.. Contamination remains a significant issue due to the inherently low abundance in aerobiome samples, with noise from laboratory reagents—often termed the kitome and extractome—complicating detection efforts. Isolating boundary-less air masses of interest to trace bioaerosol life cycles is inherently challenging. There is also a need for new approaches to measure microbial exposure and assess biological responses in real-time during atmospheric transport. A critical gap exists in the availability of portable, inexpensive sampling tools that can conserve microbial viability of various particle sizes while capturing particle and environmental data with high temporal resolution. A sampling tool that meets these criteria would avoid current trade-offs among temporal resolution, particle size, portability, and cost that have led to proliferation of methodological approaches, resulting in challenges comparing across data sets. Routine measurement infrastructure is sparse, and very few facilities are equipped to conduct dedicated, atmospherically relevant laboratory studies. From a data perspective, we face difficulties in statistically associating environmental drivers with aerobiome structure in a highly multidimensional analytical space.

Barriers, Methods: Current measurement techniques and laboratory workflows are costly, time-consuming, and dependent on interdisciplinary collaboration. Access to these resources is not equitably distributed worldwide, limiting participation from under-resourced regions and contributing to a lack of global consistency in methodological capabilities.

Gaps, Standards: The integration of environmental DNA (eDNA) databases across prokaryotic and eukaryotic organisms remains incomplete, making it difficult to comprehensively identify airborne life. Sampling, measurement, and processing techniques vary widely, leading to inconsistent data and poor comparability across studies. There is a clear need for a coordinated conceptual framework to guide quantification, characterization, and analysis across disturbance types. Furthermore, standardized, validated sampling tools are lacking; equipment that could serve as a consistent reference point in aerobiome research is virtually nonexistent.

Barriers – Standards: A fundamental barrier is the absence of consensus on which core measurements should be prioritized to enable intercomparison between studies. Variability in sampling and analytical workflows introduces inconsistencies, and there is little knowledge about how these methodological differences might bias findings. These inconsistencies complicate efforts to synthesize results across diverse research programs and geographic regions.

Responses to the third question were used primarily to help the co-leads understand expectations as the agenda was developed, as well as brainstorm ideas for continuing to foster interactions post-workshop. A summary was shared in a slide during the workshop introductory remarks (Figure 1).

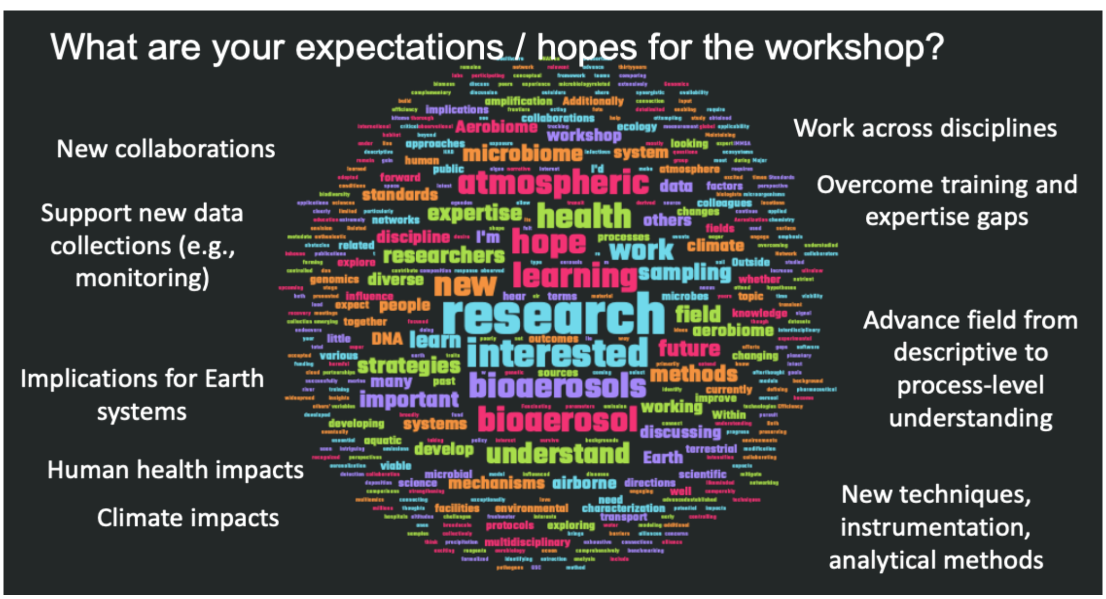

Figure 1. Word cloud generated from survey responses to Question 3, together with some specifically-identified interests.

4. Workshop Findings

During the final session of the workshop, the three breakout group reports were organized into a single document for each session using ChatGPT to summarize the notes from each breakout group that were posted in the shared Google Drive. Participants edited these in real-time, and continued to edit post-workshop. The edited documents were finalized on 15 February 2025 (Appendix 5) and ChatGPT summaries were used to provide guidance to ensure all major findings from the breakout groups were included in the summaries shown here, which also drew on information shared in the plenary and lightning talks.

As previously noted in the summaries of gaps and barriers from the pre-workshop survey and reinforced by breakout reports, there were overlaps that applied to multiple themes, for example, challenges with sampling (lack of observations, lack of appropriate instrumentation, lack of standardization) were mentioned frequently. Accordingly, after a preliminary review post-workshop, the organizers proposed to re-order the findings from the four breakouts into three major themes as follows:

- Structure and function of the aerobiome, including viability
- The aerobiome as an Earth system
    - Atmospheric processes
    - Ecological impacts
- Methods, standards, and monitoring

A final session was focused on integrating key points emerging from these sessions and brainstorming to generate “big idea” initiatives.

4a: Structure and Function, including Viability

A major theme emerging from the pre-workshop survey responses was the limited understanding of the spatial and temporal composition of the aerobiome. Although the literature includes many reports and reviews on bioaerosol composition—particularly bacteria and fungi—most are short-term, localized studies that do not fully capture community structure or viability. Long-term, spatially distributed observations, especially above the Earth’s surface, are rare. Such data are critical to understanding transport mechanisms, atmospheric lifetimes, and the drivers of emissions. Current gaps in observations hinder the ability to link atmospheric bioaerosol concentrations with surface sources and meteorological or biological variables. The need for deeper process-level understanding of emissions, transport, and deposition is addressed in Section 4b.

While bacteria and fungi have received the most attention, viruses and pollen are also important to Earth system feedbacks and public health. Ambient data on airborne viruses are sparse—most studies focus on indoor environments or healthcare settings—highlighting the need to bridge indoor and outdoor bioaerosol research. Pollen, better studied due to its role as an allergen, has benefited from recent advances in life cycle modeling based on vegetation type and phenology. Remote sensing tools, such as polarimetric lidar, provide new vertical profile information on pollen plumes in the lower atmosphere. Despite this progress, the absence of a national, spatially dense, and openly accessible pollen monitoring network remains a critical limitation for validating simulations. Some pollen types are also understudied due to limited relevance to allergies. Encouragingly, cost-effective online sensors are emerging, and a growing informal community is working to integrate models with observational networks—a model that could be extended to other bioaerosol types.

Fundamental questions persist about bioaerosol viability in the atmosphere. For example, large pollen grains can fragment into smaller, long-lived sub-particles that may influence cloud microphysics. The atmosphere, particularly at altitude, is harsh—dry, cold, and exposed to UV radiation. Atmospheric exposure to oxidants, acidity, nutrients and pollutants can also affect bioaerosol structure and function. The prevalence of sporulating organisms suggests adaptations for survival during transport, though other viable bioaerosols have been observed. The lack of data on co-existing particle types, size distributions, and mixing states hinders understanding of how attachment to other particles might shield bioaerosols from environmental stress or enable nutrient uptake. These interactions could also harm viability. Water content, proteins, polysaccharides, and surfactants may play important roles in maintaining viability, but are poorly studied. Research into how these compounds influenced SARS-CoV-2 viability in aerosols could inform outdoor air studies.

Viability post-transport is crucial to understanding bioaerosols' roles in Earth system dynamics and pathogen transmission. Yet, viability assessment methods are limited—culture-based approaches miss the majority of viable microbes. Cloud and fog interactions may preserve viability or promote activity, but questions remain. One plenary presentation noted that short in-cloud residence times may not allow dormant organisms to activate or interact. Addressing these questions requires new facilities and probes capable of detecting viability and metabolic signals under diverse atmospheric conditions.

Among the best-studied bioaerosol environmental functions to date is their role as cloud condensation nuclei (CCN) and ice nucleating particles (INPs). This has been validated in multiple lab and field studies. The ice-nucleating bacterium *Pseudomonas syringae* has been studied since the 1970s, and recent work has expanded the known spectrum of biological INPs. A potential bioprecipitation feedback cycle has been proposed, in which vegetated landscapes and their microbiomes influence cloud and precipitation processes. However, a full systems-level assessment connecting soils, plants, water bodies, the aerobiome, and the atmosphere is lacking.

Breakout discussions raised additional conceptual questions, including whether atmospheric bioaerosols form a "biome" or whether the atmosphere itself constitutes an "ecosystem." Historically, the dilute nature of atmospheric microbial communities has led to their being overlooked as significant Earth system components. This assumption is now challenged by evidence of long-range transport of viable organisms and genetic material such as antimicrobial resistance genes. Most existing studies have examined individual bioaerosol types (e.g., bacteria, fungi, viruses, pollen) in isolation. As a result, fundamental questions about potential interspecies interactions—whether synergistic, antagonistic, or otherwise—remain unanswered. A major barrier is the lack of standardized sampling and analysis methods.

Workshop participants identified key research priorities to advance understanding of aerobiome structure and function:

- **Measurement technologies:** Develop affordable sensors, high-volume samplers that preserve viability and capture the full size spectrum of bioaerosols, and new methods for viability assessment and metabolic activity detection in airborne bioaerosols.
- **Monitoring networks:** Establish standardized, reproducible protocols for characterizing a wide range of bioaerosol types, integrated with total aerosol composition and environmental parameters, including gas-phase species.
- **Undersampled bioaerosol classes:** Investigate classes with limited data, such as moss and fern spores and viral phages.

- **Particle interactions:** Develop methods to determine whether bioaerosols exist as individuals, clusters, or attachments to other particles, and how such configurations, as well as atmospheric aging processes, affect atmospheric residence times and viability.
- **Laboratory simulations:** Create facilities that replicate atmospheric conditions (e.g., tropospheric, stratospheric, in-cloud) to study bioaerosol responses to environmental stressors and mechanisms of survival.
    - **Pathogen research:** Requires access to high-containment biosafety labs, which are currently limited and not widely available to non-medical researchers.
    - **Aerosol-cloud-precipitation simulations:** Remain a challenge due to the complexity of the spatial and temporal scales involved.

4b. The Aerobiome as a System

The full lifecycle of bioaerosols within the Earth system — emission, atmospheric transport, cloud processing, and deposition — remains poorly constrained in terms of mechanisms, rates, and impacts. While a range of terrestrial, aquatic, and marine sources of bioaerosols have been identified, emission inventories, even for relatively well-studied types like pollen, are sparse. Long-term, high-resolution studies that capture spatial and temporal variability in concentrations and deposition are rare but are essential for quantifying lifecycle dynamics. During atmospheric transport, bioaerosols undergo substantial changes in viability, chemical composition, and physical properties due to environmental stressors such as temperature shifts, UV radiation, humidity, and oxidant exposure. The roles of fragmented biological particles and non-cellular plant materials in both health and ecological functions remain unclear.

One key question raised during the workshop is whether the atmosphere acts as a microbial metacommunity — or an ecosystem — with predictable ecological and biogeochemical interactions. Our current inability to answer this stems from a lack of comprehensive observations and suitable laboratory simulations. Deeper insight into feedbacks between the atmosphere, ecosystems, and health requires embracing interdisciplinary frameworks to understand Earth system flows and feedbacks, such as GeoHealth or OneHealth. This section summarizes workshop discussions around two major themes: *Atmospheric Processes* and *Ecological and Health Impacts.*

Atmospheric Processes. A major knowledge gap is the emission mechanisms and fluxes of diverse bioaerosol sources. Emissions span a wide range—from pollen rupture and mechanical disturbance (e.g., wind, rain, bubble bursting) to more complex processes such as wildfires and biosurfactant-mediated release. Emission type likely dictates whether or not emitted bioaerosols demonstrate characteristics of adaptive selection for atmospheric conditions. While some progress has been made in understanding factors like turbulence and surface wetting, most processes remain episodic, difficult to observe, and poorly characterized. As a result, only coarse, order-of-magnitude estimates of emission rates exist, with few data on when and if environmental thresholds such as humidity or temperature are in effect. Predicting how environmental change, land use shifts, disturbance events, or climate extremes will alter bioaerosol production and transport remains an open challenge.

Another underexplored area is bioaerosol deposition, both wet and dry (including fog). Deposition mechanisms and rates ultimately determine where bioaerosols exert impacts and provide vital constraints on their atmospheric budgets. However, standard parameterizations based on (effective) particle size and surface characteristics are rife with uncertainties and have recently been shown to yield large errors. This issue is compounded for bioaerosols by uncertainties in particle density, shape, and hygroscopicity. Few observational datasets exist for wet deposition, and long-term monitoring programs are needed to close these knowledge gaps. These might be modeled after, or leverage, existing monitoring networks such as NADP (National Atmospheric Deposition Program), NEON (National Ecological Observatory Network), AmeriFlux, IMPROVE (Interagency Monitoring of Protected Visual Environments), and ARM (Atmospheric Radiation Measurement) User Facility, and could include observations in addition to deposition fluxes.

The role of bioaerosols as cloud condensation nuclei (CCN) and ice nucleating particles (INPs) is one of the most intriguing aspects of their potential climate impact. Bioaerosols have long been implicated in initiating freezing at relatively warm temperatures, and multiple species carrying ice-nucleating genes have been identified. Even at low concentrations, these particles can play a disproportionate role in initiating ice formation and precipitation via primary and secondary processes. Some biological particles also serve as (giant) CCN, potentially initiating drizzle due to their large size. Additionally, evidence suggests that biological material in smoke may contribute to superfog events.

Cloud processing raises questions about bioaerosol transformation and viability. While some speculate that cloud immersion might facilitate microbial metabolic activity or particle–particle interactions, the limited residence time and dilute concentrations in most clouds challenge this hypothesis. Still, no direct observations exist to confirm or refute whether clouds, fogs, or dews preserve viability or trigger activity. Some laboratory experiments suggest bioaerosols could influence atmospheric chemistry by degrading soluble gases, but most studies do not adequately replicate atmospheric conditions. Ongoing efforts aim to close this gap using more realistic experimental systems.

Ecological and Health Impacts. The transport of plant and animal pathogens via the atmosphere is a long-recognized phenomenon. However, broader ecological functions—such as bioaerosols' potential role in nutrient cycling—are far less studied. An intriguing question raised during the workshop is whether airborne microbes contribute significantly to biogeochemistry of the atmospheric system. For example, they may be important in phosphorus cycling, in contrast to likely minor roles in carbon or nitrogen cycles. There is a need to compare bioaerosol atmospheric life cycles to other Earth system nutrient transformation and fluxes as well as to assess how bioaerosol deposition affects terrestrial and aquatic biomes.

Ecological theories—such as biogeography, metacommunity dynamics, and niche modeling—could help identify potential atmospheric biodiversity "hotspots" or "keystone" organisms and predict microbial distribution patterns and ecological effects. The bioaerosol life cycle as a mechanism for biodiversity patterns beyond disease spread and pollination has only begun to be recognized. Applying such frameworks could bridge significant gaps between atmospheric science and ecology.

Bioaerosols are increasingly recognized as important to public health. Pathogens such as SARS-CoV-2 can travel through the air, and the atmospheric spread of plant diseases like wheat rust is well-documented. Storm-driven releases of allergens, such as in "thunderstorm asthma" events, highlight the impact of meteorological processes on exposure. Advanced pollen lifecycle and emission models show promise for forecasting such events, though key pieces—like dose–response relationships for respiratory illnesses—remain underdeveloped.

Additionally, interactions between bioaerosols and urban pollution, both indoors and outdoors, are poorly understood. Pollutants may modify allergenicity or viability, for example, yet these dynamics are rarely studied. The lack of a high-time-resolution, national-scale monitoring network for aeroallergens and pathogens remains a major limitation. In response, the National Atmospheric Deposition Program (NADP) has launched an Aeroallergen Monitoring Science Committee. As highlighted in Section 4a, understanding bioaerosol viability during transport is critical but still hampered by inadequate sampling and detection technologies.

To improve understanding of the aerobiome as an integrated Earth system component, participants proposed:

- **Adopting a GeoHealth or OneHealth approach** to foster interdisciplinary research across atmospheric science, ecology, health, and microbiology.
- **Developing shared, multi-user laboratory facilities** to simulate realistic emission mechanisms and atmospheric conditions and support experiments on bioaerosol life cycles, including suspended cloud droplet systems.
- **Integrating bioaerosol detection into existing aerosol monitoring networks** (e.g., NEON, AmeriFlux, ARM) using real-time and high-sensitivity techniques to generate temporally and spatially resolved data across varied environmental conditions.
- **Establishing long-term monitoring of bioaerosol deposition**, both wet and dry, to better constrain source–sink dynamics and close bioaerosol budgets.

4c: Methods, Standards, and Monitoring

The topics addressed in this session were central not only to pre-workshop themes but also emerged in discussions across other sessions. Several key technology shortcomings and challenges were identified, most notably the lack of universally accepted and standardized methods for (1) bioaerosol collection, (2) sample processing and analysis via multiple techniques, (3) data analysis, and (4) microbial reference standards.

While diversity in sampling and analysis methods is sometimes necessary — depending on sample type, target organism size, sampling environment, and research goals (e.g., identification vs. quantification) — it also complicates reproducibility and cross-study comparisons. Sample analytical outputs vary depending on the sampling technology used, ranging from culturing and advanced imaging to molecular detection, sequencing, and electronic readouts. The lack of consistency in sampling instrumentation and their performance characteristics, collection media, and protocols even within similar studies hinders study replication and comparability. Recent studies using co-located samplers have demonstrated that sampler-to-sampler differences can produce significantly different observed community compositions, likely due to differences in sampler performance, such as size-dependent collection efficiencies and sample preservation, often unreported by manufacturers.

Classic bioaerosol sampling methods — impaction, impingement, and filtration — can induce stress or damage to microbial cells, leading to viability loss or nucleic acid degradation, which compromises accurate reconstruction of aerobiome composition. As viability is a critical parameter in many bioaerosol studies, alternative approaches are needed to replace classical culturing techniques, which detect only a fraction of viable organisms. Suggestions from the workshop included the use of lung-on-a-chip systems or organoid-based collection media as indicators of microbial activity, epigenetic viability markers (e.g., DNA/RNA methylation), propidium monoazide (PMA) treatment, and RNA activity as a proxy for viability.

Sampler innovation is underway, including lower-stress collection using condensation capture or electrostatic forces. However, these often suffer from low throughput. Strategies to concentrate bioaerosols prior to sampling (e.g., use of virtual impactors or similar techniques) may improve detection and reduce sampling duration, but size-dependent concentration efficiencies must be carefully characterized to avoid new biases or sample losses. Tools to concentrate samples post-collection should also be considered, taking into account their size-dependent concentration efficiencies and other shortcomings.

Sampler inlet design also received attention. Even for instruments designed to capture a broad particle size range, geometry and flow rate can impact the size distribution of collected bioaerosols. Additionally, wind direction and speed have been shown to influence collection efficiency in many but not all samplers.

Commonly used active samplers allow to produce quantifiable results, but are typically limited in sampling duration. Passive samplers offer extended timeframes (days to weeks) and advantages such as simplicity and low cost. Though traditionally underused, recent studies suggest they can produce semi-quantitative and sometimes quantitative results, meriting further attention. Technologies for broad, routine bioaerosol monitoring are needed to support spatial and temporal mapping. Viral taxonomy remains underdeveloped, particularly for ambient air viromes, and enhanced recovery and annotation methods for both RNA and DNA viruses are essential. Discussions also highlighted the need for vertical bioaerosol profiles extending to the stratosphere. Solar- or battery-powered samplers on balloons, UAVs, or light aircraft could help fill this data gap if made lightweight and autonomous. Horizontally-distributed multi-vessel sampling systems are needed to gain insight into the effects of time, changing environmental conditions, mixing, and deposition on bioaerosol composition and viability during transport.

Molecular sequencing approaches face particular challenges. No commercially available DNA/RNA extraction kits have been optimized for ultra-low-biomass aerosol samples; current kits are adapted from those developed for soil or other microorganism-rich matrices. This contributes to variability in yield and data comparability. Ultra-low input kits still need to be optimized for DNA/RNA co-extraction and co-amplification given the interest in both bacterial and RNA viruses. DNA contamination (e.g., from reagents, kits, or handling) further complicates analysis. Workshop participants reported methods to improve DNA/RNA yield, including specialty lysis enzymes (Metapolyzyme, Exopolyzyme), freeze fracturing, special lysis beads, and pre-amplification (e.g., multiple displacement amplification or primary template amplification). To minimize contamination and bias, multiple negative controls and positive spike-in controls (cells or nucleic acids) should be included. Statistical decontamination analytical methods should follow. However, the lack of standardized controls, and how the results from those controls are utilized, across studies impedes inter-study comparisons and meta-analysis.

Established sample analysis methods such as culturing and direct or epifluorescence microscopy could benefit from automation and AI-driven image analysis to enhance standardization and throughput. Sample preservation and archiving were also identified as constraints, particularly given the cost and limited capacity of long-term cold storage. More research is needed to assess sample stability over time in frozen filters and collection media.

Greater transparency is needed in reporting collection and analytical methods, including details on sampler characteristics, analytical controls, extraction efficiency, and measurement uncertainty. Sequence data should be publicly archived alongside standardized metadata (e.g., sampler type, flow rate, air volume collected, media used). The Genomic Standards Consortium (GSC) provides minimum metadata guidelines, and the development of a bioaerosol-specific protocol was recommended.

Bioinformatics analysis of aerobiome data relies heavily on pipelines developed for other environments. Diversity and richness metrics may need adaptation to the highly dynamic nature of airborne communities, which are influenced by meteorology and geography. Computational methods for removing background contamination (kitome and extractome, non-target air masses) remain imprecise for low-biomass samples. While groups like the International Microbiome and Multi-Omics Standards Alliance (IMMSA) and GSC are working on these issues, standardization is still evolving. Automated bioinformatic workflows and AI-driven tools could streamline data processing and improve accuracy, but more development is needed before AI can autonomously generate optimal workflows.

There is a pressing need for training in bioinformatics and molecular aerobiome methods. Many groups lack in-house expertise, and data analysis remains a bottleneck. Training opportunities—especially for early-career researchers—could help address this gap. Participants recommended interdisciplinary education in best sampling and and sample analysis practices, collaborative research and statistical design.

Participants suggested that advancements in methods, standards, and monitoring could be fostered through the following actions:

- **Establishing Best Practices**: A comprehensive manual and decision tree should be developed to guide sampling method selection based on research goals and site types. Universal benchmarking standards (e.g., for whole-cell, DNA, RNA) are needed, alongside standardized metadata reporting, potentially through an adapted MIXS checklist.
- **Standardizing Bioinformatics**: Automated, reproducible workflows and AI-based tools should be prioritized for analysis of aerobiome sequencing data.
- **Expanding Training Opportunities**: Dedicated workshops for students and early-career researchers in sampling, sample analysis, sequencing, and interdisciplinary research are needed. Visual workflow guides and active working groups could support community knowledge-sharing. Bioaerosol student chapters of relevant professional associations would foment community growth through both formal and informal activities.
- **Evaluating Sampler Performance**: Results from intercomparison studies, including passive samplers and microbial reference standards, should be consolidated and published. A centralized research and training center with shared-use facilities could help advance standardization.
- **Implementing Monitoring Networks**: Development of low-cost, automated instrumentation would support the feasibility of establishing massively-distributed bioaerosol monitoring networks, including for predicting, tracking, and modeling disease outbreaks linked to viral, bacterial, and fungal bioaerosols.

4d. Future Directions: Enabling Breakthroughs

Participants emphasized that advancing interdisciplinary aerobiome system science requires coordinated investments and interdisciplinary effort in in building and expanding data infrastructure and catalyzing synthesis, modeling, training, and experimental capacity.

Enabling Interoperable Datasets. Standardization remains an ongoing challenge, but near-term progress can be achieved through improved metadata protocols and centralized data repositories. Rather than enforce rigid standards that are likely not practical, guidance on how to collect and annotate data for cross-study utility would be transformative.

Accelerating Progress with AI and Automation. AI-based tools can help overcome current bottlenecks in sample analysis, including sequencing and data processing. Domain-specific algorithms and automated pipelines tailored to aerobiome datasets could improve reproducibility and scalability. These developments are still on the horizon and will require engagement from interdisciplinary teams, including computer scientists.

Advancing Sampling Technology. AI-based tools can also summarize the current state-of-the-art of bioaerosol sampling technologies, with focus on sample preservation and long-term low-cost sampling methods. New technology developments could enhance feasibility of monitoring networks, as well as expanding from surface-based observations into vertical distributions. A decision tree focused on enabling selection of best sampling and analysis practices tailored for a particular project would advance standardization in the field.

Building Community Infrastructure. A priority is expanding bioaerosol monitoring through low-cost instrumentation and integration with existing networks. Shared-use facilities with surmountable logistical barriers to entry for simulating atmospheric conditions (e.g., temperature, humidity, UV, pressure, nutrient substances and inhibitors) and training researchers are equally critical.

Developing Coordinated Field Campaigns. Participants advocated for a large-scale, interdisciplinary field campaign pilot. Coordinated objectives, forecasting, real-time data sharing, and harmonized protocols would yield insights into methods for creating a unique, interoperable dataset and would offer valuable collaborative experience. This kind of pilot could be used to generate new hypotheses, and inform design of regular, strategic measurements at key locations to address priority questions, determined via application of modeling and AI.

Revisiting Ecological Theory for the Atmosphere. Existing frameworks for microbial ecosystems—developed for terrestrial and aquatic systems—may or may not be applicable for the dynamic, dilute, and advective nature of the atmosphere. New theoretical foundations to fully characterize aerobiome assembly and function should be developed.

Advancing Predictive Models. With sufficient observational data, bioaerosol emissions, transport and deposition models can evolve to include inverse modeling approaches to develop better inventories. Predictive models will help guide monitoring strategies and assess potential feedbacks with climate and ecosystems. An aspirational goal of a national bioaerosol forecasting system would leverage this foundation.

Expanding Training Opportunities. Workshop participants called for new interdisciplinary training programs that fully integrate across disciplines. Summer schools, research fellowships, and interdisciplinary cohort models could be used to empower early-career scientists to lead integrative studies of the aerobiome.

Leveraging Existing Data Through Partnerships. Data collected for other purposes—e.g., health surveillance, weather forecasts, allergen forecasting—represent untapped resources. Strategic partnerships with data scientists and instrument developers can unlock these datasets and expand research capacity.

While the workshop emphasized bioaerosols in the context of their roles in the Earth system, their importance to human exposures and the role of human activities in shaping aerobiome composition and abundance were acknowledged. Follow-on activities oriented toward health impacts and drawing in participants from medical and other communities could cover those aspects more comprehensively.

5. Workshop Follow-Up

A post-workshop survey (Appendix 6) indicated broad enthusiasm for continued collaboration. Participants offered several ideas, many of which are already underway:

- A proposal for an AGU Union session for the Fall 2025 meeting on bioaerosol frontiers was submitted (accepted as of July 2025).
- Subgroups formed to address methods development, atmospheric modeling, and instrumentation characterization. Active communication continues via online platforms.
- A virtual seminar series is being planned to maintain community engagement.

The workshop succeeded in forging a cross-disciplinary community eager to co-develop tools, concepts, and campaigns to transform bioaerosol science. With coordinated follow-through on the strategies outlined here, the community is well positioned to build a foundation for long-term progress.

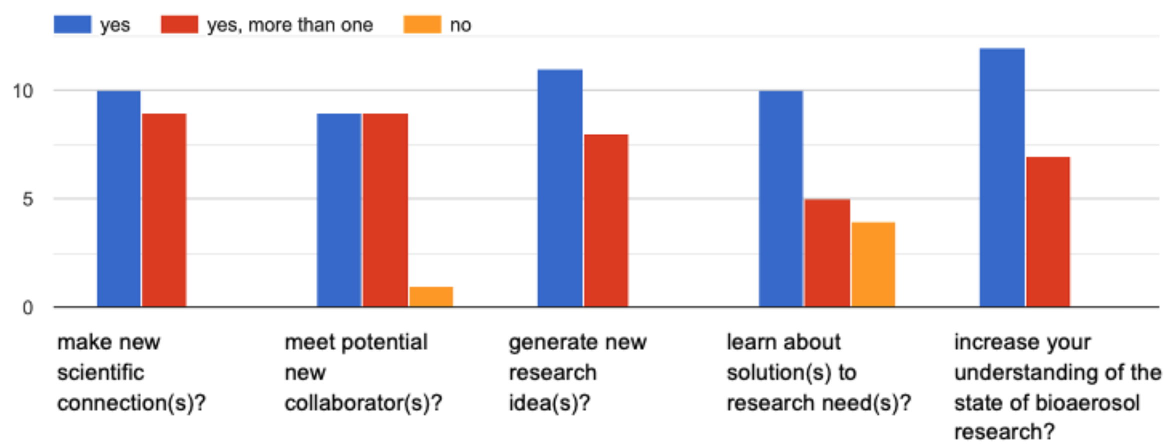

Figure 2. Response to non-narrative questions in the post-workshop survey.

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Appendices

A1. Workshop Participant Table
A2. Workshop Final Agenda
A3. Pre-Workshop Questions and Responses
A4. Icebreaker Poster
A5. ChatGPT Summaries of Breakout Group Notes
A6. Responses to Post-Workshop Survey

Appendix 1

Workshop Participants

Allison Aiken (co-lead) is a scientist in the Earth & Environmental Sciences Division at Los Alamos National Laboratory (LANL). Aiken received her PhD in Chemistry from the University of Colorado at Boulder. She is an analytical chemist specializing in direct measurement of aerosol chemistry, physical and optical properties to elucidate complex aerosol processes in the atmosphere. Her research focuses on the dynamic nature of aerosols uses chemistry to understand the changes in aerosol optical properties, water uptake and the physical properties that drive transport, particle growth and atmospheric lifetimes. Aiken is known for developing new analytical techniques in the laboratory using real-time aerosol measurements and applying them to complex ambient datasets. She is the co-founder and co-Director of the Center for Aerosol and Trace Gas Forensics (CAFE) and is the point of contact for DOE Atmospheric Systems Research (ASR) at LANL. Current work includes her role as PI for an upcoming Atmospheric Radiation Measurement (ARM) field campaign that will start in 2026 in Phoenix, Arizona. Her elected service roles include the Board of Directors for the American Association for Aerosol Research (AAAR, 2019-2022) and chair of the User Executive Committee (2021-2022) for the U.S. DOE ARM facility.

Katherine Benedict is a research scientist at Los Alamos National Laboratory in the Earth and Environmental Science Division on the Atmospheric, Climate, Ecosystem Team. Dr. Benedict holds a B.S in Earth and Environmental Science from Susquehanna University and an M.S. and Ph.D. in Atmospheric Science from Colorado State University. She is an atmospheric chemist with work on a variety of topics including atmosphere-ecosystem interactions specifically deposition of nitrogen to natural systems, aerosol chemistry, emissions of volatile organic compounds from oil and gas operations, characterization of combustion aerosol, and observations of bioaerosols. She has experience collecting, analyzing, and interpreting data from both field and laboratory settings. Dr. Benedict has been at Los Alamos National Laboratory since 2020. During this time, her work has been funded by internal laboratory support (Laboratory Directed Research and Development) and the DOE Atmospheric System Research program.

Brad Borlee is an Associate Professor of Bacteriology and Boettcher Investigator in the Department of Microbiology, Immunology, and Pathology within the College of Veterinary Medicine and Biomedical Sciences. He was previously a Senior Fellow in the Department of Microbiology at the University of Washington, School of Medicine (Seattle, WA), and earned his Ph.D. conducting microbiology research at the University of Wisconsin (Madison, WI). He and his group study environmental sensing and regulation of bacterial behaviors in the context of host-pathogen interactions and host-associated bacterial communities. Highlights of his research career include the pioneering construction of metagenomic libraries to study antibiotic resistance and identification of novel biomolecules from unculturable bacteria. In addition, Dr. Borlee has patented quorum-sensing inhibitors for the development of anti-virulence drug leads. Dr. Borlee's discovery of a biofilm-induced bacterial adhesin that binds exopolysaccharides and reinforces biofilm structural integrity has been further developed by him into a c-di-GMP biosensor to identify and evaluate antibiofilm therapeutics.

Bala Chaudhary is an Associate Professor of Environmental Studies at Dartmouth College. She earned her undergraduate degree from the University of Chicago and her M.S. and Ph.D. from Northern Arizona University, previously holding faculty appointments at DePaul University and Loyola University Chicago. Research in her lab focuses on mycorrhizas (plant-fungal symbioses), macroecology (continent-scale ecology), and movement (microbial dispersal). She uses trait-based approaches to develop predictive frameworks for microbial dispersal, community assembly and biogeography, and employs complementary approaches of macroecological field work, controlled lab experiments and data synthesis to study multi-scale questions in ecology. She is a recipient of the National Science Foundation CAREER award and advises on continent-scale biology for the National Academy of Science, Engineering, and Medicine. Prior to academia, Chaudhary worked as an environmental consultant in Los Angeles restoring drastically disturbed urban areas to create habitat for endangered species. She is an award-winning advocate for antiracist strategies in STEM and the founder of WOCinEEB, an international organization for racial and gender minorities in ecology and evolutionary biology.

Jeffrey L. Collett, Jr. received an S.B. in Chemical Engineering from MIT and M.S. and Ph.D. degrees in Environmental Engineering Science from Caltech. Prior to joining the CSU Atmospheric Science faculty, he spent two years as a postdoc in the Laboratory for Atmospheric Physics at ETH-Zurich and three years as an assistant professor at the University of Illinois in the Department of Civil and Environmental Engineering and the Institute for Environmental Studies. Collett served as head of the CSU Department of Atmospheric Science from 2011-2022, has served multiple terms on the USDA Agricultural Air Quality Task Force and Colorado's Regional Air Quality Council, was named a CSU University Distinguished Professor in 2024, and recently joined the Executive Council of the National Atmospheric Deposition Program. His interests focus on process-oriented field research, instrument development and environmental chemistry. Many of his current interests concern the characterization of unconventional sources of air pollution, including oil and gas development, agriculture, and wild and prescribed fires, areas of particular public policy interest. He also has a longstanding interest in the chemistry of fogs, clouds, and precipitation with current work focused on dry and wet inputs of reactive N and P to sensitive ecosystems.

Gavin Cornwell is an earth scientist within the Earth and Biological Sciences Directorate (EBSD) at Pacific Northwest National Laboratory (PNNL). His research focuses on improving the representation of ice nucleating particles within Earth system models. Prior to joining PNNL, he competed a doctorate at the University of California, San Diego where he used laboratory and field measurements to understand how aerosol particles affect cloud properties. In particular, he focused on the sources of ice nucleating particles. He joined PNNL in 2019 as a postdoctoral researcher, focusing on the characterization of ice nucleating particles in agricultural soils. He is the recipient of a 2024 DOE Early Career Research Program award, which will focus on biological ice nucleating particles, their emissions, and their effects on the Earth system.

Barbara Ervens is a Senior Scientist at the National Centre for Scientific Research (CNRS), Institute of Chemistry of Clermont-Ferrand, University Clermont Auvergne, France. She earned her Ph.D. from the University of Leipzig, Germany, and held research scientist positions at the National Oceanic and Atmospheric Administration (NOAA, Boulder), affiliated via the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder, the Cooperative Institute for

Research in the Atmosphere (CIRA) at Colorado State University. Her research focuses on the development and application of atmospheric process models to describe chemical, microphysical, and biological processes within aerosol particles and cloud droplets. Her main research areas have been focused on the formation of secondary organic aerosol in the aqueous phase of particles and clouds (aqSOA). In addition, sensitivity model studies were directed to explore the role of physicochemical properties of organic aerosols acting as cloud condensation nuclei (CCN) and ice nuclei (IN) to the formation of warm and mixed-phase clouds. She has been the principal investigator on several major research projects, including the the project 'MOdeling BIologically-Driven processes In clouds' (MOBIDIC, 2018 - 2023), as part of the French Presidential Initiative 'Make Our Planet Great Again'. In this project, her group investigated the role of bioaerosols, particularly bacteria, in atmospheric processes. They examined the extent to which biodegradation of organics by bacteria can compete with chemical reactions within clouds, shaping atmospheric composition. The project also studied the potential impact of properties, ageing, and transformation of biological aerosol particles on cloud microphysics and atmospheric chemistry. She serves as the Co-Chief-Executive-Editor for the interactive open-access journal Atmospheric Chemistry and Physics and as the Chair of the Publications Committee of the European Geosciences Union (EGU).

Morgan Gorris is a Staff Scientist in the Information Systems and Modeling group at Los Alamos National Laboratory where she studies GeoHealth: the nexus of health, humans, and the Earth system. She focuses on how weather and climate affect environmental infectious disease dynamics, including where diseases are a threat, forecasting the number of disease cases, and projecting how these diseases will respond to climate change. As for bioaerosols, Morgan thinks a lot about dust as an exposure source for infectious diseases, especially for the fungal disease coccidioidomycosis (Valley fever). Morgan was on LANL's COVID-19 response team and gained an appreciation for epidemiological modeling of airborne communicable diseases. Morgan was an author for the Human Health Chapter of the 5th National Climate Assessment (NCA), is now an author on the NCA6 Chapter on Air Quality, and actively serves on several committees, including the GeoHealth section of the American Geophysical Union, the Dust Alliance for North America, and the US Climate Variability and Predictability Program Working Group on Climate and Health. Morgan graduated from the University of Michigan with her BSE in Earth System Science and Engineering, earned her PhD in Earth System Science at the University of California, Irvine, and completed her postdoc at LANL as a Director's Postdoc Fellow.

Erik Hanschen is a Staff Scientist in the Genomics and Bioanalytics group at Los Alamos National Laboratory where he uses genomics and experimental evolutionary biology to study biosurveillance and bioremediation. He focuses on how evolutionary biology can provide novel approaches to national security problems, with heavy reliance on genomic analysis on a variety of timescales, from evolution during week long experiments to evolution during hundreds of millions of years. He continues an interest in green algal evolution and use for biofuel production, applying the principles of agricultural domestication to algal biofuel improvement, As for bioaerosols, Erik is an outsider with some cool methods that might be applied to different questions. Erik completed his undergraduate work at the University of British Columbia in Vancouver, Canada, his PhD at the University of Arizona, and a postdoc studying algal-bacterial symbioses at LANL as a Director's Postdoctoral Fellow.

Pierre Herckes is a professor in the School of Molecular Sciences at Arizona State University. His research focuses on Atmospheric Chemistry, particularly aerosols, clouds, aerosol-cloud interactions, and their impacts on air quality and climate. A significant portion of his work involves applied projects addressing real-world air pollution challenges. Additionally, he has a strong focus on Environmental Analytical Chemistry, developing innovative tools to investigate the sources, occurrence, and fate of pollutants in the environment. Current research in this area includes the detection of emerging contaminants such as nanomaterials and perfluorinated compounds in environmental and biological samples. Dr. Herckes has extensively studied organic matter in clouds and aerosols. His recent work also included the biological components and the aerobiome. This includes ongoing research on pathogen detection and variability in the atmosphere, with a particular focus on Coccidioides, the causative agent of Valley Fever, which is endemic to Arizona. Another area of interest is aerobiome in fogs and clouds, its processing during fog/cloud cycling, and potential impacts on cloud chemistry. Dr. Herckes earned his degree in Chemical Engineering from ECPM (formerly EHICS) in Strasbourg and completed his MS and PhD degrees in Environmental Physical Chemistry at Strasbourg University, France. Before joining Arizona State University, he was as a postdoctoral researcher and research scientist in the Atmospheric Science Department at Colorado State University.

Alex Huffman is an Associate Professor in the Department of Chemistry and Biochemistry at the University of Denver (DU). He received his undergraduate degree in Chemistry from Pepperdine University and a doctoral degree in Atmospheric/Analytical Chemistry from the University of Colorado-Boulder before working as a postdoctoral scientist at the Max Planck Institute for Chemistry in Mainz, Germany, where he began his focus on real-time detection of bioaerosols. He is an experimentalist whose projects flow from his primary expertise as an aerosol scientist and an analytical chemist into countless adjacent disciplines. His research focuses on the development, improvement, and application of strategies to detect and quantify biological aerosols, related proteins, and other aerosol-phase analytes of environmental or health interest. Among many projects, his group uses fluorescent and Raman spectroscopy to analyze bioaerosols in outdoor and built environments. They have also helped lead development and improvement of a number of real-time aerosol instruments, including single-particle fluorescence sensors, particle counters, and cloud condensation nuclei counting instruments. He has published more than 60 peer-reviewed research articles and reviews, in addition to scientific and news media editorials. He has mentored five PhD students, four MS students, and more than 60 undergraduate researchers since joining the faculty at DU in 2012. He teaches primarily environmental, analytical, and general chemistry courses at DU.

Leda Kobziar is the Professor of wildland fire science in the Department of Forest, Rangeland, and Fire Sciences at the University of Idaho and Director of the Master of Natural Resources program. She earned MS and PhD (2006) degrees in fire ecology from the University of California at Berkeley and served as Associate Professor of fire science at the University of Florida from 2006-2016. She draws from her experience as a wildland fire practitioner and working with fire managers across the US and Europe to advance fire ecology and smoke aerobiology (pyroaerobiology) using custom UAS-based field sampling methods combined with laboratory fire experiments. She has published over 60 articles and book chapters on fire ecology and wildfire management, including recent papers establishing the emission, transport, and impacts of microbes in wildland fire smoke. She has mentored seven PhD and over 150 master's degree students, served as the President of the Association for Fire Ecology, and is a recipient of the Association's Distinguished Leader in Education and Presidential Leadership awards. Dr. Kobziar is an associate editor for Fire Ecology and Forests and is a recipient of the Mid-Career Research Excellence, Outstanding Faculty Advisor, and Faculty Woman of the Year awards at the University of Idaho. She has served as PI for numerous federal grants including from the NSF, USDA, EPA, NPS, JFSP, USFWS, and as co-PI for grants from the W. M Keck Foundation and Murdock Charitable Trust. Dr. Kobziar has been featured in the media for her pioneering role in pyroaerobiology.

Sonia Kreidenweis (co-lead) joined Colorado State University in 1991 to initiate the program in Atmospheric Chemistry in the Department of Atmospheric Science. Her primary research theme is the study of the physics, chemistry, and optics of atmospheric particulate matter, and in particular, the nucleation and growth of liquid water and ice by atmospheric aerosols and the subsequent impacts on formation of clouds and precipitation. Most recently, she is co-PI of BROADN, the NSF Biology Integration Institute award to

CSU, focused on the role of biological aerosols in ecology and climate. She was named a CSU University Distinguished Professor in 2014 and was elected to the National Academy of Engineering in 2024.

Natalie Mahowald is the Irving Porter Church Professor in Engineering and Director of Graduate Studies for Atmospheric Sciences in the College of Engineering.at Cornell University. She has undergraduate degrees in German and physics from Washington University, an M.S. in natural resource policy from the University of Michigan, and a Ph.D. in meteorology from Massachusetts Institute of Technology. Mahowald conducted her postdoctoral research at Stockholm University in Sweden prior to holding a faculty position at the University of California, Santa Barbara from 1998-2002. She then spent five years as a scientist at the National Center for Atmospheric Research (NCAR) before joining Cornell as a faculty member in 2007. Her research group is focused on understanding feedbacks in the earth system that impact climate change. This includes global and regional scale atmospheric transport of biogeochemically important species such as desert dust, as well as the carbon cycle. They examine these issues through a combination of 3-dimensional global transport and climate models, as well as analysis of satellite and in situ data.

Gediminas "Gedi" Mainelis is a Professor in the Department of Environmental Sciences at Rutgers, the State University of New Jersey, USA. He has a Bachelor's degree in physics from Vilnius University, Lithuania, and a Ph.D. in Environmental Health from the University of Cincinnati, Ohio, USA. He has over 20 years of experience in aerosol and bioaerosol research and related topics. Dr. Mainelis has focused on developing and validating bioaerosol sampling technologies, exposure assessment, and airborne microbiome. Over the past years, his research expanded to investigate indoor air quality issues, including SARS-CoV-2 exposures and their mitigation. His research efforts have resulted in over 120 peer-reviewed publications and book chapters. In addition, multiple papers from Dr. Mainelis's group have been included in most downloaded article lists of various peer-reviewed journals. His laboratory has been awarded several patents for developing novel bioaerosol collectors. Dr. Mainelis has served as Chair of the Bioaerosols and Health-Related Aerosols (twice) working groups of the American Association for Aerosol Research (AAAR). He is an editor (associate) of the Aerosol and Air Quality Research journal. Prof. Mainelis is a recipient of the Research Excellence Award from Rutgers University and the Lyman A. Ripperton Environmental Educator Award presented by the A&WMA.

Linsey Marr is a University Distinguished Professor and the Charles P. Lunsford Professor of Civil and Environmental Engineering at Virginia Tech. She leads the Applied Interdisciplinary Research in Air Laboratory, which studies pollutants in indoor and outdoor air. She is especially interested in emerging or non-traditional aerosols such as microorganisms and engineered nanomaterials and how they are transformed in the environment. Prior to the pandemic, she was one of a small number of researchers who studied viruses in the air. Marr is a MacArthur Fellow, a member of the National Academy of Engineering, and a Fellow of the American Association for Aerosol Research, American Geophysical Union, and International Society of Indoor Air Quality and Climate. She received a B.S. in engineering science from Harvard College and a Ph.D. in civil and environmental engineering from the University of California, Berkeley and completed her post-doctoral training at the Massachusetts Institute of Technology.

Marina Nieto-Caballero is a Research Scientist at Colorado State University specializing in bioaerosols and Next Generation Sequencing. Her research includes infectivity studies of coronavirus, field studies on air quality monitoring in schools and public transportation, atmospheric bioaerosols linked to permafrost thawing, and bioaerosol sampler technology assessment. Marina has been a member of the American Association for Aerosol Research (AAAR) since 2017 and is the current AAAR Chair for the Bioaerosols Working Group. She received a B.S. in Chemical Engineering from the Universitat Autònoma de Barcelona, a M.S. and a Ph.D. in Environmental Engineering from the University of Colorado at Boulder and completed her postdoctoral training at Colorado State University in the Atmospheric Science Department.

Misty Peacock is the Director of the Salish Sea Research Center at Northwest Indian College in Bellingham, Washington. The mission of the Salish Sea Research Center is to prepare the next generation of environmental scientists and leaders through fostering respect for indigenous knowledge of nature, providing opportunities for students to gain a solid background in scientific methods, and fostering critical thinking skills and self-motivation. At the Salish Sea Research Center, students and faculty conduct environmental research that supports healthy, clean, and vibrant environments that sustain tribal communities. Misty holds a Ph.D. in Biological Oceanography from the University of California, Santa Cruz. Jordan Peccia is the Thomas E. Golden, Jr. Professor and Chair of Chemical & Environmental Engineering at Yale University. Research in the Peccia lab integrates environmental microbiology and genetics with engineering to address important environmental problems. Principle areas of research include human exposure to microbes and associated human health impacts, wastewater-based epidemiology, and biological control of global methane emission. Along with quantitative engineering-based fundamentals and tools, we have developed extensive molecular and computational biology skill sets and strategic collaborations in public health, epidemiology, and data sciences.

Anne Perring is an Assistant Professor Chemistry at Colgate University. Prior to Colgate, she spent 9 years at NOAA working on a variety of airborne, ground-based and laboratory atmospheric chemistry studies. Her current research focuses on primary biological aerosol (bacteria, fungal spores and pollen), warm temperature ice nuclei and molecular biomarkers. She also has a continuing collaboration with NOAA to measure black carbon aerosol from airborne platforms to better understand its sources, chemical transformations and radiative impacts in the atmosphere.

Kimberly Prather is an American scientist who is an Atmospheric Chemist, Distinguished Chair in Atmospheric Chemistry, and a Distinguished Professor at the Scripps Institution of Oceanography and the Department of Chemistry and Biochemistry at UC San Diego. Her work focuses on how human emissions are influencing the atmosphere, climate, and human health. She is the founding Director of the NSF Center for Aerosol Impacts on Chemistry of the Environment (CAICE), an NSF Center for Chemical Innovation. CAICE has transferred the full complexity of the ocean-atmosphere system into the laboratory to investigate how phytoplankton, bacteria, and viruses in the ocean influence atmospheric chemistry, clouds, and climate. She is also the founding co-Director of Meta-Institute for Airborne Disease in a Changing Climate (Airborne Institute) funded by the Balvi Foundation. The Airborne Institute focuses on both understanding the impact of climate change on the air we breathe, as well as developing implementable solutions to improve indoor and outdoor air quality globally. In April 2020, she was elected to membership in the National Academy of Sciences in honor of outstanding contributions to aerosol chemistry. In 2019, she was elected as a member of the National Academy of Engineering. She is an elected Fellow of the American Geophysical Union, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences.

Allison Steiner is a professor of atmospheric sciences in the Department of Climate and Space Sciences and Engineering and the Department of Earth and Environmental Sciences at the University of Michigan. She received her B.S. in chemical engineering from Johns Hopkins University and her Ph.D. in atmospheric sciences from Georgia Institute of Technology. Her research uses and develops models to explore the interactions of the biosphere and atmosphere, with the goal of understanding the natural versus human influence on climate and atmospheric chemistry. She has served as editor for the Journal of Geophysical Research-Atmospheres (2014-2018), the National Research Council's committee on The Future of Atmospheric Chemistry Research (2016), the National Academy of Sciences Board on Atmospheric Sciences and Climate (2016-2021), and as President of the Atmospheric Sciences section of the American Geophysical Union (2023-2024).

Betsy Stone is a professor in the Department of Chemistry and Department of Chemical and Biochemical Engineering at the University of Iowa. Atmospheric chemistry research in the Stone Group seeks to advance understanding of the chemical composition and sources of atmospheric particulate matter. Recent projects include characterization of atmospheric pollen under extreme weather conditions with chemical, physical, and biological methods; development of instrumental methods for the separation and quantification of molecular markers of primary aerosol sources and secondary organic aerosol (SOA) tracers in atmospheric aerosols, using gas and liquid chromatography and tandem mass spectrometry; source apportionment of ambient particulate matter in urban and remote locations; and characterization of emissions from sea spray, biomass burning, and waste burning through field and laboratory experiments.

Scott Tighe is currently technical director of the University of Vermont Genomics Facility. He has expertise in all areas of genomics, microbiology and Mycology with specific applications for identification of fungi from bioaerosol samples. He specializes in next generation sequencing (Illumina, Singular G4, and Oxford Nanopore MinION, GridION, and PromethION instrument), PCR (PCR, RTqPCR, ddPCR), single cell analysis, flow cytometry, metagenomics, microbiome, biophotonics, and biomolecular detection of ultra-low biomass nucleic acids in the environment. Scott first began working in microbiology in 1985 at Northern Arizona University and currently has over 200 manuscripts and presentations in molecular and environmental science both nationally and internationally. Scott has performed genomic analysis in the field in Greenland, Romania, Saudi Arabia, Crete, Tahiti, to name a few and was first to perform DNA sequencing in Antarctica. He is currently Chair of the ABRF Metagenomics Research Group and Extreme Microbiome Project (XMP), co-leader of the International Metagenomics and Microbiome Standards Alliance at NIST, Board member of the Genomics Standards Consortium, and developer the NASA uTitan payload deployed to the International Space Station to study DNA extractions in zero-gravity.

Elizabeth Trembath-Reichert is an Assistant Professor in the School of Earth and Space Exploration at Arizona State University. Her research focuses on microbially mediated Earth-life interactions, with the goal of identifying key players in global biogeochemical cycles and determining their rates of activity in past and modern environments. She integrates a range of techniques, including geochemical, gene-based and statistical methods, and applies them across various scales, from molecules to oceanic basins. Her particular area of expertise is determining single cell rates of microorganisms in low activity and low cell density environments.

Marina Vance is an Associate Professor and the McLagan Family Faculty Fellow in the Department of Mechanical Engineering at CU Boulder, with a curtesy appointment in the Environmental Engineering Program. Her research group focuses on experimental investigations into the physical and chemical characteristics of aerosols, from emissions to subsequent transformations, in both indoor and outdoor environments. She is the recipient of an NSF CAREER Award, an EPA STAR Early Career Award, and a Fulbright Scholar Award for Research. She was one of the principal investigators in the HOMEChem and CASA Indoor Chemistry field studies. Vance received her PhD in Civil and Environmental Engineering from Virginia Tech and her MS and BS degrees in Environmental Engineering from the Universidade Federal de Santa Catarina in Brazil.

Kathleen C. Weathers' (co-lead) path to her position as Distinguished Senior Scientist at the Cary Institute of Ecosystem Studies (Millbrook, NY) was (and is!) sinuous. Weathers is an ecosystem ecologist focusing on air-land-water interactions. Her research includes unraveling the importance of fog in the maintenance of ecosystems through its delivery of water, nutrients, pollutants, and microbes from oceans to air to terrestrial ecosystems; impacts of global change on lake ecosystem function worldwide; why, where, and how cyanobacterial blooms are occurring in nutrient-poor lakes and their consequences; and how scientists and community scientists can co-create policy and management solutions. She has also published on the culture and practice of interdisciplinary science, including: how diversity transforms scientific discovery, challenges and opportunities of big data in network science, and the science of and best practices for team science and interdisciplinary, network collaboration. Weathers has served as both a National Science Foundation (NSF) rotating Program Director, and as an NSF Expert, as a Marie Tharp Fellow at Columbia University, and as a Volunteer Research Director for a Lake Association where she conducts locally sewn and globally grown research at the interface of science and society. Weathers was co-Chair of the grassroots Global Lake Ecological Observatory Network (GLEON) for approximately 10 years and led its development from infancy to adulthood. She has also served as elected President of the 9,000-member Ecological Society of America (ESA); on EPA's Clean Air Scientific Advisory Committee (CASAC), which recommends air quality standards to the US EPA Administrator, and currently as co-Chair of EPA's BOSC. She also serves on several not-for-profit boards of trustee. She is an elected Fellow of the American Association for the Advancement Science (AAAS) and the ESA.

Chang-Yu Wu is Professor and Department Chair of Chemical, Environmental and Materials Engineering Department at the University of Miami. He is also the director of Center for Aerosol Science and Technology (CAST) at the University of Miami. As the PI of Aerosol and Particulate Research Laboratory (APRL), his research interests are in the areas of aerosol science technology, in recent years focusing on instrument development for viable virus aerosol sampling and understanding the transmission of virus aerosols. He is a Fellow of American Association for Aerosol Research. He received his BS in Mechanical Engineering from National Taiwan University and his MS and PhD in Environmental Engineering from University of Cincinnati.

Workshop Support

Kevin Barry is a Postdoctoral Fellow in the Department of Atmospheric Science at Colorado State University. His current and recent research projects are interdisciplinary, often involving aerosol sampling and laboratory analysis, with a focus on ice nucleating particles and microbial composition in the changing Arctic.

Appendix 2

Workshop on Bioaerosols in the Earth System
AGENDA

ARRIVAL: Tuesday, February 4

5:30 – 7:00 PM Reception and Ice Breaker

Please join the group in the Legends Room at the Hilton starting at 5:30 pm. Appetizers and soft drinks will be served; a cash bar is available at the Spring Creek Bar and Grill in the lobby area. We will lead an ice breaker activity when most of the group is assembled.

DAY 1: Wednesday, February 5

6:30 - 8:00 AM Breakfast on your own (present buffet voucher)

8:00 AM Carpool to CIRA Commons (meet in lobby at Hilton by 7:55 AM)

8:30 AM Arrival on-site

9:00 AM Welcome and Introductory Remarks

Workshop Co-Organizers

SESSION 1: Structure and function of the aerobiome system

9:30 AM Plenary 1, *Allison Steiner*: "Pollen as a bioaerosol in the atmosphere: Connecting grains from observations to atmospheric models"

9:45 AM Session 1 Lightning Talks (≤5 min each)

Leda Kobziar, Katie Benedict, Natalie Mahowald, Misty Peacock, Bala Chaudhary

10:15 AM Summary of survey responses and charge to breakout groups *(Allison Aiken)*

10:30 - 10:45 **BREAK**

Formation of Session 1 breakout groups *(participants will form 3 groups and appoint a rapporteur)*

10:45 - 11:30 AM Breakout group discussions

11:30 AM Reports from breakout groups

12:00 PM **LUNCH**

SESSION 2: Pathogens in the system

1:00 PM Plenary 2, *Linsey Marr:* "Form and Function of Bioaerosols in the Earth System"

1:15 PM	Session 2 Lightning Talks (≤5 min each)
	Jordan Peccia, C.-Y. Wu, Morgan Gorris, Nina Vance, Pierre Herckes
1:45 PM	Summary of survey responses and charge to breakout groups *(Kathie Weathers)*
	Formation of Session 2 breakout groups *(participants will form 3 groups and appoint a rapporteur)*
2:00 - 2:45 PM	Breakout group discussions
2:45 PM	Reports from breakout groups
3:15 - 3:30 PM	**BREAK**

SESSION 3: Atmospheric processes and viability

3:30 PM	Plenary 3, *Barbara Ervens*: "Living bioaerosols: Questions and challenges for atmospheric scientists and microbial ecologists to explore the airborne microbiome"
3:45 PM	Session 3 Lightning Talks (≤5 min each)
	Jeff Collett, Gavin Cornwell, Elizabeth Trembath-Reichert, Brad Borlee
4:10 PM	Summary of survey responses and charge to breakout groups *(Allison Aiken)*
4:25 PM	Formation of Session 3 breakout groups *(participants will form 3 groups and appoint a rapporteur)*
4:25 - 5:00 PM	Breakout group discussions
5:00 PM	Reports from breakout groups
5:30 - 7:00 PM	***RECEPTION AND DINNER***, CIRA Commons
	Speaker: Kim Prather, "Marine bioaerosols: What do we know?"
~7:15 PM	Carpool to Hilton

DAY 2: Thursday, February 6

6:30 - 8:00 AM	Breakfast on your own (present buffet voucher)
8:00 AM	Carpool to CIRA Commons (meet in lobby at Hilton by 7:55 AM)
8:30 AM	Arrival on-site

SESSION 4: Methods and Standards

9:00 AM	Plenary 4a, *Gedi Mainelis*: " Bioaerosols at the edge of space: challenges, tools and interdisciplinary frontiers"
9:15 AM	Plenary 4b, *Scott Tighe*: "Characterizing Bioaerosols and the Aeromicrobiome: Technical Advancements of low biomass Environmental Monitoring and Applications"
9:30 AM	Session 4 Lightning Talks (≤5 min each)
	Betsy Stone, Marina Nieto-Caballero, Anne Perring, Erik Hanschen, Alex Huffman
10:00 AM	Summary of survey responses and charge to breakout groups *(Sonia Kreidenweis)*

10:15 - 10:30 AM	**BREAK**
	Formation of Session 4 breakout groups *(participants will form 3 groups and appoint a rapporteur)*
10:30 - 11:15 AM	Breakout group discussions
11:15 AM	Reports from breakout groups
11:45 PM	**LUNCH**
12:30 PM	**Session 5: Workshop summary and next steps** *Discussion of manuscript, other ideas for continuing momentum, and task assignments (Workshop Co-Chairs to lead)*
~2:00 PM	Depart for airport, Hilton, or Old Town Ft. Collins

Appendix 3

This section provides the unedited (but organized) responses to the three pre-workshop questions.

Bioaerosols in the Earth System Pre-Workshop Survey Results: **Key Research needs**

What are current limitations on progress in Earth System bioaerosol research? What do you view as <u>the</u> (up to 3) most urgent science questions and/or knowledge gaps for interdisciplinary bioaerosol research scientists to explore and overcome in the coming decade?

1. Bioaerosol sources (terrestrial and aquatic) and aerobiome structure

Bacteria, fungi, and viruses are easy to detect. What is the human health influence and ecosystem role of biological particles (that are not intact cells or viruses) and other plant materials that are not easily detected?

Emissions inventory from natural and anthropogenic sources

Few long-term studies to characterize spatial distribution and temporal trends.

How does bioaerosol contribute to the total aerosol population across rural to urban gradients?

Sources of atmospheric bioaerosols

There are not enough observations to understand the sources or distribution. We need routine monitoring in many locations of the many kinds of bioaerosols, which is difficult and not done.

What are the impacts of land and climate onto bioaerosol productions.

What are the main sources and spatial/temporal distributions of airborne viruses?

What is the biopause?

What is the vertical profile of bioaerosols near the surface?

2. Bioaerosol emissions mechanisms and fluxes

How can we study the role of biosurfactants in emission?

How do environmental changes affect bioaerosol sources and dynamics? Understanding the impacts of land use changes, biodiversity shifts, and climate extremes on bioaerosol generation, composition, and transport.

How does climate variability (outside of short-term drivers like temperature and wind) influence the release of bioaerosol to the atmosphere? Can we understand biological drivers of emissions?

Is bioaerosol rupture (e.g., the fragmentation of larger bioaerosol into smaller aerosols) an important process in the atmosphere?

Knowledge gap: better understanding of aquatic aerosol emission mechanism(s).

What are the collective and relative roles of disturbances in bioaerosol emission, transport, and dispersal? How do the characteristics of the disturbance (e.g. intensity, spatial coverage, duration, type) influence the mechanisms of bioaerosol emission, survival, and transport? Are there commonalities across resulting airborne assemblages reflective of selection?

What controls the relative abundance of ocean vs terrestrial (vs other) bioaerosols?

3. Atmospheric transport, removal, and lifetimes

How do atmospheric transformations of bioaerosols impact their viability, chemistry, and physical properties?

What is the extent to which atmospheric chemical and physical conditions and processes shape the abundance, diversity, survival of the microbiome?

Understanding the mechanisms of atmospheric transport of pathogens, including entrainment, survival, if they are particle-attached or not, and source regions

4. Bioaerosols in clouds and precipitation

How do atmospheric processes change the aerobiome? Cloud-aerosol processing alters aerosol chemistry, but what impact does it have on the aerobiome?

How do bioaerosols impact cloud and ice formation in the atmosphere?

What is the role of bioaerosols in climate-relevant processes? Understanding the mechanisms by which bioaerosols influence cloud formation, precipitation, radiative forcing, etc. to improve representation in climate models.

5. Atmospheric functions and survival mechanisms

Are microbes actively metabolizing while in the atmosphere?

Are the interactions between airborne microbes with other microbial species and/or chemicals additive, synergistic, or antagonistic?

How do airborne microbes maintain their viability during their transport from their source to the receptor?

How do we increase integration of bioaerosols in earth system models, specifically using the One Health approach and/or a climate justice lens. Specifically, how do can the scientific community support equitable access to data and cross-section data sharing?

Is the atmosphere a habitat where microorganisms are active, thrive and survive or is it merely a transient space of passive particle transport?

Much of the modern work on bioaerosols is based on DNA sequencing, which reveals an impressive diversity. However, we typically do not know whether the organisms detected are dead, dormant, or active. There is very limited understanding of their actual activity and the extent to which the air acts as a true habitat vs a transport medium.

The metabolic processes and survival of bioaerosols in atmosphere outside of water or cloud droplets.

Understanding of functional roles of bioaerosols in climate systems, such as ice nucleation or biogeochemical cycling.

What constrains limits to life in the atmosphere?

What proteins and surface associated polysaccharides are microbes making that protect them from desiccation.

6. Impacts on ecosystems and health, including airborne pathogens

Documenting what pathogens and bioaerosols are in the atmosphere

Lack of a well-defined exposure - health effects relationship.

Measuring the prevalence of airborne pathogens

Mechanistic understanding of respiratory bioaerosol emissions and their survival rates in different environmental conditions.

Contributions of bioaerosols to nutrient deposition

Effects of bioaerosols on atmospheric chemistry

How bioaerosols influence ecosystems regarding their role in nutrient cycling or as pathogen vectors.

How do bioaerosol emission mechanisms scale with ecosystem impact? Are higher "dosage" (i.e. more, or uniquely influential microbes such as pathogens) bioaerosol emission events more impactful on downwind ecosystems, and what governs the answer to this question? Is this predictable? Do ecological effects of disturbance-driven bioaerosol dispersal increase where disturbances are less frequent, and alternatively, maintain rather than change ecosystems where disturbances are frequent (e.g. recurring ecosystem processes like wildland fire in savannas, grasslands)?

What are the impacts of the bioaerosols?

What are the key climate-relevant bioaerosol processes and properties that impact the earth system?

What is the minimal representation of bioaerosol(s) in numerical prediction models required to adequately simulate their effects on weather and climate?

7. Indoor air quality and built environment

How are comingled factors of urbanization and climate change impacting human health concerns associated with bioaerosols? Changes to airborne allergies, i.e. from changing pollen or spore species dominant in urban environments (due ; affected by chemical alteration from water- or air-borne pollutants; from changing seasonal patterns of temperature and precipitation; from increasingly urban populations.

Impacts of the airborne component of the indoor microbiome on quality of live.

Quiet, high-volume sampling of bioaerosols into liquid that can be used in occupied spaces

What are the impacts of the various interactions between bioaerosols and physical/chemical environment? How do traditionally considered “bioaerosol” particles change their resultant properties [i.e. physical/hydroscopicity/CCN or INP; or as related to health impact] when the particles chemically age, physically change, or externally mix with other particle types (i.e. soot, gas-phase oxidants, other non-bio particles)?

8. Bioaerosol sampling technologies, low biomass analyses, and standards

DNA and RNA recovery and detection with low signal to noise (dealing with the kitome and extractome)

Efficient amplification strategies from ultra-low biomass environments

Ensuring the accurate and unbiased extraction of low biomass sequencing from air filters

High recovery sampling protocols

How can we reliably reproduce bioaerosols to study under controlled conditions?

Integration of eDNA databases for blasting across all prokaryotic and eukaryotic life.

Lack of standardized protocols for bioaerosol sampling and analysis. While many tools are available, they provide different answers even when analyzing the same environment. We started moving toward more standardized testing after IAC 2018, but still a lot remains to be done.

Reproducible (common sampling and analysis so they can be directly compared) measurements of the spatial distribution of bioaerosols

Research methods that are biased for/against certain regions, organismal groups, spatial/temporal scales.

Statistics of characterizing how environmental drivers correlate and cause microbiome differences. How do we prove environmental driver X is associated with community Y? How is this performed in a highly multidimensional context?

What are the appropriate scales (time, space, density) of measurement and monitoring to advance understanding of local to global bioaerosol flux?

What properties of bioaerosol are important? What measurement should everyone be making to facilitate inter comparisons?

OVERARCHING

Integration of research communities that approach bioaerosol research from different perspectives: ecological, agricultural, human health, etc.

Bioaerosols in the Earth System Pre-Workshop Survey Results: **Barriers to Progress**

What are current limitations on progress in Earth System bioaerosol research? What do you view as <u>the</u> (up to 3) most important barriers to filling/bridging the questions / gaps you listed above? What information, data, tools, or equipment do you most need from another discipline in order to move your bioaerosol research forward?

You may provide a narrative or bullet points, however you prefer. We will share these insights with the group ahead of time, so please be succinct.

1. Support for bioaerosol studies

Funding: having enough evidence to support that this is an important topic

Analysis of samples is resource-intensive

Funding people. Data and research networks are great, but we need people to do the work.

Measurement techniques and laboratory methods are expensive, time consuming, and require a multidisciplinary team

Current analytical tool to identify microbial species is not affordable to most researchers and is limited to few researchers.

Bioaerosol not being implemented in most numerical prediction models

Access to high performance computing.

Unequal access to research methods in different regions around the world.

Funding to conduct large multidisciplinary studies in geographically varied regions.

2. Methods development needs

High recovery Sampling protocols for Viruses

Common (non-destructive and fast) airborne sampling methods used by all groups (allows intercomparisons)

Unified methods for sample collection and processing (including contamination controls and primer sets, sequencing methods).

We lack a portable and lightweight sampling tool that can efficiently collect bioaerosols while conserving their viability.

The low concentrations of microorganisms in the atmosphere represent a major challenge for statistically relevant measurements. Main barriers and limitations to characterize the atmospheric microbiome as a small, but highly dynamic fraction of the total Earth' microbiome include the current lack of (1) research infrastructures for routine measurements to determine abundance, diversity, viability of atmospheric microorganisms. Such infrastructures should entail Lagrangian set-ups as well as high resolution measurements to quantify emission and deposition fluxes; (2) strategies for dedicated lab or chamber studies under controlled, atmospherically relevant conditions to disentangle the multitude of physicochemical factors or stressors (e.g., oxidants, temperature, aerosolized state, …) that may affect the microbiome's evolution.

Extremely limited capability for real-time bioaerosol measurements and consistent sampling and analysis methods for bioaerosols emitted and transported during disturbance events (e.g. volcanoes, windstorms, wildfires, hurricanes). Lack of coordinated conceptual framework for quantification, characterization, and comparison across disturbance types.

Statistical frameworks are poorly developed and usually assume normal distributions and low dimensionality to datasets

Lack of standardized, well-characterized sampling equipment that would serve as a reference in various studies. Limited knowledge of how any selected sampling and analysis protocols affect the result of any study.

Challenges in detection and standardization of methods. What do we really need to measure, can we measure it "easily" to make more routine measurements, what are best practices?

The ability to conduct in situ observations or realistically replicate airborne conditions remains a significant challenge. Many laboratory studies are biased due to the use of specific and often artificial growth conditions (media).

Low biomass and detection challenges, especially for metagenomics sequencing of bioaerosols (sampling, sample preservation, DNA extraction, library prep, sequencing, and data analysis).

Understanding the emission source of bioaerosols specifically as it relates to rates and mechanisms - including the answers to the basic questions (where, how, when) and then being able to compare data (standardized measurements), and lack of datasets.

What could we learn about our ecosystem and human health if we had real-time bioaerosol detection?

Access to equipment and chambers that allow study of aerosols under controlled conditions. This is a limited resource that does not exist in very many places.

Need cheap ways to observe bioaerosols and know what type is in atmosphere

Need for fast, reliable, robust, inexpensively deployable sampling and measurement techniques that deliver information at relatively high-time resolution and at level of taxonomic specificity that provides information necessary to answer process-level questions (about e.g. emission, deposition, transport, growth, etc.) related to the atmospheric, ecological, agricultural, or public/individual health interest.

WGA amplification strategies from sub-picogram amounts of DNA (and RNA)

Determining rapid/real-time answers on which bioaerosols are present (ideally instantaneous)--targeted and non-targeted--and how they are co-mixed with other pollutants (gases + aerosols)

Each sampling method introduces its own artifacts

Air filters are notoriously challenging, I want to explore new approaches to DNA collection

Limited data and difficulty accurately measuring personal exposures to various bioaerosols. We need new ways to measure exposure and the effects of exposure. Maybe biomarkers or other manifestations of exposure that took place.

Lack of standards for the bioaerosol field (culturing, DNA extraction methods, DNA sequencing, and data analysis pipelines) so that data from published studies can be usable or comparable to other studies.

Measurement limitations and the need for standardization

Instrumentation to monitor microbes during flight to evaluate in vivo responses without killing the microbe in real time.

Need for standardization of sampling, measurement, calibration techniques that enable efficient comparison of information across users, applications, and deployment locations.

Efficient amplification strategies from ultra-low biomass environments

Workflow used in different studies by different groups -- taking samples from air to filter/solution to analysis is challenging and highly variable (comparisons questionable)

Infrastructure needed for conducting vertical bioaerosol measurements

3. Lack of monitoring networks

Ability to routinely observe atmospheric bioaerosols and their deposition

A lack of a distributed network of collocated measurements of bioaerosol, aerosol, and meteorology

Lack of long term measurements; most studies are relatively short and intensive campaigns

The lack of observations is currently the largest constraint. More atmospheric observations are needed, both at the surface and aloft in the atmosphere.

I think bioaerosols have yet to capture the public imagination to such an extent that government agencies would invest in monitoring networks. A large investment would be required. We have extensive PM monitoring networks because of their relevance to human and animal health- how do we promote understanding and investment in bioaerosol monitoring to advance understanding? Is connection to human, plant, crop, animal health the key, or is it weather? We need to present a united voice for the need for large-scale measurement networks.

Need broad distribution of measurement methods in atmosphere so we know where bioaerosols are important.

Long-term, longitudinal studies are needed, and require working across disciplinary silos of atmospheric studies, the various sciences that deal with emission events/processes, and environmental microbiology. Basic measurements of pre- and post-emission process bioaerosols are lacking, as well as tracking of bioaerosols from their sources to their sinks and following up with measurements of their impacts.

4. Need for interdisciplinary research

Collaborative research including physiology and aerosol researchers.

There is a "training" gap, as most aerosol researchers come from engineering or meteorology backgrounds, while microbiome experts are typically trained in (micro)biology or ecology. This results in largely exclusive training paths. Although there is some overlap in environmental engineering, it is often limited to pathogen studies and/or water treatment. It is also very hard to find graduate students willing to learn the part they are missing.

Understanding the biological drivers for the release of pollen as a bioaerosol is a topic that needs more cross-disciplinary research. A large gap for prognostic modeling is understanding how biological factors are influenced by longer term climate.

Knowledge silos to bioaerosol research - increased collaboration with microbiogists, atmospheric scientists, public health officials, and ecosystem studies. Specifically in how to meld varied datasets.

Public perception of nuanced bioaerosol science, including a lack of understanding of human and ecosystem health that are impacted by bioaerosols.

Continued challenges in working across disciplines – i.e. difficulty acquiring funding for truly interdisciplinary projects/questions; challenges from disparate loci of knowledge, whether at departmental/college/institution level, whether because different types of researchers attend different meetings, whether because they are funded by different directorates or agencies, whether because focused on different sides of similar scientific questions; administrative barriers to bringing students into a graduate program focused within one particular college/department when broader or different knowledge/expertise may be useful.

5. Need for process studies

The low concentrations of microorganisms in the atmosphere represent a major challenge for statistically relevant measurements. Main barriers and limitations to characterize the atmospheric microbiome as a small, but highly dynamic fraction of the total Earth' microbiome include the current lack of (1) research infrastructures for routine measurements to determine abundance, diversity, viability of atmospheric microorganisms. Such infrastructures should entail Lagrangian set-ups as well as high resolution measurements to quantify emission and deposition fluxes; (2) strategies for dedicated lab or chamber studies under controlled, atmospherically relevant conditions to disentangle the multitude of physicochemical factors or stressors (e.g., oxidants, temperature, aerosolized state, …) that may affect the microbiome's evolution.

Extremely limited capability for real-time bioaerosol measurements and consistent sampling and analysis methods for bioaerosols emitted and transported during disturbance events (e.g. volcanoes, windstorms, wildfires, hurricanes). Lack of coordinated conceptual framework for quantification, characterization, and comparison across disturbance types.

Understanding the emission source of bioaerosols specifically as it relates to rates and mechanisms - including the answers to the basic questions (where, how, when) and then being able to compare data (standardized measurements), and lack of datasets.

Measurement techniques and laboratory methods are expensive, time consuming, and require a multidisciplinary team

Determining rapid/real-time answers on which bioaerosols are present (ideally instantaneous)--targeted and non-targeted--and how they are co-mixed with other pollutants (gases + aerosols)

Understanding the biological drivers for the release of pollen as a bioaerosol is a topic that needs more cross-disciplinary research. A large gap for prognostic modeling is understanding how biological factors are influenced by longer term climate.

Instrumentation to monitor microbes during flight to evaluate in vivo responses without killing the microbe in real time.

Methods to assess atmospheric transport mechanisms of pathogens

Long-term, longitudinal studies are needed, and require working across disciplinary silos of atmospheric studies, the various sciences that deal with emission events/processes, and environmental microbiology. Basic measurements of pre- and post-emission process bioaerosols are lacking, as well as tracking of bioaerosols from their sources to their sinks and following up with measurements of their impacts.

We need to expand experiments with rotating drums and other technologies that maintain microorganisms airborne longer. We need to conduct more experiments that simulate stratospheric conditions; also conduct bioaerosol experiments in stratosphere.

Not enough information about the interactions, for example, with ice clouds.

Bioaerosols in the Earth System Pre-Workshop Survey Results: **Expectations**

What interested you in participating in this workshop? What are your expectations / hopes for workshop outcomes? What are your impressions of the "aerobiome" as an emerging theme, within your discipline and outside of your discipline?

I am interested in networking with collaborators to build multidisciplinary teams. I think the atmospheric transport of pathogens is understudied. Aerobiome is an exciting new field with important health implications, as well as Earth system science applications

Aerobiome is a new and upcoming field in genomics. While many labs have in-house methods, there are no recognized standards. As these techniques become more widespread, many hospitals, pharmaceutical facilities, and other healthcare facilities may soon require formalized protocols and metadata standards, which could be developed through mechanisms such as the international microbiome and multiomics standards alliance (IMMSA) and/or Genomics Standards Consortium (GSC). While we have obtained millions of viable samples over the past thirty-years, genomics will clearly be the detection method of the future but there remains little data on efficiency. Major concerns include 1) Efficiency of various collection methods related to DNA recovery, 2) availability of DNA-free sampling and amplification reagents 3) applicability of ultra-low biomass as an input to both DNA extraction and amplification 4) benchmarking viability data to DNA aerobiome data and 5) developing software and sampling strategies to mitigate the "kitome" background signal. These all need to be controlled if we expect the field to advance and be accepted by our scientific peers.

I am looking forward to participating in this workshop to learn more about others' bioaerosol sampling methods and study goals. With expertise in factors controlling bioaerosol aerosolization from ocean and river sources, I am interested in comparing these aquatic sources to terrestrial ones to understand their global impacts on climate, health, and precipitation. My hope is to develop a network for collaborating on sampling and analysis protocols, enabling comparisons across various locations, times of year, and altitudes. Additionally, I'm interested in exploring whether bioaerosols remain intact and viable during atmospheric transport (w/ an emphasis on human health connections).

Within - discussing methods, obstacles, and strategies. Outside - learning about additional datasets and approaches that are complementary. Both - discussing funding mechanisms for bioaerosol work from an ecology perspective.

I am NOT a bioaerosols expert but am interested in learning more as they are relevant to my research on cloud chemistry and nutrient deposition

This is an intriguing and important topic to explore. I'd like to learn from colleagues with expertise in this important topic and share my thoughts learned from past research endeavors in bioaerosol. Identifying future research directions and forming research and education alliances will be the outcomes I hope to see.

Maintaining microbial biodiversity is essential for preserving planetary health. While the microbiome of surface ecosystems, such as soil and water, has been extensively studied, the characterization of the atmospheric microbiome and factors that influence it is currently in a comparably early stage.

I expect that the workshop brings together researchers from the fields of atmospheric sciences, aerobiology, and microbial ecology to explore strategies for more comprehensively exploring aspects of the atmosphere as acting as a habitat or as a transient space for airborne microorganisms. This will eventually lead to a more thorough characterization of the microbiome of the total Earth system and its potential modification in a changing climate.

I hope to discuss interdisciplinary and synergistic efforts in terms of experimental and modeling strategies that have been successfully applied in terrestrial and aquatic environments and discussing whether and how these approaches may be adapted to atmospheric conditions.

I hope we can collectively envision a conceptual framework defining why bioaerosol research is a critical pursuit with broad-scale and diverse implications for all Earth systems. I am super enthusiastic about learning from the group, as this line of work requires diverse knowledge, expertise, and perspectives.

Network with like-minded colleagues; exhaustive discussion of knowledge gaps and barriers; "Aerobiome" is currently an emerging field, but it is mostly a descriptive science, with little connection with environmental processes and variables.

Increase collaboration

I have limited experience in bioaerosols but I am very interested in learning and connecting with other researchers.

I am looking forward to learning about what others are working on. We don't attend many microbiology-related meetings, and when we have presented our work, we often felt like outsiders. This time, we're excited to meet some of the people we know through their publications and gain insights into their research. I'm also eager to learn how others are overcoming training and expertise challenges, as well as to hear about the latest hypotheses and the directions people are taking in their research.

I have been attempting to model bioaerosols for about 15 years and we continue to be extremely data-limited. I hope to develop new collaborations to make progress in developing new observational networks that can be used to improve models, and working to understand new frontiers in aerosol measurement technologies that can help us understand the fate of bioaerosols in the atmosphere. Additionally, I would also like to develop new collaborations with biologists on the emissions source questions.

My interests lie in strengthening multidisciplinary networks, and engaging in partnerships that extend beyond the workshop. I hope to engage with researchers in fields that are more advanced/established in bioaerosol research. Related to my discipline, aerobiome is the nexus of atmospheric systems, marine (or freshwater) systems, and public health outcomes. Aerosolization can be an afterthought in terms of harmful algae research, though it may exceptionally important as climate changes intensifies HAB events. Outside my discipline I'm particularly interested in understanding how it can influence policy changes related to public health.

Within my discipline, I'd love to hear more about how researchers can improve tracking human exposure to airborne infectious diseases. More broadly, I'm very interested in learning more about earth system processes that are influenced by airborne microbes.

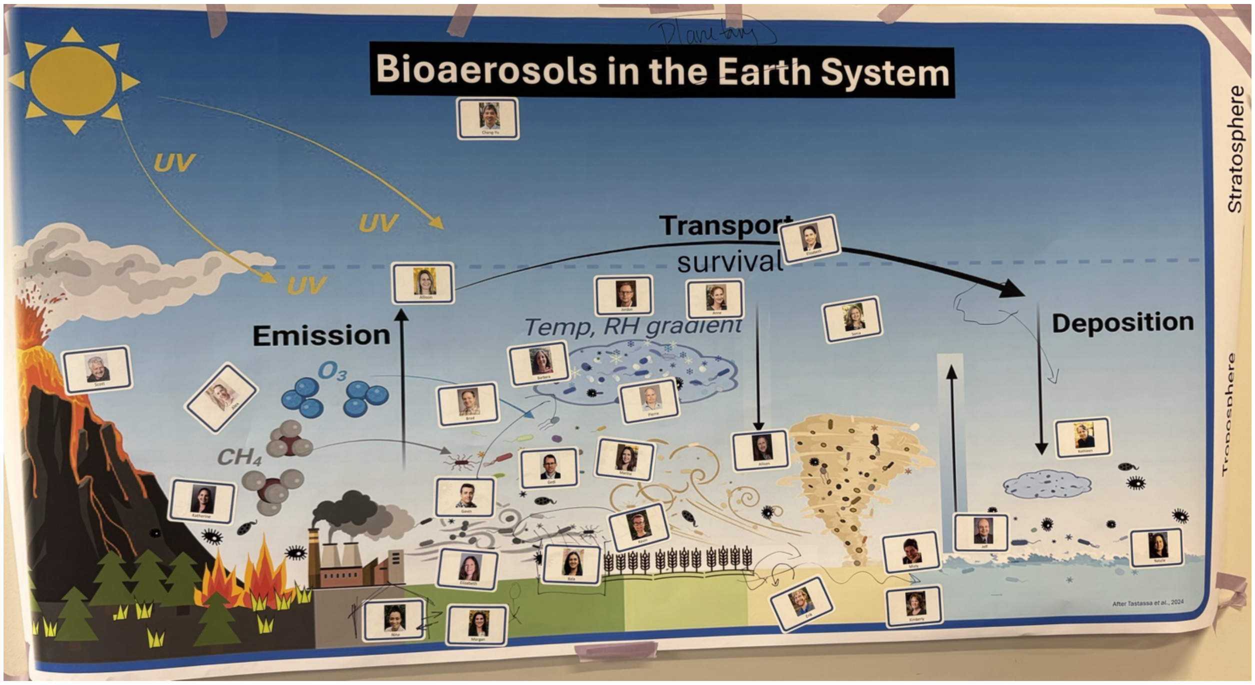
I would like to connect with others doing this work to learn and contribute to the narrative that will set future research agendas. I would also like to get ideas on how to fund this work in the future.

Interest is derived primarily from a desire to interact with people from diverse scientific backgrounds who are focused on working together to identify mechanisms that allow microbes to survive emission and transit in the air, and how those traits shape and select the composition of the aerobiome in response to changing environmental parameters.

Fascinating way to understand this poorly observed type of the aerosols: and to understand where the bioaerosols are coming from we need the genetic material.

Appendix 4

Earth system poster for breakout activity, adapted from *Tastassa et al.* (2024). Participants were asked to place themselves in the relevant portion of the Earth system and briefly describe their research interests.



Appendix 5

Following are the ChatGPT-summarized notes form breakout discussions, after editing and commenting by workshop participants. These were downloaded from the shared Google drive and edits accepted on 15 February 2025.

Breakout 1:
Summary of the Structure and Function of the Aerobiome System

1. Knowledge Gaps and Research Needs

- **Defining the Aerobiome as an Ecosystem (Systems Biology Approach)**
  - The **aerobiome is rarely studied as a whole**—most research focuses on bacteria, fungi, pollen, or viruses, or plant/animal bits individually.
  - Is the **atmosphere a biome or an ecosystem**? If so, how does it function?
    - Overcome the bias that since it is a dilute system, there is “nothing there” or that “it doesn’t matter”

- Does biogeographic or metacommunity theory (e.g. neutral theory, patch dynamics) inform aerobiome structure and function?
- More research is needed to determine whether microbes are **actively metabolizing in the atmosphere** (outside of cloud droplets) or if they exist in a dormant state.
- Air (indoor and atmospheric) [comment: separate these, since conditions are very different] is an "extreme" [comment: not as traditionally defined] environment that stresses microbes (low moisture, UV, oxidative stress) and airborne microbes respond (inactivation, pathogenicity, allergenicity) to this environment.
- What are the ecological processes and concepts that translate from terrestrial/aquatic systems to the aerobiome, are new ones needed?
- Which emission and atmospheric conditions are selective for bioaerosols?
- How do temporal and spatial scales define the aerobiome?
- Big picture questions:
    - When and where are bioaerosols important for climate or biogeochemistry?
    - When and where is atmospheric transport of bioaerosols important for transport of pathogens or genetic materials?
    - Are human pathogens transported long distances through the atmosphere in meaningful quantities (and remaining pathogenic)?
    - Does the atmosphere exert selective pressure on microbes?
    - How important is the aerobiome in global biodiversity patterns?
    - How can our work inform solutions for urgent health crises or environmental justice challenges? (e.g. Kim's talk, pandemics, air quality in India)
    - How is climate change impacting the aerobiome?

- **Bioaerosol Sources and Transport**
    - **The spatial and temporal variability of physical and biological** emission and deposition mechanisms and rates, including re-suspension need to be constrained.
        - Relative roles over time of lower-magnitude, more continuous dry deposition vs. higher magnitude, event-driven wet deposition
    - **Emission mechanisms are poorly understood**, especially for **newly identified sources** such as:
        - Waterfalls, surf zones, and turbulent rivers.
        - Desert dust mixed with bioaerosols.
        - Anthropogenic soil disturbance (industrial agriculture, mining, overgrazing)
        - Wildfires and biomass burning (potential biological content in smoke affecting cloud formation and superfog).
        - Ocean waves
        - High winds and disturbance of soil crusts
        - Emissions for some species have been studied, but are species specific (e.g. soil-born fungal pathogens, wheat rust) and many more species exist
        - Pollen emission modeling is more mature.
        - How do emissions mechanisms affect bioaerosols (form, composition, viability)
    - **Human, animal and environmental interactions**:
        - How do **human-associated and animal-associated microbes** (e.g., wastewater emissions) affect natural microbiomes in oceans and soils, and the resulting bioaerosol release?
        - How do environmental conditions (e.g., T, RH, UV, ozone, pollutants, oxidants, dust, PM, and other potential stressors, and other environmental conditions **impact bioaerosol survival and function (including pathogenicity and allergenicity)**? [comment: some conditions might be beneficial]

        - How does climate interannual variability (e.g., drought, precipitation, temperature) influence bioaerosol emissions?
    - **Bioaerosol transport modeling is challenging**:
        - [comment: Could also be framed as how bioaerosol transport may be different than other aerosol processes due to size, shape and buoyancy - this affects turbulent and deposition processes]
        - Residence time in air, at different altitudes - do the same concepts apply as for 'any' aerosol particle?
        - Transport pathways depend heavily on **aerodynamic properties of the carrier particle, not the microbe alone**.
        - **Deposition processes (wet and dry) remain poorly constrained**.(e.g., assume spherical shape of particles)(can also vary with carrier particle)
        - Uncertainty in **how far bioaerosols travel**, especially irregular-shaped particles.
        - [comment: Are bioaerosol more likely to be emitted from regions with a canopy (which may influence their vertical transport)?]
        - Microphysical properties of bioaerosol may affect how far they are transported (e.g. more efficient wet deposition of ice nucleation active bioaerosol).
        - How can we use traits (morphological, physiological, phenological, genetic) of microbes/bioaerosols to move toward a predictive understanding of emission, transport, and deposition?
- **Microbial Interactions and Functions in the Atmosphere** [comment: Not sure these two points should be combined as they can be mutually exclusive.]
    - **How do bioaerosols interact in the air?**
        - Are interactions **synergistic, mutualistic, commensalistic, competitive, facilitative, or antagonistic**?
        - Do bioaerosols have traits (e.g., **spore surface depressions**) that facilitate microbial attachment and survival?
        - (How) does gene expression and phenotype change when a microbe becomes airborne
        - (How quickly) Can microbes adapt to the quickly changing conditions in the atmosphere, e.g. in clouds ?
    - To what extent do **airborne microbes influence ice nucleation and cloud formation?**
        - Is **ice nucleation due to proteins**, and do they need to be intact? What other macromolecules affect ice nucleation activity? Can we identify a common molecular property that allows extrapolating/parameterizing ice nucleating ability by bioaerosols?
        - Does biological material in **smoke contribute to convective cloud formation**?
        - What is the relative importance of bioaerosols as compared to other aerosol types in cloud formation?
    - **Do bioaerosols transport nutrients** that influence ecosystems?
        - Example: Aerosol deposition could be **delivering phosphorus to lakes and oceans**, altering aquatic ecosystems. Evidence suggests bioaerosols are important for transport of P, but not N or C.
        - High concentration deposition events may occur in concert with storms/ large wildfires, providing an opportunity to test hypotheses
        - How can the atmosphere be described in terms of its trophic level?

2. Barriers to Progress

- **Measurement Challenges**
    - **The fundamental problems** associated with bioaerosol measurements are difficulty in sampling (sizes, efficiency, recovery) and very low concentrations
    - **Viruses are difficult to quantify**—could techniques like **flow cytometry or genetic amplification** or Digital PCR help? [comment: genetic amplification and Digital PCR are already done]
    - **Size constraints in measurement tools**:
        - Most atmospheric measurements are capable of collecting **particles smaller than PM10**, potentially missing important bioaerosol carriers.
        - Few instruments collect nano-sized bioaerosols
    - **Lack of real-time bioaerosol monitoring techniques**—need for tools that combine sampling and detection in one device.
    - Large-scale emission events tend to be hazardous, need remote sampling capabilities
- **Data Standardization and Interdisciplinary Disconnects**
    - **Few monitoring networks** track bioaerosol distribution and variability.
    - **Lack of standardized definitions** (e.g., what constitutes an "active" aerobiome?).
    - **Data collection is inconsistent** across different bioaerosol communities and within (pollen vs. fungi vs. viruses), and among different emitters (water, land, etc.)
- **Theoretical and Modeling Limitations**
    - **There are a hierarchy of models available for specific purposes from single drop, regional to global scale that would all require the description of processes or parameterizations for the specific scale**
    - **[comment: What is the appropriate level of detail needed for specific applications? Do you need to know gene expression, species-specific information, broad categories?]**
    - **No comprehensive framework links atmospheric bioaerosols to ecological and biogeochemical cycles**.
    - Theory is based on free-living organisms and not symbiotic organisms whose emission, transport, and deposition may rely on another completely unrelated organism.
    - **Large-scale environmental changes (e.g., climate change, pollution) may alter the aerobiome**, but these shifts are not well-documented.

3. Opportunities for Advancing Knowledge

- **Interdisciplinary Approaches**
    - Investigate **interactions among different types of bioaerosols**—are there synergistic effects on health or climate?
    - Standardize **measurement techniques across disciplines** to improve data comparability and detection efficiencies.
        - Yes and, quantify errors and biases for a variety of measurement approaches, because standardization may not make sense when sampling different events of interest to different disciplines (airborne vs. ground-based, during a hurricane vs. at an observation tower)
    - **Develop a detailed model of bioaerosol pathways**—current understanding is limited and could build on existing hierarchy of models.
- **Expanding Sampling and Data Collection**
    - **Better geographic and temporal resolution** in sampling—**urban vs. rural differences, seasonal variability**.

    - Leverage **existing deposition networks (e.g., NADP samples)** to study bioaerosol deposition rates.
    - Create new monitoring networks or extend existing ones
    - **Identify natural experiments** (e.g., desert dust events, wildfire plumes) to study dispersal mechanisms.
    - Improve airborne measurement technologies to support a range of sampling needs (remote, hazardous conditions, extreme environments)
- **Innovative Experimentation and Field Studies**
    - **Large-scale prescribed burns (and opportunistically in advance of wildfires)**:
        - Spike fire-affected areas with **isotopically labeled microbes** to track emission and transport.
        - [comment: Barcodes are another option for labeling, although we may not want to disperse these in the environment.]
        - Characterize source microbial communities, track in smoke and downwind
        - Field test for microbial tolerance of high temperatures, winds, desiccation/ or/ microniches protecting bioaerosols
    - **Chamber experiments**:
        - Assess viability and cloud condensation activity of different bioaerosols under conditions that simulate those environments.
        - ‘Ageing timescales’ under atmospherically relevant conditions
        - Test environmental tolerances of pathogenic microbes
        - Subject pathogens to stressors, assess epigenetic or transient changes to virulence
    - **New detection methods**:
        - Develop **real-time sequencing and rapid viability assays** for airborne microbes.

4. Wild Ideas and Future Directions

- **Tracking bioaerosols from emission to deposition [to effects?] to characterize their modification due to atmospheric processing**:
    - Use **stable isotope labeling** or **genetic markers** to study movement.
- **The “Duck Theory”**: Challenging assumptions that bioaerosols **can’t travel far** due to size.
- **Bioaerosol interactions with microplastics**—could they serve as microbial habitats?
- **Leverage existing aerosol monitoring networks (IMPROVE, ASCENT, NADP) with relatively cheap measurements (passive samplers).**
    - **Establish appropriate bioaerosol sampling, storage protocols prior to this**
- **Establish global bioaerosol conference, and/or working groups, and/or communication networks** to unify methodologies and data sharing.

5. Key Themes Across the Discussion Groups

1. The Aerobiome as an Ecosystem

- Does it function as an **ecobiome**, with structured relationships and metabolic activity?
- How do airborne microbes interact with their environment and other microbial species?
- How deterministic/stochastic is the distribution/diversity of the atmospheric microbiome?

2. Bioaerosol Transport and Deposition

- **Newly recognized sources** (coastal zones, wildfires, desert dust) require more study.
- **Transport modeling is complex**, requiring improved understanding of size, composition and **morphology since that impactsresidence time, deposition rates, and atmospheric processing as its impacts on viability is poorly understood.**

3. Bioaerosol-Climate Interactions

- **Ice nucleation and cloud formation**—does biological material affect precipitation?
- **Biogeochemical cycling**—do bioaerosols contribute nutrients to ecosystems (including atmospheric ecosystem)? Do they lead to significant conversion rates of C, N, P, S compounds?

4. Experimental Approaches

- **Large-scale burns, sea spray in coastal regions or potentially agricultural or desert dust studies** to track microbial dispersal from source to downwind regions.
- **Chamber studies** to simulate atmospheric conditions and study microbial survival.

Breakout 2:
Summary of Pathogens in the System

1. Knowledge Gaps and Research Needs

- **Pathogen Presence and Viability**
    - We lack a **clear understanding of airborne pathogen viability**, particularly in real-world atmospheric conditions.
    - There is a vast diversity in the response of different pathogens to atmospheric stressors.
    - **Spatio-temporal monitoring** is limited—uncertainty exists about **who is there, when, and where** pathogens persist across environmental gradients (e.g., urban vs. rural, aquatic vs. terrestrial).
    - **Climate change and land use change may alter pathogen distributions**, but we lack systematic monitoring to track these shifts.
    - **Viability constraints** depend on atmospheric conditions, including turbulence, desiccation, temperature, uv light and interactions with other particles and gases.
- **Pathogen Transport and Environmental Interactions**
    - **Mechanisms of emission** (e.g., wind, dust storms, hurricanes, fires, plant or fungi dispersal) may impact pathogenicity.
    - **Human-borne pathogens** are difficult to maintain in a viable state during sampling.
    - **Role of organic coatings** on pathogen survival is not well understood.
    - **Turbulence affects bioaerosol transport**, but it is challenging to accurately represent in models, possibly leading to overestimation of dry deposition.
- **Modeling Challenges**

- **Current models focus on one specific attribute or type of bioaerosols, and there are a hierarchy of these models, but no comprehensive model.**
- **Current atmospheric transport models (CESM, E3SM, WRF, HYSPLIT, FLEXPART)** would benefit from more pathogen-specific inputs, such as:
  - **Survival rates**
  - **Emission rates**
  - **Particle size distributions**
  - **Aerosol properties (surface roughness, density, shape)**
- **Dormancy vs. viability**: Pathogens may be dormant but still viable upon deposition, yet this aspect is missing from many models.
- **Microbial community interactions**: We do not fully understand **whether airborne microbes interact** or how they influence pathogen survival.

2. Barriers to Progress

- **Limited Infrastructure and High Costs**
  - **BSL-3 facilities** are scarce, expensive, and primarily controlled by medical professionals, limiting access for environmental research.
  - **Only 13 regional biocontainment centers** exist in the U.S., and **NIH funding cuts** have reduced user access.
  - **Virus sampling techniques often inactivate the virus**, making viability assessments unreliable.
- **Standardization and Coordination Issues**
  - No **agreed-upon best practices** for pathogen sampling, extraction, and analysis.
  - **Non-standardized DNA extraction methods** impact pathogen/bioaerosol recovery rates.
  - Optimised Microbiome and metagenomic sequencing should be considered and use of 16s DNA sequecing should not be the default because of cost.Different methods such as WGS should be used for total unbias bio–assessment for pan-genomes
  - [comment: 16S is really crude at the taxonomic level- it cant provide fine enough resolution and needs to be sunsetted]
  - **Lack of a community-shared database** for airborne pathogen data.
  - Lack of access to historical data produced by government agencies considered to be security concerns
- **Interdisciplinary Disconnects**
  - **Environmental scientists, medical professionals, and agricultural researchers** approach pathogen research differently, leading to gaps in collaboration.
  - **Bioaerosol and biosecurity researchers lack coordination with chem/bio/warfare-related studies**, despite overlapping interests.
  - **Plant pathogen research** assumes pathogens are always present and become problematic only under specific conditions—this differs from how airborne pathogen research is conducted.

3. Opportunities for Advancing Knowledge

- **Improved Sampling and Measurement Techniques**
  - Develop a **portable, gentle sampler** that preserves pathogen viability (and ideally with high flow rate).

    - Create new **DNA extraction kits specifically for air samples** to improve recovery efficiency and standardization.
    - [comment: Need to assess low input DNA kits, which might be valuable]
    - Develop new enzymes to assist in recovery of RNA and DNA from bioaerosol samples.
    - Apply future viability preservation reagents such as Suspend-CCX for transport, shipping and archiving samples
    - **Active vs. passive sampling comparison**: An intercomparison study of samplers would help prescribe the best tool for each biological question.
    - **New real-time detection methods**: Could we adapt **rapid sequencing** or **pathogen-specific quick tests** for environmental samples?
    - Consider **spiked standards** to evaluate extraction and recovery efficiencies.
- **Leveraging Existing Resources**
    - Utilize **biocontainment centers** to constrain viability estimates for modeling.
    - Engage with **biowarfare sites (DHS)** that collect pathogen samples and may share leftover materials.
    - **Tap into existing sensors** that provide microbial taxonomic information.
- **Interdisciplinary Collaboration**
    - Connect **airborne pathogen research with medical, veterinary, and agricultural fields** to improve health impact assessments.
    - Foster partnerships with **biocontainment facilities** and advocate for increased access in environmental pathogen studies.
    - Strengthen **community-shared resources** for sampling, collection, and analysis.

4. Wild Ideas and Future Directions

- **Novel Sampling and Surveillance Approaches**
    - **Passive sampling onto live cells** to assess pathogen viability in real-time.
    - **Disease surveillance through sewage testing**
    - **Building design innovations** for pathogen mitigation, integrating real-time sampling into air circulation systems.
- **Theoretical Frameworks for Pathogen Distribution**
    - Could the **atmosphere function as a microbial metacommunity**? Applying **biogeographic and metacommunity ecology theories** might improve our understanding of pathogen dispersal and interactions.
    - Need to **link measurements to theory**—observations should be guided by ecological principles rather than reactive data collection.

5. Key Themes Across the Discussion Groups

1. Pathogen Viability and Transport

- Many pathogens in the atmosphere may be **dormant but viable**, requiring specialized sampling methods.
- Presence/abundance can be determined via PCR or WGS but actual viability determination requires different tools/methods
- **Turbulence, organic coatings, and environmental stressors** play major but poorly understood roles in pathogen survival.

- The impact of **different transport mechanisms (hurricanes, dust storms, fires, etc.) on viability** is an emerging research need.

2. Measurement and Infrastructure Challenges

- **Current virus sampling techniques often destroy viability**, limiting our understanding of infection risks.
- **Lack of access to BSL-3 and biocontainment centers** is a major bottleneck.
- **Standardized nucleic acid extraction methods** for air samples are urgently needed including implementing multi-enzyme cocktails such as metapolyzyme for cell wall digestion and freeze-fracture techniques. **3. Interdisciplinary and Practical Solutions**
- Stronger **collaboration between environmental, medical, and agricultural sciences** will improve pathogen tracking and risk assessment.
- **Leveraging existing biowarfare sampling efforts** may provide valuable pathogen data.
- **New real-time pathogen detection** methods could revolutionize airborne disease monitoring.

4. Theoretical and Experimental Advances

- Applying **biogeography and metacommunity theories** to bioaerosols may help predict dispersal and survival.
- **Field experiments combined with lab validation** will be crucial for testing transport and viability models.
- **Expanding disease surveillance efforts (e.g., sewage monitoring, passive environmental sampling)** could improve outbreak predictions.

Breakout 3:
Summary of Atmospheric Processes and Viability

1. Knowledge Gaps and Research Needs

- **Microbial Viability and Metabolism in the Atmosphere**
  - Do **microbes remain viable and metabolize** in the atmosphere, or do they become dormant?
  - Does the presence of **cloud droplets or high humidity** enhance survival and metabolic activity?
  - Can airborne microbes **degrade or utilize atmospheric chemicals** (e.g., formaldehyde, nitric oxide) as nutrients?
  - How do **microbial interactions** shape survival—are they **synergistic, antagonistic, or neutral**?
- **Bioaerosol Role in Atmospheric Processes**
  - What is the **functional role of bioaerosols** in:
    - **Ice nucleation**: How important are the effects of biological particles on cloud glaciation? Are proteins responsible? Do they need to be intact? What other macromolecules affect ice nucleation?

            - Are bioaerosols attached to dust more effective/important than without dust?
        - Cloud droplet nucleation: what role do bioaerosols play in warm cloud drop formation?
        - **Cloud processing**: Does biological content affect precipitation? Are bioaerosols physically or chemically changed by interactions with clouds? (e.g., rupture processes)
        - **Biogeochemical cycling**: Could airborne microbes represent an important nutrient transport pathway (e.g., phosphorus deposition in lakes: estimates suggests not important for N or C in most regions)?
        - PyroCb development
    - Does the **biological content of smoke** contribute to **superfog formation**?
    - How does **dust from deserts and wildfires** interact with bioaerosols? Or how important are desert and agricultural dust events or wildfires for bioaerosol emissions.
- **Microplastics and Bioaerosols**
    - Can airborne **microplastics provide a substrate or food source** for microbes?
    - Do they **increase microbial viability** in the atmosphere? More generally, how does the presence of other types of atmospheric aerosol alter microbial viability?
    - [comment: alternatively, may decrese microbial viability, but likely variable and species specific]
- Tracking the full cycle of transport from emission to deposition
    - Emission sources are hugely diverse and episodic and thus challenging to constrain
    - We do not have a complete picture of loss (aka flux) processes, especially wet and dry deposition

2. Barriers to Progress

- **Measurement and Sampling Challenges**
    - **Low microbial concentrations** in the atmosphere make statistical analysis difficult.
    - **Current samplers often kill microbes**—how can we preserve viability?
    - **Single-droplet characterization** is needed to determine if microbes are suspended with nutrients or water and the frequency of microbes in droplets.
    - **Difficult to sustain droplets in lab experiments** long enough to mimic atmospheric conditions.
    - **Lack of facilities** to study bioaerosol growth cycles under realistic conditions.
    - Under-utilization of natural “experiments” (emission events): need a field-ready interdisciplinary team
- **Modeling and Experimental Limitations**
    - **There are a hierarchy of models available, but usually focused on one type of bioaerosols….we are missing a comprehensive model that covers all bioaerosols**
    - **Mixed bioaerosol populations are poorly represented in models**—many assume homogeneous mixtures.
    - **Viability estimates in many models do not account for environmental factors** like radiation, turbulence, or humidity.
    - **Turbulence plays a major role** in emission, transport and deposition but may be difficult depending on the model scale May not capture some of the final spatial scales that lead to localized emissions and transport.

    - **Studies tend to focus on microbes with short replication times**, which may bias our understanding of airborne microbial life cycles.
    - Models are not currently sensitive to mechanism of emission- if any mechanisms are even modeled
- **Interdisciplinary Challenges**
    - **Lack of a shared vocabulary**—for example, does an "active" ecosystem require replication?, what is theory (or are the theories) for the different disciplines
    - **No standard methods for contamination control** during sampling.
    - Atmospheric microbiome studies often focus on a specific type of microbe and specific classes of microbes are regularly ignored. Specific examples of omitted microbes include **moss and fern spores, as well as viral phages**.
    - Few established opportunities for networking (people and infrastructure)

3. Opportunities for Advancing Knowledge

- **Developing Better Measurement Techniques**
    - Improve **cloud chamber facilities** to study microbial survival and metabolic processes in controlled conditions.
    - Create **a portable, inexpensive, gentle sampler** that maintains microbial viability.
    - Develop a **DNA extraction kit specifically for air samples**, optimized for microbial recovery.
    - Develop rapid detection for airborne pathogens of interest (of humans, animals or plants)
- **Enhancing Models and Atmospheric Understanding**
    - Use **niche modeling approaches** to identify atmospheric **microbial biodiversity hotspots**. How are aerobiome hotspots different than terrestrial hotspots?
    - Investigate which **atmospheric conditions** (e.g., prolonged stagnation events) allow for microbial community persistence.
    - Compare **bioaerosol properties of the same species across different geographic regions** to understand environmental influences.
    - Need to understand the relative importance of bioaerosols for climate and biogeochemistry: probably focussed on the role of bioaerosols as ice nucleating particles and phosphorus biogeochemical transports.
    - Need to understand the relative importance of the atmosphere for the transport of biotic material and the modification of microbiomes or ecosystem function.

- **Expanding Theoretical Frameworks**
    - Model using the GeoHealth or OneHealth framework for deeper insights of human-environmental feedback loop
    - Does the **atmosphere function as a microbial metacommunity** (ecosystem?) with structured ecological relationships?
    - Could **atmospheric biodiversity mirror surface and aquatic biodiversity hotspots**?
    - Investigate the **role of filtration sampling processes** in shaping microbial community structure—do only specific microbes survive?

4. Wild Ideas and Future Directions

- **Unconventional Sampling and Analysis**
    - Use **passive collection onto live cells** to track metabolic activity in the atmosphere.

    - Develop **spiked microbial standards** to test sampling and extraction efficiency.
    - Investigate the **impact of electrical charges on microbial interactions**, particularly for viruses.
- **New Conceptual Approaches**
    - Conduct **systematic atmospheric sampling** to determine the **true diversity of bioaerosols**, including fungi, spores, and viruses. [comment: in a spatially distributed network? what about vertical?]
    - Explore whether **high-stress, oligotrophic airborne environments** harbor specialized microbial communities.
    - Examine whether **the atmosphere contains endemic microbes** that have adapted to extreme conditions.

5. Key Themes Across the Discussion Groups

1. Microbial Survival and Function in the Atmosphere

- **Do airborne microbes remain viable and/or metabolically active?**
- **How do they interact with other atmospheric particles or gas-phase species?**
- **What role do atmospheric microbes play in cloud formation, cloud processing, and biogeochemical cycling?**

2. Measurement and Sampling Limitations

- **Existing methods often compromise viability**—new samplers are needed.
- **Microbial concentrations in the atmosphere are too low for many traditional approaches**—statistical techniques must be refined.
- **Cloud and droplet experiments are difficult to sustain long enough to provide realistic insights.**

3. Modeling and Atmospheric Transport

- **While there are a hierarchy of models available (from water drop to regional to global),they are usually focused on a specific kind of bioaerosols…We do no have a comprehensive model of all bioaerosols**
- —new approaches are needed to incorporate microbial interactions.
- **Turbulence, atmospheric stability, and humidity** play critical roles in transport but can be **not well constrained, depending on scale**.
- **We lack niche models for predicting microbial biodiversity patterns** in the atmosphere.

4. Theoretical and Experimental Advances

- **Applying biogeography and metacommunity theories** could improve predictions of airborne microbial communities.
- **Niche modeling could help identify atmospheric biodiversity hotspots** and predict where viable microbes persist.
- **Understanding filtering mechanisms** could help explain which microbes survive transport and deposition.

Breakout 4:
Summary of Methods and Standards

1. Knowledge Gaps and Research Needs

- **Standardized Methods and Best Practices**
  - There is **no universally accepted standard method** for bioaerosol collection and analysis, making cross-study comparisons difficult.
  - Different analyses are appropriate depending on whether you need **identification or quantification.**
  - Methods should be optimized based on **sample type, size range, and research goals** (e.g., molecular, imaging, culture-based).
  - A **decision tree** could guide researchers in selecting appropriate sampling techniques based on downstream analyses.
  - Need for a **comprehensive manual** (like CRC's for other fields) to establish best practices in bioaerosol research.
  - **Lack of microbial reference standards** relevant to bioaerosol research.
  - **Benchmarking standards for novel instruments** are still investigator-dependent.
  - We lack good spatial and temporal coverage of different bioaerosol types.
  - We don't know how much air needs to be sampled to fully capture "what's there".
  - Do repeated smaller-volume samples add up to single long-duration samples? Why or why not?
- **Bioinformatics and Analytical Challenges**
  - **Many research groups lack dedicated bioinformaticians**, making data analysis a major bottleneck.
  - Bioinformatic pipelines vary, so there may be biases in results.
  - **Genotyping requires high sample purity**, but computational tools could help overcome this challenge.
  - **AI-based analysis** could speed up bioinformatics workflows and improve identification and sequencing analysis. [comment: AI isn't quite there yet for developing bioinformatic workflows and analyses itself, but automated and standardized workflows is a great idea]
  - **Viral taxonomy is underdeveloped**, with more focus placed on bacteria and fungi—what about slime molds?
  - Do **sample diversity and richness metrics** developed for soil and water microbiomes apply to air microbiome, or they need to be modified?
- **Sampling Optimization and Device Integration**
  - **Personal samplers** could provide **personal exposure** and potentially **high spatial resolution** but need development and better characterization.
  - Need **high-efficiency DNA extraction kits** optimized for air samples.
  - Optimizing **sampling** remains a challenge, especially in new outdoor environments, and differs for single-particle microscopy vs. bulk loading
  - **Coarse particle issues**—many samplers are designed for fine particles, but larger bioaerosols (e.g., large fungal spores, pollen) require different inlets and collection techniques.
  - Need specific samplers optimized for ultrafine bioaerosols

- **Water and salinity interactions** in sampling bioaerosols, particularly viruses and bacteria, need more investigation.
- Is it possible that cheaper and relatively commonly measured elements (e.g. P, K) can provide some insight into whether bioaerosols are present?
- Specific conditions require specific samplers- how this impacts results is not characterized

2. Barriers to Progress

- **Technical and Logistical Challenges**
    - **Contamination** remains a pervasive issue in sequencing-based studies. [comment: We've implemented a variety of process negative controls that might be a helpful recommendation to standardize across the field]
    - **Temporal resolution** in sampling is challenging due to the time, cost of sample analysis, and sampling logistics.
    - **Sampler inlets need to be optimized for coarse particles**, requiring improved sampling technology.
    - Sampler inlet sensitivity to wind direction and speed
    - **Inlet size issues**—not all samplers capture the full spectrum of airborne biological particles and even if the instrument is designed to capture a large size range the geometry of inlets and flow rates may limit the observed size distribution, also collection efficiency is affected by wind speed, so these challenges can be moving targets in outdoor environments
    - **Electricity requirements**, battery limitations, and manual sample change out for samplers can limit deployment in remote areas.
- **Storage and Data Sharing Issues**
    - **Cold storage is expensive** and essential for preserving bioaerosol samples—this limits long-term studies.
    - Many researchers **do not submit sequences to public databases**, making data sharing and meta-analysis difficult. (also not all relevant metadata, such as sampler type and flow rate, may be recorded and shared; collection efficiency is rarely reported/discussed)
    - [comment: one model for a shared databases is from the oceanography community: https://www.bco-dmo.org/]
- **Interdisciplinary and Funding Limitations**
    - **No centralized bioaerosol network exists in the USA**—efforts are fragmented, and there is no coordinated, large-scale data collection.
    - **Funding bioaerosol networks is difficult**—they require long-term support, but no agency has committed resources.
    - **Training gaps**—many new researchers entering the field lack foundational knowledge in best sampling and sequencing practices as well as how to lead and participate in interdisciplinary, collaborative research (the latter is true for early and later career researchers!).
    - The goals of the various bioaerosol communities can vary widely making unified sampling approaches challenging.
    - Historical shifts in funding and research focus—interest in bioaerosols surged after 9/11, dipped, then resurged during COVID-19, but funding remains inconsistent.

3. Opportunities for Advancing Knowledge

- **Intercomparison Studies and Training**
  - Conduct **a large-scale sampling intercomparison study** across research groups to compare methods.
  - [comment: Are there aerobiome-relevant standards (whole cell and DNA)? It would be great to have those for intercomparison studies. There are standards for fecal samples, soil samples, etc. but I'm unaware of any for aerobiology studies.]
  - Establish **training workshops** for graduate students and early-career researchers to learn best practices in bioaerosol sequencing and analysis as well as how to conduct interdisciplinary, collaborative research.
  - Develop a **visual workflow guide** illustrating research questions, optimal methodologies, and common pitfalls.
  - **Active vs. passive sampling comparison**: An intercomparison study of samplers would help prescribe the best tool for each biological question.
- **Technology and Infrastructure Development**
  - Create a **Swiss Army knife-style sampler** that integrates multiple collection methods.
  - Develop a **passive sampler with viability detection** (e.g., cells embedded in medium to assess growth).
  - Investigate the use of **epigenetic markers (e.g., DNA methylation)** as a potential surrogate for microbial viability. [comment: possibly, develop additional non-DNA-based assays for detection (molecular markers?)]
  - Establish **a centralized bioaerosol center** that integrates research, data sharing, and training. Also could consider development of large-scale shared-use facilities for interdisciplinary studies of processes (analogy of the wave chamber at UCSD, might include computing)
  - [comment: there are also centers to simulate space conditions or Mars conditions that could be of potential interest.]
  - **Single-droplet characterization** is needed to determine if microbes are suspended with nutrients or water and the frequency of microbes in droplets.
  - Massively distributed long-term sampling networks using low-cost samplers
  - **Organoids (e.g., lung-on-a-chip systems)** could be used in field studies to assess biological responses to airborne biological particles.
- **Leveraging AI and Automation**
  - **AI-powered image analysis and automated slide readers** could improve efficiency and standardization.
  - **Quick screening tools** could allow for **on-the-spot sample comparisons** to identify related samples.
- **Networking and Collaborative Efforts**
  - Encourage interdisciplinary collaboration between **atmospheric scientists, microbiologists, and engineers** to develop better sampling and analysis tools.
  - Expand bioaerosol **monitoring networks** to include **personal samplers** and high-throughput sampling strategies.
  - Citizen science contribution?
  - Standardize reporting of **size detection ranges, sampling techniques, and associated uncertainties** in all publications.
  - Formation of working groups / communities to keep up with rapid advancements.
  - Include a retrospective perspective in published report, i.e. assess progress since other similar workshops and past efforts to coordinate interdisciplinary momentum and progress within the bioaerosol field – and the barriers that have limited their achievement of those goals.

    - Leveraging data and experience from BioWatch network (https://www.dhs.gov/sites/default/files/publications/BioWatch%20Factsheet.pdf).

4. Wild Ideas and Future Directions

- **Multi-functional sampling devices** capable of capturing a broad range of bioaerosols in **one integrated system**.
- **A universal bioaerosol network** with standardized protocols and long-term funding. [comment: what would an atmosphere focused LTER or NEON system look like?]
- **Bioaerosol-specific training programs** to build expertise in the field.
- **Industry partnerships** to develop field-deployable organoid models for bioaerosol exposure studies.

5. Key Themes Across the Discussion Groups

1. Standardization and Best Practices

- **No single method fits all bioaerosol research questions**—a decision tree or manual is needed.
- **Intercomparison studies** can help define best practices across different sampling techniques, storage conditions, and measurements.
- **More explicit reporting in publications** is necessary for method transparency and reproducibility, including positive and negative controls, collection and extraction efficiency, and measurement uncertainty. Sequence data deposition also should be a minimum.

2. Data Analysis and Bioinformatics

- **AI and automation could streamline bioinformatics workflows** and improve large dataset processing. [comment: repeated (again) from bioinformatic sections above, automation is a great idea but this development in AI is going to require the larger buy in from bioinformatics field more generally]
- **Genotyping and sequencing challenges**—contamination and purity issues need to be addressed.

3. Sampling and Measurement Improvements

- **A need for passive samplers with viability detection**.
- **Optimization of sampling** across a wide range of particle sizes (from viruses to large bioaerosols)).
- **Integration of in situ detection and sampling in a single device**.

4. Infrastructure and Collaboration

- **Lack of a centralized bioaerosol monitoring network**.
- **Funding and support are required for long-term bioaerosol studies**.
- **Interdisciplinary collaboration is critical for progress in this field**.
- Development of large-scale shared-use facilities for interdisciplinary studies of processes / data analyses

Appendix 6

This section provides the unedited responses (20 responses) to the post-workshop survey.

Workshop feedback: Which parts worked well? What was your favorite part(s)?

- I thought the size and overall format were ideal. We got to hear from everyone in a formal way but also had time for more open ended discussion.
- Breakout sessions of workshop worked really well, definitely the favorite part
- This was such a fulfilling workshop. The format worked great. It kept engagement through a lot of material. We got to hear from everyone, whether a long talk or lightning talk. The long talks were very digestable at 20 min length. My favorite part was the people.
- All of it was really well organized.
- I enjoyed the discussions and the multiple short talks.
- The initial questions that were sent--they helped shape the workshop. My favorite part was hearing from and meeting new people working in other fields.
- I thought the format of a longer talk and several lightning talks has helpful in keeping engaged in the topics
- Everything went really well. I liked the breakouts.
- Lightning talks as it presented short overview of what people were doing and why they were there.
- The small discussion groups were my favorite part of the workshop. The discussions were informative and respectful, and it seemed like each group had a nice splitting of expertise. It was interesting to see the common themes, and the ideas that only one or two groups noted. I also really appreciated the longer talks on topics that were not part of my research expertise. In particular, I thought Gedi's and Scott's talks on methods were both really interesting.
- This was well organized. Just wish we had time for a two questions after the 5min talks. Maybe switching the groups around just for networking purposes But over all, Good mix of subjects and scientists.
- The lightning talks coupled with plenary talks and subsequent discussion was a very effective format that established some state of the science content, new ideas, and useful discussion prompts.
- The logistics and organization went very smoothly. I enjoyed hearing from all participants through lightning talks and plenaries, as well as opportunities for further discussion in breakout groups and breaks.
- I liked the idea of a 15 min plenary and short lightning talks. I wish there was more time for Q&A after presentations, before we went into breakouts. I really liked the intro part Tuesday evening.
- It flows very well, and everyone sticks to the timeline. Organizing the talks by themes is great. Ample time to interact with participants to brainstorm ideas and to bond. Organizers are in great control of the flow and the workshop is really organized.
- Breakout group discussions. Interdisciplinary groups. Favorite part: meeting new people!
- I think that the breakout sessions were effective as was the presentation format (longer talks + lightning talks)
- The break-out discussions were very useful and efficient.
- I thought the organization of the meeting was excellent. The organizers planning everything very well to make the use of time extremely efficient. I was impressed.

What did not work as well? What would you have liked to have seen added/removed/condensed? Were there any key missing areas?

- The breakout discussions felt a little repetitive. It might have been good to shuffle groupings around or have more clear/distinct tasks to work on for each one. It felt like we had a rushed conversation in the first one that touched on most things and then subsequent conversations started with "we kind of already talked about this".
- I didn't get much out of lightening talks, the longer talks were great to see the bigger picture and gaps, but the lightning talks were too short a glimpse to see any real insight.
- Very minor, but rotating the break out groups may have helped spur extra ideas.
- All of it was great. Maybe a little bit longer? but 1.5 days was good too.
- Nothing stands out to me here, aside from maybe changing break out groups more to discuss with a wider range of people?
- It might have been better to condense the questions down into fewer sessions as much of the discussion was overlapping. Perhaps we could have gotten thru all discussion on Day 1 and then used Day 2 to discuss next steps and the key gaps.
- I don't have any substantiative complaints
- I would have like to change the breakout groups for each session to facilitate more varied interactions. By the last breakout it seemed like we didn't have as much to discuss (even though the topic was different). It would have been nice for the organizers to also present.
- Some of the "plenary" talks as the presenters focused too much on the presenter research or their view point pet peeve.... It would have been more helpful to provide a broader overview to set up the break-out sessions. While it could have been way worse, this was still too much self-centered for some of the talks.
- I thought the discussion groups could have used more time. The breadth of the topic was so wide that it often felt like we were just getting started and then the session would be over. Maybe another 15 or 30 minutes?
- No issues
- The only thing I would have suggested was done differently would have been to change the composition of the discussion groups to promote additional interactions and perspective sharing. I felt that I only really got to hear extensively from one sub group of people.
- I think I would have liked the breakout groups to change halfway through, in order to have more interactions with others in the workshop.
- Maybe it was unavoidable, but the four sessions overlapped quite a bit. I think a session on the role of bioaerosols in atmospheric processes would have been helpful, given the overall topic.
- It would have been great to have experts from health care and agriculture to participate.
- Mixing up the breakout groups on different days might have been nice to have more in-depth discussions with different people.
- No key missing areas in terms of research. But it would have been nice to have read your proposal text (or part of it, or perhaps just a charge/mission statement) before the workshop.
- Although I liked the location, it was a little tiring to spend all day in the same building. Perhaps incorporating a 30-min reflective walk outside (assigning pairs to walk & talk) would have helped with the post-lunch slump.
- I missed getting to know the people who were in other subgroups. I understand the reasoning behind this, but it was a shame. Maybe there could have been additional opportunities for mixing it up in the evening.

What were your key takeaways? We would appreciate hearing any specific examples of how you might change or add to your research plans/directions as a result of connections you made or things you learned at the workshop.

- New potential collaborations are awesome. I have more ideas for how to get good microbial data for a project even though that's not my specialty. Reinforced my interest in this topic when it can sometimes feel isolated.
- Hoping to add more aerosols to my sequencing portfolio, but need collaborator for this
- I have a better idea of how I could retry air sampling for pathogens after hearing from other researchers and understanding what tools folks are using. I made a connection with a modeler who was excited to help me incorporate my data into a transport model. I understand where to best find the scientific information on bioaerosols I am looking for and whose work to follow.
- So many ideas! I'm in contact with lots of folks for more follow up.
- I suppose that thinking of the atmosphere as an ecosystem held general novelty? And more logistically, additional conferences and journals that might be of interest to the larger team I am working with.
- It was also interesting to learn how much terminology differed. For example, I think if you asked everyone to define bioaerosols and the best method to quantify them you would get 30 different answers.
- Key takeaways are how we are all doing things differently. Huge effort but very little coordination on sampling, processing, and lessons learned.
- I was most interested in hearing how bioaerosols impact climate. I though Allison's talk was great, but beyond that, I'm not sure I saw a ton of evidence or compelling data on climate influence...other than some very interesting fundamental questions about microbial activity in air
- Communication across disciplines could use some work in the bioaerosol community. By then end of the workshop it was clear to me that we all have slightly different goals that fall along a similar trajectory at varying degrees of specificity.
- I was blown away by the differences in aerobiome results depending on the samplers. This was the single thing standing out. I was already aware of the kitome. It was also interesting to see the variety of bioaerosol people, some I will certainly contact and who work on pollen, fungal pathogens or algae, so not limited to bacteria.
- I was very surprised to hear just how inconsistent the DNA sampling was, and filled with artifacts and/or potentials for contamination. Another note I had was that I don't know if we came up with a satisfactory way to ensure that the really targeted measurements of species could be used to inform the work of people working at much larger scales. Is there an answer, I don't know?
- I learned that Bioaerosols has not advanced as much as other technical areas and more efforts are needed to combine manufacturers and scientists needs. The cross over of the key areas still seems to be isolated. This needs to change. I was surprised that many folks are not involved at a much larger level of collaborations. In genomics, it seems nearly all research progresses thru larger collaboration to address entire "systems". When heard that some folks generate manuscript solely from within there own labs, with just PI and students, I was surprised.
- Key takeaway: we have the same questions and face the same challenges in bioaerosol research, and broadly agreed about the cutting edges and contours in need of attention. This suggests that the group that was assembled well-represented the state of the science, and were quickly able to fill in the gaps in other participants' knowledge so that our discussions could hone in on the frontiers and critical research needs, including methodology, theory, and implications. My brain is still spinning with the (enduring) questions related to the existence of an aerobiome, and how we would define its ecosystems given the complexity of identifying boundaries and flows of energy and matter across boundaries and into/out of the aerobiome. I've started a list of potential "principles of aerobiology" and would love to have others join in the brainstorming. As far as research plans, I will be following up with multiple workshop participants to identify new

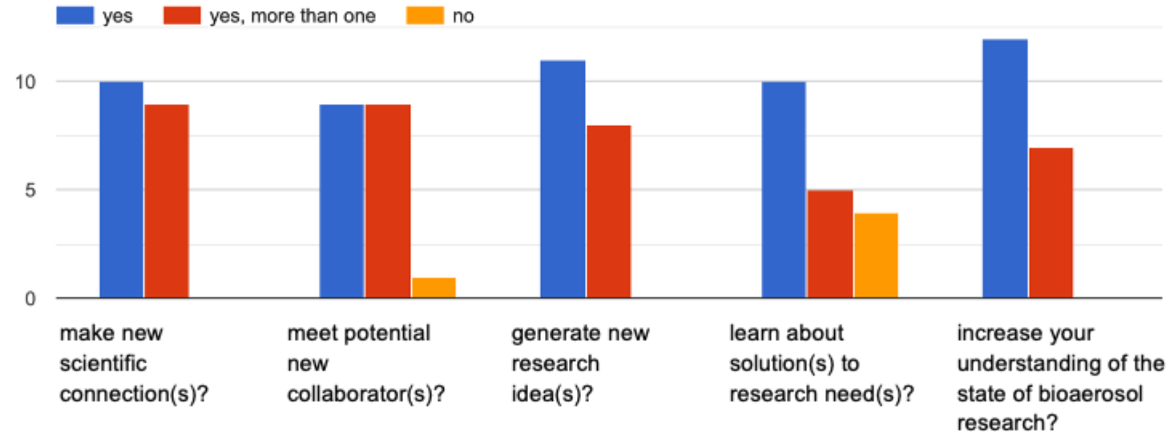
opportunities for utilizing large-scale and predictable emission events to advance understanding of bioaerosols emission/transport/function/deposition "lifecycles". There are many ideas that I think could be implemented in upcoming burn experiments even as soon as this spring. I'm already in discussion with a new collaborator to input new bacterial and fungal emission factors from wildfires into global-scale atmospheric process model- this is something I've wanted to do for years!

- Genomics is advancing very quickly and is a powerful tool to utilize in aerobiome studies. An important limitation is that too many studies focus on a particular bioaerosol class, limiting a comprehensive understanding and evaluation of the atmosphere as an ecoysystem.
- Bioaerosols is a complex topic... It was helpful to hear about various techniques that people are using and various bioaerosol aspects people are exploring.
- Compared to bacteria and fungi, we lack data about the very small and very large bioaerosol particles (viruses and pollens). Tools to efficiently sample and characterize them are not as robust as those for bacteria and fungi. (2) Need to proactively engage different communities. (3) Is the atmosphere itself an ecosystem, not just a transport medium? Are cloud/fog a microbiome?
- I met some new people from different communities, especially in biology. e.g., set up a meeting to discuss relationships between pollen and ecological masting events. Also really liked hearing about how different communities assess/investigate.
- Folks want "best practices" and "standardization", however, this is not novel as past reviews have pointed it out in the past - how can a product from this workshop be different and lead to action?
- Though I was aware that atmospheric microbiome measurements are complicated, I think it was very illuminating to think about that we may miss a large fraction of them since we don't look in the right size range.
- It was really useful to learn about gaps. I had wrongly assumed many things were known and that opened up a lot of opportunity for new ideas.

Any feedback on logistics?

- Logistics were great. Very smooth, kept us occupied but not rushed. AMAZING FOOD!
- No, everything went smoothly!
- Logistics good: I thought the caterer was especially good. The building was good.
- Logistics all good.
- no, I thought it was a very well run meeting
- None.
- Excellent. The quality of the catered food was one of the best I ever saw for such events.
- No issues
- Beautifully executed. I can't thank you enough for enabling my participation via zoom.
- I did not have a great experience at the hotel - a few minor issues with housekeeping and the front desk. The location was very convenient! :)
- Heidi did a great job with all the bookings.
- Logistics were so thorough and Heidi is amazing.
- See my previous comment on an outside walk.
- It was perfectly organized.
- None!

As a result of the workshop, did you:



Any comments / expansion on the above?

- This was very rewarding for me as an early career scientist. Thank you very much for inviting me.
- I loved meeting new people across disciplines.
- There appears to a great need for collaborations to address "systems". Since grants thru NIH for example, are systems biology as directed, I don't see that in the bioaerosol space. This is the same issue we had in the mid-90s with bio aerosols. People did their own thing. Rarely connected. And I saw the field diminishing because of this.Therefore networking is probably the most critical piece to get this discipline to the same level there's other fields. This was one of the reasons we started putting together these virtual groups such as WhatsApp. People might think of them as silly social media outlets however the NIH recognizes these to be now a critical element in communication among diverse groups.. While some see networking as non-profit and non-productive, it is a critical part of getting collaborations going. I could go on and on about this, but I think this group was a good start. Well done indeed. The question is if NSF finds Bioaerosol as an important next discipline and if they can support it.
- I think we might have benefited from a "solutions" closer, where we took a list of the challenges and gave everyone a chance to opine on how they dealt with them. We could have each person volunteer to be the "go to" resource on something in particular, something narrow so no one is over-taxed but we create a community to help our science move forward. Some lightning or plenary talks had great ideas, but we didn't have time to learn enough about them. This might, however, be the subject of an entire workshop, itself.
- Great group of people!

Any additional comments regarding the sessions or overall agenda?

- The organizing committee was thorough and thoughtful. They truly made this a success with their planning.
- The talks were all excellent.
- This was overall great! Quite intense but useful. The only minor thing I would thing that could be changes is have the plenaries more focused on the breakout sessions and like this set them up as to no have that separation plenary and then a moderator giving instructions.
- Just adding a day to expand the agenda. I like the idea of 10 minute talks with more people and more diversity in the science but other than that this was excellent
- Very smoothly run, impeccably organized.

- I liked that there was a mix of expertise, including "bioaerosol-adjacent." It shows the breadth and impact of the topic.
- Some of the themes were a bit redundant, but I think we moved around this effectively.
- The agenda was very well designed - a good mix of informative, multidisciplinary talks and interactive discussions
- It could have been more days, but I understand then it's hard to get people to commit.

Any suggestions for maintaining momentum? Please indicate if you are potentially willing to lead (L) or participate (P) on a subgroup (and which one(s)) to coordinate follow-on communications (and add your name). We particularly encourage early-career scientists in the field to use this as an opportunity to take a leadership role in helping lead their favorite area.

- I would be willing to either lead or participate in the subgroup about the atmosphere if that was helpful.
- I can help pitch a Union Session for AGU. This could be co-organized with GeoHealth, Atmosphere, and Biogeosciences. We could use this as a way to invite people from our group as panel members to discuss their research who have never been to AGU (Bala mentioned she was interested). It would be great if 1 of the 3 organizers could report on our workshop and findings. Session proposals should be solicited around April.
- I am happy to be involved in subgroups that are Activity or ecology related.
- We need subgroups to keep talking with a goal for how we can advance the field. So often in these workshops we get to a point that exposes holes--how can we build bridges to keep the efforts that went into this workshop going? I believe there are many younger folks that would step up and help keep things going. It does not have to fall on the organizers.
- Willing to participate but I do not see myself having the bandwidth to lead anything.
- I would be willing to participate in the atmosphere processes subgroup.
- I believe what the outlined on our last day was good and I am happy to participate and help drive this forward. I still think It would be good to have some people join in the WhatsApp group if they wanted just to have and open discussion pipeline available. We could change the name of it as you all see fit. You may have the administration oversight of it as well. I'm just trying to get collaborations and discussions from people from one side of the country to the other by some small effort. But yes I am happy to participate
- I'm interested in participating and potentially leading...not sure what sub groups we are selecting from. As I mentioned above, I'm interested in two major things: experimental opportunities (including both field-based and laboratory work) to test hypotheses, and the development of guiding principles/truths about the state of knowledge in aerobiology. I'm not early career, but with regards to research in bioaerosols and microbiology, I'm probably newer than most!
- Would like to participate in measurements / methods subgroup
- Something like community of science with periodic seminars and maybe meetings. I would be willing to Lead a subgroup on sampling tools and practices.
- Webinars and manuscripts (editorial/viewpoints). I'd like to participate in the coordination of the pathogens and methods subgroups.
- I'd be interested to both lead and participate. Unclear how the subgroups will be organized (e.g., as in the breakouts?) post-workshop, so some guidance on that would be helpful!
- Would like to participate in measurements / methods subgroup
- I would love to initiate a group on model development to describe biological processes and processing in atmospheric models of different scales.

- I am interested in efforts that build ecological theory into research on bioaerosols. I don't think I could lead this right now, but I would love to participate. I am also interested in participating on work that focuses on fungi and human health.