FEATURE

A Role for Environmental Engineering and Science in Preventing Bioaerosol-Related Disease

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Environ. Sci. Technol., 42 (13), 4631-4637• DOI: 10.1021/es087179e • Publication Date (Web): 01 July 2008

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Environmental technologies and modeling approaches must be coupled with public-health efforts and microbiological research.

Exposure to various airborne allergens, pathogens, and biotoxins increases as a consequence of flooding. Airborne mold levels from a recent baseline study of homes flooded after Hurricane Katrina meet or exceed the levels found in cotton mills and concentrated agricultural environments.

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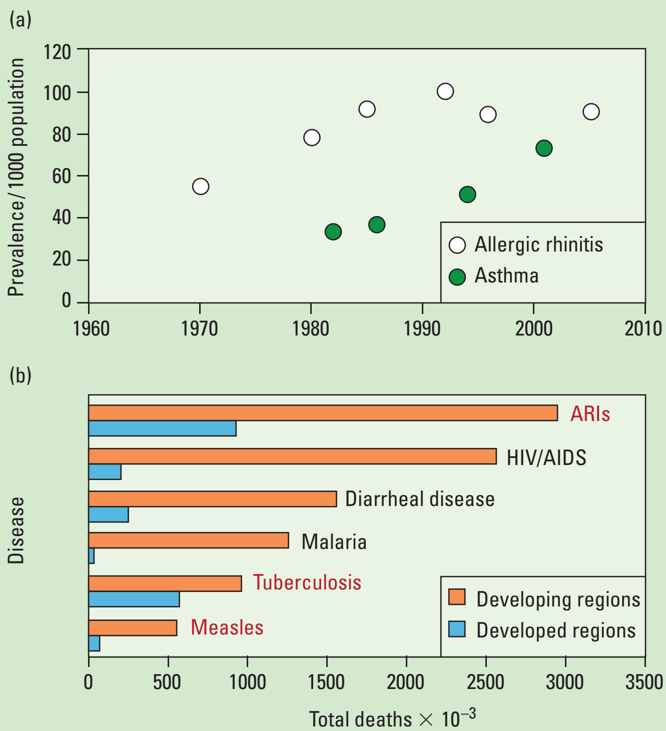
Through allergies, asthma, and infectious disease, biological aerosols are associated with a tremendous global health burden. Environmental engineers and scientists have important roles to play in mitigating this burden, but airborne biological agents present challenges that are different from those engineers faced in controlling waterborne disease in the 20th century. Biological aerosol sources are both environmental and human, the airborne exposure route is poorly established, dilute concentrations preclude quantitative exposure assessment of etiological airborne agents, aerosol treatment may only partly interrupt exposure, and there are no environmental regulations to guide and promote research and intervention.

Mitigating and preventing environmental exposure to bioaerosols will therefore require a broader approach in which engineers forge stronger collaborations with public health and social sciences and integrate biotechnology with aerosol science. This article describes the present and pending health and environmental burden associated with bioaerosols, explains why environmental science and engineering are appropriate disciplines to address these and other problems associated with bioaerosols, delineates the disciplinary and technological barriers as well as opportunities facing environmental scientists and engineers in this field, and describes the new technologies and synergistic collaboration that may assist in meeting these challenges.

FIGURE 1

Incidence and leading causes of death

(a) Increasing incidence of allergies and asthma in the U.S. Data are compiled from Refs. 34 and 35 and include children and adults. (b) Leading causes of death from infectious disease. Data from Ref. 36. Bars with red text represent diseases linked to bioaerosols. Developing countries are represented by high and very high mortality strata (population 2.4 billion), and developed countries are represented by regions with low and very low mortality (population 3.4 billion). Deaths from ARIs do not include tuberculosis or measles deaths.



The global health burden of airborne biological disease

Bioaerosols are composed of viable and nonviable microorganisms, allergenic particles, plant and insect debris, microbial toxins, and viruses that are suspended in air. Their concentrations in the atmosphere are significant. An estimated 16% of the mass of primary atmospheric aerosols is from biological sources (*1*), and biological content ranging from 4% to 11% of the total mass in $PM_{2.5}$ (particulate matter less than 2.5 μm in aerodynamic diameter) has been described (*2*). Although airborne biological agents have been implicated in chemical and physical atmospheric processes that influence climate (box on p 4633), their association with infectious and noninfectious disease constitutes their most profound human impact and is the focus of this article.

Airborne biological allergens, fungi, thermophilic actinomycetes, endotoxin, and (1 → 3),β-D glucan are associated with noninfectious airway diseases such as allergies, asthma, and hypersensitivity pneumonitis. In the developed world, allergies and asthma are a major cause of illness and disability. Up to 35 million of the 40–50 million Americans who suffer from allergies are sensitive to airborne allergens. Airborne biological allergens can trigger asthma attacks in 60–90% of asthmatic children and 50% of asthmatic adults (*3*), and there is broad consensus that allergy and asthma prevalence increased during recent decades (Figure 1a). Areas of highest asthma prevalence and greatest increase are urban settings (*4*). With the fraction of global urban population projected to increase from 45% to 59% by 2025, the associations between asthma and the urban environment may become even more profound (*5*).

The global health burden of infectious respiratory disease is even larger than that of allergy and asthma. Three of the top 10 causes of death in the developing world are linked to airborne pathogens (Figure 1b). Acute respiratory infections (ARIs) (including bacterial and viral pneumonia, influenza, tuberculosis, and measles) are the leading cause of death from infectious disease, outpacing both AIDS and diarrheal disease, and most commonly affecting children under the age of five (*6*). Roughly one-third (more than 2 billion people) are infected with the tuberculosis-causing bacterium (*Mycobacterium tuberculosis*). Respiratory infections in the developed world are seldom fatal, and etiological agents are different; however, there are similar rates of infection (4–6 per child per year). More than 1 billion acute respiratory infections occur per year in the U.S. (*7*). This level of morbidity far exceeds those of infections caused by food-borne pathogens (by 10 times) and drinking-water-borne pathogens (by 10,000 times) (*8*, *9*).

Bioaerosol research is within the realm of environmental engineering and science

Human exposure and response to airborne biological agents can be mediated by the environment through interactions with indoor and outdoor aerosols, global environmental change, and anthropogenic activities that emit pathogens directly into air. Table 1 (on p 4634) summarizes relevant environmental research questions associated with bioaerosols.

Indoor and outdoor air quality. Environmental hypotheses proposed to explain the rise in asthma and allergies include effects of increased or altered human exposure to airborne allergens and interactions between airborne allergens and pollutants such as tobacco smoke, NO_2, SO_2, ozone, respirable particulate matter, and diesel emission particles. These interactions may increase allergen potency or pathogen infectivity. For example, the presence of NO_2 and ozone in the atmosphere nitrosates the amino acid tyrosine (leading to 3-nitrotyrosine residues) and causes an increase in the protein's allergenicity to humans (*10*). Sorption of microbial toxins and pathogens to black carbon, diesel emission particles, or other organic and inorganic particulate matter may concentrate biological mass and influence the particle size distribution—affecting environmental fate and transport, aerosol sampling efficiency, and lung deposition properties (*11*). Concurrent exposure to organic matter, metals, and endotoxins in indoor and outdoor aerosols may provide an adjuvant effect, thereby enhancing the potency of inhaled allergens and increasing the susceptibility to infection (*12*). Specifically in the indoor environment, moisture is the environmental parameter most strongly correlated to respiratory health effects (*13*). The significance of moisture on specific causative agents has not been resolved; however, microbial growth and survival are certainly important contributors, and efforts are under way by the World Health Organization to establish guidelines for dampness and mold in indoor environments (*14*).

Bioaerosols and clouds

Biological particles are common throughout the lower troposphere, exist in the upper troposphere, and have been detected well into the stratosphere at 40 km above sea level. They are in raindrops, clouds, snow, and hail, and their surface characteristics make them effective cloud condensation nuclei (CCN) and ice nuclei. Evidence is now emerging that their presence in the atmosphere may influence climate. An estimated 1000 Tg/year of biological particles are emitted as primary aerosols—a substantial fraction (16%) of total primary particles (*1*). Moreover, researchers have estimated that bacteria and microalgae, as well as extra polymeric substances produced in oceans, are released by bubble bursting and form a significant fraction of CCN in the Arctic (*37*), and up to 65% of primary particles over the ocean during planktonic blooms are organic macromolecules (*38*). Finally, a report on the atmospheric microbial degradation of monocarboxylic and dicarboxylic acids that act as CCN in cloud samples indicates potential secondary effects of microbial activity (*39*). These recent findings suggest an important role of bioaerosols in cloud production and, by extension, a potential influence on global climate.

Environmental change. Predicted and measured changes in global climate such as higher rainfall, extended growing seasons, and greater levels of CO_2 have resulted in reports of increased fungal growth (*15*) and have been associated with elevated pollen production in ragweed (*16*). Changes in global ecosystems may also cause the emission of bioaerosols that affect both human disease and environmental degradation. One important example is the extended drought, overgrazing, and drying of Lake Chad, which has contributed to the tremendous emission of dust laden with bioaerosols from the Sahel regions of Africa. This dust is transported by prevailing winds to the Caribbean, where it has been linked with increased asthma rates in humans and the introduction of pathogens suspected in die-offs of coral reef sea life (*17*). One ecological study estimated that ~20% of the species identified in these dust storms could cause disease in plants and animals and that ~10% were known opportunistic human pathogens (*18*). Recently, climate models have predicted increased aridity in the southwestern U.S. to a level similar to that of the 1930s Dust Bowl years (*19*).

Anthropogenic pollution as a source of pathogens. A final important association of bioaerosols and the environment is the aerosolization of biomass through anthropogenic activities. Pathogens and other antibiotic-resistant microorganisms can be dispersed through common agricultural activities, including concentrated animal feed operations (CAFOs) and land application of agricultural waste and biosolids. A relevant exposure route in this case is gastrointestinal infection through aerosol capture in the upper respiratory tract, where microorganisms are then moved by ciliary action and passed into the digestive tract through the pharynx. Recent evidence lends strong credibility to aerosol-mediated *E. coli* O157:H7 infection near concentrated livestock operations (*20*) and airborne norovirus infections in indoor environments (*21*). Exposure to *Legionella pneumophila* from showers and air conditioning systems causes an estimated 8000–18,000 infections in the U.S. each year—roughly equivalent to the reported amount of cases caused by infection from drinking water.

An underdeveloped environmental and public-health research field

Given the environmental and health significance of bioaerosols, the limited development of this field by environmental scientists and engineers seems strange. There are at least three reasons for this. First, exposure to bioaerosols is mostly indoors. As a consequence, there are no direct regulations and few guidelines to drive science and engineering to reduce disease prevalence. For most airborne diseases, therapeutics rather than environmental prevention are now considered the dominant solution. Second, atmospheric science researchers are classically trained in aerosol physics and chemistry to address the industrial discharge of particles and chemical toxins. The skill sets to perform both aerosol and biological research are rare. Atmospheric scientists infrequently consider the biological fraction, whereas aerobiology studies often undervalue the important physical and chemical characteristics of particulate matter. The third reason is a matter of microbiological paradigm. Modern epidemiology, microbiology, and environmental engineering were in part based upon the idea that disease is not caused by something in the air. Before observations

TABLE 1

Bioaerosols and environmental research

Allergy/asthma	**Topic:** Noninfectious airborne diseases such as respiratory allergies, which can exacerbate asthma, are prevalent, and have increased dramatically during recent decades. **Research Questions:** • What synergistic or antagonistic impacts do chemical and particulate air pollutants have on human response to airborne allergens? • Is climate change affecting the amount and potency of airborne allergens? • How can changes in building design, installation of control systems, and maintenance affect exposure to indoor bioaerosols? • When are bioaerosol exposures beneficial, and when are they hazardous?
Acute respiratory infection	**Topic:** ARIs kill more children worldwide than diarrheal disease. One-third of the global population has been infected with *M. tuberculosis*. SARS and bird flu are at least opportunistically aerosol-transmitted infections. **Research Questions:** • For which ARIs does aerosol transmission play a significant role? • Under what circumstances do aerosols contribute significantly to transmission of influenza? • How effective can indoor treatment systems and personal protection be in reducing transmission of influenza and other respiratory infections? • How well can low concentrations of etiological agents be measured in the atmosphere and indoor air?
Global climate	**Topic:** Bioaerosols influence cloud formation, which in turn influences climate (also see box on p 4633). **Research Questions:** • What species of microorganism and their cellular components form cloud condensation nuclei (CCN)? • What atmospheric reactions do microorganisms catalyze that influence the formation of ice and clouds? • What is the global impact of bioaerosol-derived CCN?
Airborne particulate matter	**Topic:** In combination with abiotic components, the biological component of particulate matter is associated with asthma and other respiratory health problems. **Research Questions:** • What are the relevant size distributions of biological particulate matter/allergens? • What are the dominant sources of indoor biological particulate matter? • What is the impact of bioaerosol deposition, building penetration, and resuspension in indoor environments? • What percentage of organic particulate matter is of biological origin? • What are the health effects of this fraction? • Can abiotic and biotic particles interact in the atmosphere in such a way that health impacts are increased?
Global dust	**Topic:** Deforestation and climatic and environmental changes have contributed to the production of greater amounts of fugitive dust released from Asia and Africa. **Research Questions:** • Can microorganism DNA sequences or other methods be used to track sources and eventual deposition of dust? • What is the role of the biological content of dust in increased allergy and asthma incidence in affected areas, as well as in agricultural, aquatic, and human infectious disease?
Domestic and agricultural waste	**Topic:** Human domestic and agricultural activity produces aerosols containing pathogens, biotoxins, and antibiotic-resistant bacteria. **Research Questions:** • What are the aerosol sources of and exposures to *L. pneumophila*? • Can land application of biosolids and concentrated animal feed operations result in acceptably low risks to workers and nearby residents?

in 1854 from which John Snow deduced that cholera was caused by something in water, the dominant theory was that "bad air" or "miasmas"—poisonous vapor containing foul-smelling decomposed particles of organic matter—caused disease. When the miasma theory was discredited, a foundation was laid for linking infectious disease transmission with water and not air. We note the further irony of recent investigations that suggest wind aerosolization has assisted in the dissemination of *Vibrio cholerae* epidemics throughout continents (*22*).

Today, droplet exposure and contact are typically listed as the major exposure pathways for ARIs, leaving the existence and significance of airborne exposure for important respiratory diseases (SARS, avian flu, bacterial pneumonia, and the common cold) as matters of debate. Fueling this debate is the growing anecdotal and mechanistic evidence that the airborne route is significant for influenza (*23*). Certainly the loss of life, high morbidity, and loss of productivity in the workplace each year are motivation enough to understand the exposure pathways for ARIs. Given the increasing potential for H5N1 avian influenza to emerge as a highly lethal pandemic virus, the importance of resolving the uncertainties surrounding the exposure route with well-designed studies looms large.

The re-emergence of bioaerosol science and engineering

Dogma, tradition, and the lack of regulations may have led to the underdevelopment of bioaerosol research in the past, but bioterrorism, concerns over emerging respiratory infectious agents, and to a lesser extent recognized increases in allergies and asthma are driving new and significant progress for this highly important exposure. These advances have come in the areas of modeling, measurements, and treatment and have involved environmental engineers and scientists.

Modeling. New evidence for the airborne transmission of the SARS corona virus comes from the coupling of computational fluid dynamic (CFD) models to epidemiological evidence; results strongly suggested transmission from an aerosol plume that exited a high-rise apartment and advected across a courtyard to other apartments where high infection rates were observed (*24*). In another recent example, the retrospective application of a room aerosol particle balance demonstrated that previous studies used to shape current perceptions that colds are not transmitted by the airborne route were based upon a study design that was limited in its capacity to detect airborne transmission (*25*). A final example is the use of a stochastic Markov chain model to study the transmission of respiratory disease in health care settings and ferret out important social, environmental, and etiological practices that impact risk of infection (*26*). Such models demonstrate the potential of an engineering approach as well as the need for a more fundamental understanding of biological aerosol behavior. This includes a clearer knowledge of pathogen die-away kinetics in aerosols and on surfaces as well as aerosol dynamic processes, including settling and surface deposition rates, resuspension, quantitation of human and other emission rates, and the particle size distributions of biological material. The important distinction of humans or human activities as a source strongly necessitates the collaboration of engineers, public-health specialists, and in some cases, social scientists.

New technologies for measuring exposure. Describing the identity, concentration, and environmental fate of airborne biological agents is essential for the prediction of airborne exposure, risk estimation, and improving our understanding of how bioaerosols interact within the environment. An inherent barrier to these measurements and the major difference between the study of microbiology in aquatic and aerosol environments is the dilute nature of biological materials in air. Compared with aquatic and terrestrial environments, where total microorganism concentrations are on the order of $10^6/cm^3$ or greater, bioaerosol concentrations are commonly $<1/cm^3$, and often $<1/m^3$ in the case of infectious aerosols. Moreover, the collection efficiencies as a function of aerodynamic diameters of particles have not been commonly characterized for commercially available bioaerosol samplers. This has led to the dearth of size-resolved bioaerosol information and the associated inability to take advantage of the physical and mathematical frameworks used in studying particle dynamics.

Bioterrorism research has already and significantly produced new sampling and detection solutions. Programs such as the U.S. Department of Homeland Security's BioWatch, sponsored research initiatives by the U.S. military, and several new startup companies have driven the research and development of new versions of high-volume bioaerosol samplers. One promising version uses the unique fluorescence emission of biomolecules to recognize and sort bioaerosols from abiotic aerosols in real time (*27*). With reductions in cost and the increasing availability of data on sampler efficiency and recovery for a variety of particle size ranges, it is hoped that mainstream research will soon benefit from these emerging technologies.

On the detection side, aerosol research is moving, albeit slowly, beyond the well-established limitations of culture-based methods toward the incorporation of molecular biology into measurements (*28*). For the first time, qualitative estimations of airborne etiological agents such as norovirus and rhinoviruses (*25*, *29*) and quantitative estimation of airborne *M. tuberculosis* (*30*) have been made. These, as well as culture-independent DNA-based source-tracking methods and cloning analysis for aerosolized biosolids (*31*) and new U.S. EPA methods that use qPCR to characterize indoor environments for fungal spores (*32*), have delivered on their promise to provide insights on disease exposure pathways that were not possible with traditional cultivation or microscopic methods. In addition to specific agents, the fundamental microbial ecology of indoor air and the atmosphere is now being investigated by several research groups using molecular cloning and high-throughput array techniques (*33*).

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A gust of wind produces particulate matter from an agricultural field 24 hours after class B biosolids were plowed into soils. Although more than 5 million dry tons of biosolids from municipal wastewater treatment facilities and some 1.2 billion tons of manure are applied to land in the U.S. each year, infectious risk and toxicological effects of the associated aerosols have not been determined.

Treatment. Initially catalyzed by an increase in tuberculosis in the U.S. in the mid-1980s, progress in treating indoor air has been substantial in the past 15 years. Technologies that are currently used or in development for indoor air purification include filtration, aerosol ultraviolet irradiation, electrostatic precipitation, unipolar ion emission, and photocatalytic oxidation. In developed nations, humans spend greater than 90% of their time in the built environment. By extension, disease caused by airborne agents can be substantially reduced by engineering appropriate treatment systems within those structures.

Wider implementation of air treatment systems into new buildings is a growing trend, but there are important needs for the design of treatment systems in order to realize their full potential. First, a rationale for focusing on aerosol infection transmission is needed to drive development and installation of treatment systems and to gauge the effectiveness of treatment. This rationale must come from a clearer understanding of the airborne exposure route developed through well-designed epidemiologic studies as well as application of the modeling and measurement methods described above. Second, the testing of treatment systems must move beyond well-characterized surrogate bacterial and fungal organisms and determine treatment efficiencies for specific etiological agents, especially viral agents. Finally, many popular treatment systems, such as increased ventilation airflow to change room air or increased blower capacity to overcome pressure drops from HEPA filters, are power-intensive. Upper room UVC systems that use low-pressure mercury vapor lamps or electrostatic precipitation can be more energy-efficient than ventilation and filtration, but much work remains to define the optimal fixture and installation designs on the basis of an understanding of inactivation characteristics of target organisms and particle movement within occupied spaces. Certainly the focus areas of indoor environmental quality and energy efficiency in Leadership in Energy and Environmental Design (LEED) building certification can encourage development of energy-efficient indoor treatment systems and promote building techniques and materials that prevent biological indoor air quality problems.

Conclusions and environmental research needs

The current known and potential morbidity and mortality associated with airborne biological agents, coupled with the gaps in knowledge about exposure route, aerosol concentration and fate, and treatment effectiveness provide a strong rationale for the participation of environmental scientists and engineers in this area of research. Addressing these problems will require altering some paradigms in environmental research. Public-health and environmental science must be strongly integrated into the study of bioaerosols, and aerosol science must integrate and improve biology and biotechnology tools for application to aerosol samples. Given the high chronic disease incidence and morbidity in developed nations as well as the high mortality in developing regions, a more global research perspective is required.

Persistent and new bioaerosol-related public-health burdens are now intersecting with enabling technologies. Recent advances in aerosol sampling and microbial aerosol detection should facilitate environmental engineering and epidemiologic studies to determine sources, gauge the significance of the airborne route in disease transmission, and measure the effectiveness of new treatment schemes. Coupling the diverse approaches from environmental engineering, air quality, and microbiology with new technologies and modeling efforts will enable a much improved ability to address airborne biological disease research questions and help to usher in a new era where allergies, asthma, and respiratory infections are viewed as a preventable problem, rather than accepted as a matter of course.

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References

(1) Jaenicke, R. Abundance of Cellular Material and Proteins in the Atmosphere. *Science* **2005**, *308*, 73.

(2) Womiloju, T. O.; et al. Methods To Determine the Biological Composition of Particulate Matter Collected from Outdoor Air. *Atmos. Environ.* **2003**, *37*, 4335–4344.

(3) National Institutes of Health. *Airborne Allergens: Something in the Air*; Report 03-2045; NIAID: Bethesda, MD, 2003.

(4) Ring, J.; et al. Why Are Allergies Increasing? *Curr. Opin. Immunol.* **2001**, *13*, 701–708.

(5) Masoli, M.; et al. The Global Burden of Asthma: Executive Summary of GINA Dissemination Committee Report. *Allergy* **2004**, *59*, 469–478.

(6) World Health Organization. *Removing Obstacles to Healthy Development: World Health Organization Report on Infectious Diseases*; WHO/CDS/99.1; WHO: Geneva, 1999.

(7) Committee on Acute Respiratory Infections. Acute Respiratory Infections: The Forgotten Pandemic. Communiqué from the International Conference on Acute Respiratory Infections held in Canberra, Australia, July 7–10, 1997. *Int. J. Tuberculosis Lung Dis.* **1998**, *2*, 2–4.

(8) Craun, G. F.; et al. Outbreaks in Drinking-Water Systems. *J. Environ. Health.* **2002**, *65*, 16–25.

(9) Mead, P. S.; et al. Food-Related Illness and Death in the United States. *Emerging Infect. Dis.* **1999**, *5*, 607–625.

(10) Franze, T.; et al. Protein Nitration by Polluted Air. *Environ. Sci. Technol.* **2005**, *39*, 1673–1678.

(11) Pandya, R. J.; et al. Diesel Exhaust and Asthma: Hypothesis and Molecular Mechanisms of Action. *Environ. Health Perspect.* **2002**, *110* (S1), 103–112.

(12) Ormstad, H. Suspended Particulate Matter in Indoor Air: Adjuvants and Allergen Carriers. *Toxicology* **2000**, *152*, 53–68.

(13) Bornehag, C. G.; et al. Dampness at Home and Its Association with Airway, Nose, and Skin Symptoms among 10,851 Preschool Children in Sweden; A Cross-Sectional Study. *Indoor Air* **2005**, *15*, 48–55.

(14) World Health Organization. *Development of WHO Guidelines for Indoor Air Quality: Dampness and Mould*; WHO: Copenhagen, 2007.

(15) Gange, A. C.; et al. Rapid and Recent Changes in Fungal Fruiting Patterns. *Science* **2007**, *316*, 71.

(16) Rogers, C. A.; et al. Interaction of the Onset of Spring and Elevated Atmospheric CO_2 on Ragweed (*Ambrosia artemisiifolia L.*) Pollen Production. *Environ. Health Perspect.* **2006**, *114*, 865–869.

(17) Garrison, V. H.; et al. African and Asian Dust: From Desert Soils to Coral Reefs. *BioScience* **2003**, *53*, 469–480.

(18) Griffin, D. W. Clouds of Desert Dust and Microbiology: A Mechanism of Global Dispersion. *Microbiol. Today* **2005**, November.

(19) Seager, R.; at al. Model Predictions of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science* **2007**, *361*, 1181.

(20) Keene, W. E.; deBroekert, M.; Gillette, K. A Large *Escherichia coli* O157:H7 Outbreak at a County Fair. In *Programs and Abstracts of the International Conference on Emerging Infectious Diseases*, Atlanta, Feb 29–March 3, 2004.

(21) Marks, P. J.; et al. A School Outbreak of Norwalk-like Virus: Evidence of Airborne Transmission. *Epidemiol. Infect.* **2003**, *131*, 727–736.

(22) Paz, S.; Broza, M. Wind Direction and Its Linkage with *Vibrio cholerae* Dissemination. *Environ. Health Perspect.* **2007**, *115*, 195–200.

(23) Tellier, R. Perspective: Review of Aerosol Transmission of Influenza A Virus. *Emerging Infect. Dis.* **2006**, *12*, 1557–1661.

(24) Yu, I. T. S.; et al. Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus. *New Engl. J. Med.* **2004**, *350*, 1731–1739.

(25) Myatt, T.; et al. Detection of Airborne Rhinovirus and Its Relation to Outdoor Air Supply in Office Environments. *Am. J. Resp. Crit. Care Med.* **2004**, *169*, 1187–1190.

(26) Nicas, M.; Sun, G. An Integrated Model of Infection Risk. *Risk Anal.* **2006**, *26*, 1085–1096.

(27) Davitt, K.; et al. Spectroscopic Sorting of Aerosols by a Compact Sensor Employing UV LEDs. *Aerosol Sci. Technol.* **2006**, *40*, 1047–1051.

(28) Amann, R.; Ludwig, W.; Schleifer, K.-H. Phylogenetic Identification and In Situ Detection of Individual Microbial Cells without Cultivation. *Microbial. Rev.* **1995**, *59*, 143–169.

(29) Brooks, J. R.; et al. A National Survey on the Residential Impact of Biological Aerosols from the Land Application of Biosolids. *J. Appl. Microbiol.* **2005**, *99*, 310–322.

(30) Chen, P.-S.; Li, C.-S. Quantification of Airborne *Mycobacterium tuberculosis* in Health Care Setting Using Real-Time qPCR Coupled to an Air-Sampling Filter Method. *Aerosol Sci. Technol.* **2005**, *39*, 371–376.

(31) Baertsch, C.; et al. Source Tracking Aerosols Released from Land-Applied Class B Biosolids during High-Wind Events. *Appl. Environ. Microbiol.* **2007**, *73*, 4522–4531.

(32) Haugland, R. A.; et al. Quantitative PCR Analysis of Selected *Aspergillus*, *Penicillium*, and *Paecilomyces* Species. *Syst. Appl. Microbiol.* **2004**, *27*, 198–210.

(33) Brodie, E. L.; et al. Urban Aerosols Harbor Diverse and Dynamic Bacterial Populations. *Proc. Natl. Acad. Sci. U.S.A.* **2007**, *104*, 299–304.

(34) Mannino, D. M.; et al. Surveillance for Asthma—United States, 1960–1995. *Morbid. Mortal. Weekly Rep.* **1998**, *47*, SS1.

(35) National Center for Health Statistics. *Fast Stats A to Z: Asthma*; www.cdc.gov/nchs/fastats/Default.htm.

(36) World Health Organization. *The World Health Report 2004—Changing History, Annex Table 2: Death by Cause, Sex, and Mortality Stratum in WHO Regions, Estimates 2002*; WHO: Geneva, 2004.

(37) Leck, C.; Bigg, E. K. Source and Evolution of the Marine Aerosol—A New Perspective. *Geophys. Res. Lett.* **2005**, *32*, L19803.

(38) O'Dowd, C. D.; et al. Biogenically Driven Organic Contribution to Marine Aerosol. *Nature* **2004**, *431*, 676–680.

(39) Ariya, P. A.; et al. Microbiological Degradation of Atmospheric Organic Compounds. *Geophys. Res. Lett.* **2002**, *29*, 2077.