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MINIREVIEW

Multiscale Airborne Infectious Disease Transmission

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ABSTRACT Airborne disease transmission is central to many scientific disciplines, including agriculture, veterinary biosafety, medicine, and public health. Legal and regulatory standards are in place to prevent agricultural, nosocomial, and community airborne disease transmission. However, the overall importance of the airborne pathway is underappreciated; e.g., the U.S. National Library of Medicine's Medical Subjects Headings (MESH) thesaurus lacks an airborne disease transmission indexing term. This has practical consequences, as airborne precautions to control epidemic disease spread may not be taken when airborne transmission is important but unrecognized. Publishing clearer practical methodological guidelines for surveillance studies and disease outbreak evaluations could help address this situation. To inform future work, this paper highlights selected, well-established airborne transmission events, largely cases replicated in multiple, independently conducted scientific studies. Methodologies include field experiments, modeling, epidemiology studies, disease outbreak investigations, and mitigation studies. Collectively, this literature demonstrates that airborne viruses, bacteria, and fungal pathogens have the ability to cause disease in plants, animals, and humans over multiple distances, from near range ($<$5 m) to continental ($>$500 km) in scale. The plausibility and implications of undetected airborne disease transmission are discussed, including the notable underreporting of disease burdens for several airborne-transmitted diseases.

KEYWORDS atmosphere, airborne infectious disease, aerosol, droplet nuclei, inhalation exposure

Air is not a sterile medium, as initially demonstrated in the early-19th-century experiments of Louis Pasteur. Bacteria and fungi are ubiquitous in the atmosphere and reach concentrations of about 10^4 and 10^3 cells m^{-3} in air, respectively (1–4). These facts are well understood and elucidated within the field of aerobiology, which has documented the life cycles, including the atmospheric transport and dispersion, of naturally occurring airborne viruses, microorganisms, and bioaerosols (5–7).

Both near-range and long-range airborne infectious disease transmission events are well documented in the plant biology, veterinary and agricultural biosafety, clinical medicine, and public health literature. However, these findings are not always widely disseminated across these specialties or to the wider scientific community. As a consequence, the true scope and characteristics of airborne disease transport can be underappreciated. This has practical consequences when airborne disease transmission is not recognized during a disease outbreak, and so precautions against airborne disease transmission to control epidemic disease spread may not be taken.

To assist the scientific community in better understanding the characteristics of long-distance airborne infectious disease transmission and its prevention and control, we provide here a selective, documentary review of well-established examples of airborne disease dispersions sorted according to transmission distance scale. The examples include the near-range-scale ($<$5-m) spread typically seen in clinical medicine up to continental-scale ($>$500-km) transmission. Due to its rapid development, this review

Citation Dillon CF, Dillon MB. 2021. Multiscale airborne infectious disease transmission. Appl Environ Microbiol 87:e02314-20. https://doi.org/10.1128/AEM.02314-20.

Editor Harold L. Drake, University of Bayreuth

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Accepted manuscript posted online 4 December 2020

Published 29 January 2021

does not review the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)/coronavirus disease 2019 (COVID-19) literature, but it highlights key prior coronavirus studies.

ATMOSPHERIC INFECTIOUS DISEASE TRANSMISSION

Near range (<5 m). In the medical context, near-range airborne disease spread (<5 m) is common and occurs when infected individuals generate large quantities of infectious droplet particles (and droplet nuclei) when coughing or sneezing (8, 9). Tuberculosis (TB) and measles virus (rubeola) have long been known to transmit over this distance (10, 11). *Bordetella pertussis* (whooping cough), varicella-zoster virus (chickenpox), mumps virus, rubella virus (German measles), and *Neisseria meningitidis* (bacterial meningitis) are additional examples (12, 13). This near-range airborne disease spread is known to contribute to the overall disease burden as lower respiratory infections and tuberculosis are the 4th and 10th leading causes of death worldwide (14). Finally, 2% of U.S. adults (6.5 million) are hospitalized each year for the treatment of community-acquired pneumonia caused in part by the near-range airborne transmission of common bacteria and viruses, including influenza virus (15). We note that the airborne disease transmission pathway can contribute to overall disease transmission, even when other—droplet (>5-μm-aerodynamic-diameter particles) and contact—pathways are important (e.g., see references 16 and 17).

With respect to pathogenic coronaviruses, avian infectious bronchitis virus (IBV) disease was the first near-range airborne-spread disease to be clinically recognized in 1931. Currently, IBV is a high-mortality-rate upper respiratory infection with a global economic impact on poultry production (18). IBV has multiple routes of transmission, including inhalation, drinking of contaminated water, and direct contact (19). Vaccines are a mainstay of IBV disease control (20), with multiple strain-specific vaccines in routine use to improve morbidity and mortality. Live IBV vaccines are given by spray or aerosol or in drinking water (19). Humans can be infected, but human disease is not documented (21).

Human-pathogenic coronavirus infections were first identified in the early 1960s, and 4 strains (human coronavirus strain 229E [HCoV-229E], HCoV-OC43, HCoV-NL63, and HCoV-HKU1) are globally distributed (22, 23). These pathogens pose a substantial burden due to days lost from work and school and medical costs (23, 24). Infections occur at all ages, but disease is more severe in young children, the elderly, and patients with underlying medical conditions (25–28). While there is limited published research on the airborne transmission pathway, we note that these viruses are known to persist in the atmosphere (29) and collectively constitute the third most common cause of acute respiratory tract disease (30). Notably, a single population-based prospective community survey with active case finding documented a large HCoV-229E outbreak in which one-third of the community was infected and respiratory illnesses in the community doubled. Most cases were upper respiratory illnesses; however, 40% also had lower respiratory tract involvement (31).

Short range (5 m to 50 m). The airborne spread of human pathogens within buildings has been particularly well documented in both schools (32, 33) and medical care facilities (34–36). Indeed, Riley et al.'s experimental studies of clinically active tuberculosis are classic examples of airborne disease transmission. Air from a clinical TB ward of active human cases was routed to an animal exposure chamber located in the building ventilation duct system distant from the patients under treatment. Typical clinical disease subsequently developed in the test animals (10). In a follow-up study with a prospective case-control design, unprotected exposed animals again contracted tuberculosis, but an animal control group with UV-irradiated air did not (37). The latter study findings have been replicated (38, 39).

Separately, an expert panel review noted 10 studies documenting airborne disease transmission in medical settings (hospitals, clinics, and nursing homes) (34). These studies showed a direct contributory role of ventilation rates and building-related airflows in the pattern of the airborne spread of disease at distances farther than could have been spread by an infected person coughing, sneezing, or breathing. Airborne outbreak examples included *Mycobacterium tuberculosis*, rubeola virus (measles), varicella-zoster virus (chickenpox), and variola virus (smallpox) (37, 40, 41). The U.S. Centers for Disease Control and Prevention also defines tuberculosis, measles, and chickenpox as airborne-transmitted diseases, which require formal isolation precautions in hospital settings (42).

We note that within hospital settings, high-infection-risk patient areas are designed with physical and ventilation barriers to minimize airborne infections. These building design features include, but are not limited to, permanently sealed hospital room windows and HEPA air filtration (34, 43–45). UV germicidal irradiation is also routinely used to reduce airborne disease risk in hospitals and other facilities, especially for tuberculosis control (46).

With respect to pathogenic coronaviruses, the 2003 Hong Kong SARS epidemic provided several notable examples of short-range airborne disease transmission. The first was a large hospital outbreak (34, 47, 48). Disease attack rates were highest (65%) in the same treatment bay (<5 m) as the index case (an undiagnosed SARS patient), slightly lower (52%) in a nearby treatment bay (10-m nominal distance from the index patient) that readily exchanged air with the index patient treatment bay, and much lower (18%) in patient areas (10-m nominal distance from the index patient) where the air was less well shared with the index patient treatment bay. The temporal and spatial spread of infection was consistent with computer modeling of building airflows and particle physics. Two other localized outbreaks were (i) transmission over a distance of several meters while flying on an airplane (49) and (ii) spread within high-rise residential buildings and between buildings 50 m apart (50, 51). Subsequently, the possibility of airborne disease transmission was investigated in a 2015 hospital outbreak of Middle East respiratory syndrome coronavirus (MERS-CoV) (52).

In plant biology and biosafety studies, short-range (<50-m) airborne particle and pathogen transmissions are thought to be the most frequent scenarios. For example, initial median windborne (anemochorous) plant seed dispersals are typically short (<10 m), but the 95th percentile for airborne seed dispersion occurs over longer distances and varies significantly by species (53–55). In plant pathology studies of wheat stripe rust (*Puccinia striiformis* f. sp. *tritici*) and the wind-dispersed banana plant fungus *Mycosphaerella fijiensis* (56, 57), single-field experimental studies are used to model initial local-plot/field-level airborne pathogen dispersal and clearly demonstrate short-range airborne infection transmission. These studies have also been used to develop source (emission) estimates for larger-scale, long-distance disease spread and propagated epidemics (57).

Medium range (50 m to 500 m). Epidemiological disease outbreak studies provide human data for medium-range airborne disease transmission. Well-documented examples include ongoing community-level outbreaks of Legionnaires' disease (*Legionella pneumophila*) from building cooling towers (58–66), Q fever (*Coxiella burnetii*) transmission from livestock farms to their surrounding communities (67), as well as histoplasmosis (*Histoplasma capsulatum*) and *Aspergillus fumigatus* and *A. flavus* dispersions from construction work or sites where contaminated soil is disturbed (68–74). On this spatial scale, best practices and regulatory standards aim to reduce the risk of the airborne transport of infectious particles. Guidelines exist to control occupational and environmental construction-associated dust during building renovations. In regions of endemicity, these guidelines are codified into law to reduce infections (75, 76).

Newcastle disease (ND) virus, an avian paramyxovirus, is one well-known example of an airborne disease. It is a commercially important pathogen globally in poultry production (77–80). ND has the potential to transmit over medium-range distances, as demonstrated by positive viral cultures of air samples at 60 m in field experiment studies (80). Recent experimental work has reconfirmed an airborne transmission route for ND virus (78), and some live-virus vaccines are delivered via fine aerosolized powders (79). While vaccines are a mainstay of disease control, the disease remains endemic in many countries (78). Studies have shown that negative air ionization and dilute viricidal chlorine aerosols are useful in preventing ND virus infections (81, 82).

Porcine reproductive and respiratory syndrome virus (PRSSV) disease in swine also has global economic impacts despite the availability of vaccines (83). Medium-range PRRSV airborne transmission at distances of 80 to 120 m has been clearly demonstrated in experimental field studies (84, 85). Field studies and a long-term controlled production model prospective study with positive and negative controls demonstrated the efficacy of air filtration to protect animals in farm buildings from airborne PRRSV (84). Indeed, air filtration of farm buildings is effective at controlling pandemic PRRSV infections, even when conventional controls, intended to protect against other infection pathways, have failed. Building air filtration systems have since become an industry standard in U.S. pig breeding and production (86). Filtration has also shown efficacy in reducing emissions of airborne methicillin-resistant *Staphylococcus aureus* (MSRA) from farm buildings (87).

Furthermore, with respect to potential medium-range airborne disease transmission, there is also a long-standing, yet still evolving, literature that supports existing regulatory standards aimed at protecting workers and nearby communities from airborne pathogen dispersal from environmental sites such as composting facilities, sewage processing and wastewater aerosols, agricultural gray water aerosols, livestock feed yards, and land applications of manure (88–96). As one example, a protective ring of up to 250 m is commonly specified under the assumption that existing air monitors detect little to no viable infectious airborne material beyond that point (92, 93, 97).

Long range (500 m to 500 km). Long-distance atmospheric infectious disease dispersions, termed LDD in the plant biology and agricultural biosafety literature, have been shown to play crucial ecological roles in plant species invasion, migration, and survival as well as plant pathogen dispersal (98–104). In veterinary biosafety studies, this field is well advanced in its understanding of the connection between airborne pathogen transport and dispersion and disease epidemics (105–108).

Biosafety experimental field studies also clearly demonstrate kilometer-range dispersion of plant pathogens. For example, fungal plant pathogens are an increasing threat to world food security (109). A wind-dispersed banana plant fungus (*Mycosphaerella fijiensis*) field experiment documented 1-km airborne dispersal in one generation (56). Studies such as these together with the above-mentioned plant biology and biosafety literature demonstrate that airborne infection probability initially decreases rapidly with distance, which is then followed by a regimen of lower-probability kilometer-range LDD events (termed a "long dispersion tail").

In the United States, long-range airborne spread of economically significant plant disease across the landscape is an ongoing concern. Predictable seasonal airborne pathogen incursion pathways across the continent are well identified and routinely monitored to protect crop yields. These continental-scale incursions typically proceed in a stepwise series of shorter (long-range) airborne dispersions. Chief examples are the seasonal airborne south-to-north U.S. dispersion incursion pathways across the Midwest Great Plains for wheat stem rust (*Puccinia graminis* f. sp. *tritici*), the pandemic spread of tobacco blue mold spores (*Peronospora tabacina*) across the eastern United States, and seasonal U.S. airborne invasion by soybean rust (*Phakopsora pachyrhizi* Sydow) (103, 110–113).

In the veterinary literature, there are many examples of probable kilometer-range airborne infection transmission. For example, Newcastle disease virus, equine influenza (A/H3N8) virus, highly pathogenic avian influenza A (H7N7) virus, PRRSV, and *Mycoplasma hyopneumoniae* are important ongoing diseases, and each has evidence for long-range airborne transmission (114–119). The best-described long-range airborne-transmitted disease in animals is foot-and-mouth disease virus (FMDV), an economically significant disease of veterinary livestock. Long-range FMDV aerosols have contributed to a number of costly, regional-scale disease outbreaks in Europe, including airborne transmission from continental Europe to the United Kingdom (120, 121).

FMDV research has motivated the development and testing of scientific models and forecasting capabilities for long-range infectious aerosol dispersions with the aim of limiting epidemic spread (105–108, 122–126).

In the human epidemiology literature, many well-documented examples exist for airborne disease transmission over distances of >1 kilometer downwind. *Coxiella burnetii*, an endemic disease of ruminants and livestock, is also the cause of Q fever in humans (127). Long-range outbreaks of airborne disease spread from animal farms to human populations have been documented in many European countries (128–132). Notably, the recent regional-scale Q fever epidemic in 2007 to 2010 in the Netherlands was caused by infectious aerosols emitted from small-animal farms (133–137). The epidemic resulted in 4,000 clinical cases and 2,700 hospitalizations (135). A more recent 2018 follow-up of this outbreak showed that among the 519 chronic Q fever cases identified, 86 patients had died (138).

Legionella pneumophila dispersions from building cooling towers are also an ongoing source of kilometer-range community Legionnaires' disease outbreaks despite the introduction of preventive legal regulations for cooling equipment maintenance (63, 139). Significant kilometer-range airborne Legionnaires' disease outbreaks have been reported in many countries, including the United States, France, Norway, Sweden, and Spain (58–62, 64–66, 140–143), and airborne disease models have been developed (144).

The fungal pathogens *Histoplasma capsulatum* and *Coccidioides immitis* and *C. posadasii* cause significant human disease when inhaled (histoplasmosis and coccidioidomycosis [valley fever], respectively). Both are endemic in the United States: histoplasmosis in the eastern and midwestern states and coccidioidomycosis in the American West and Southwest (72, 145). Based on observational epidemiological studies, citywide airborne outbreaks of histoplasmosis are suspected to have occurred, two at a community level (146–148). A series of three large-scale histoplasmosis outbreaks that occurred in urban Indianapolis, IN, may also have resulted from airborne dispersion (149–151).

Coccidioidomycosis occurs after inhalation of fungal spores, which are widely distributed in southwestern U.S. soils (152, 153). Forty percent of exposed persons will have clinical symptoms, ranging from an influenza-like illness to disseminated disease and chronic meningitis. Symptomatic disseminated disease requires aggressive treatment and has increased rates of hospitalization and mortality (154, 155). Desert dust cloud dispersions containing *Coccidioides* spores are an important ongoing cause of disease, and legal standards prevent high-risk persons from being assigned to prisons in areas of endemicity (156). In addition, long-range airborne dust cloud *Coccidioides* dispersal events triggered by natural disasters have caused significant regional coccidioidomycosis outbreaks in the U.S. state of California (157). Kilometer-scale airborne transmission occurred in the Los Angeles area following the 1994 Northridge earthquake, where strong aftershocks generated landslides on the slopes of the Santa Susana Mountains, resulting in large, contaminated dust clouds (158–160). These clouds were blown by ambient winds into the urban Simi Valley and Ventura County areas, causing a coccidioidomycosis outbreak (203 total cases, 55 hospitalizations, and 3 fatalities).

Continental range ($>$500 km). Continental-scale airborne dispersion events, especially plant seed dispersions, have been well studied and influence the spread of invasive species, metapopulation dynamics, and plant diversity (54, 100, 101, 161). Continental-scale transport of common environmental bacterial species, either on normal atmospheric air currents or in association with dust cloud dispersions, has also been well demonstrated (2, 162–164). As one example, bacterial communities from the Saharan desert are known to travel airborne to high European Alpine lakes (165, 166). Pathogenic bacteria have also been observed in the ambient atmosphere, including plant, animal, and human pathogens (167–169). Furthermore, airborne transmission of *Neisseria meningitidis*, a major cause of meningitis worldwide, is under investigation in the endemic Sahel region of North Africa as outbreaks occur most often in dry months with frequent dust storms (164, 168).

Airborne continental-scale disease spread often proceeds as a series of sequential long-range airborne transmission events over the landscape (saltatory transmission). However, individual continental-scale airborne disease transmission events, i.e., a single airborne plume transporting pathogens more than 500 km, are also documented in the literature (98, 110, 170, 171). Most but not all of the existing examples are from agricultural biosafety studies where these events are termed "single-step" LDD pathogen invasions (98). These types of events are thought to be rare and often associated with extreme weather events or natural disasters (110, 157). However, routinely occurring, single-step LDD events could be more frequent, although this possibility has not been systematically investigated. For example, a sentinel LDD study of airborne plant-pathogenic fungi (*Erysiphe graminis* f. sp. *hordei* [barley mildew] and *Erysiphe graminis* f. sp *tritici* [wheat mildew]) demonstrated transmission over a distance of 650 km across the North Sea from Great Britain to Scandinavia (171). Samples were obtained using disease-free receptor plant populations and compared to unexposed control plants, and a multiyear series of samples was obtained in the regions with the highest-expected-transmission probability.

A major weather-related single-step LDD event was the 2,000-km airborne dispersion of Asian soybean rust (*Phakopsora pachyrhizi*) across the Caribbean from northwestern South America to the United States during Hurricane Ivan (110). This 2004 event marked the invasion of Asian soybean rust into the North American continent. The event was anticipated as the spread of Asian soybean rust from Brazil northward in South America was being monitored and Brazil had lost a significant fraction of its soybean production to this pathogen. Among other measures (and prior to the event itself), predictive atmospheric dispersion modeling for potential airborne transport to the United States during tropical cyclone seasons was conducted, and the U.S. Department of Agriculture deployed disease forecasting systems and field tested a detailed response plan for use in the event that soybean rust was identified (110). Soybean rust was detected infesting soybean fields in Louisiana (as predicted) within 2 weeks after Hurricane Ivan had passed. Subsequently, Asian soybean rust has remained endemic in many southern states, especially in the initial epidemic outbreak area (172).

A clear human disease example of single-plume continental-scale airborne disease transmission is the 600-km dispersion of *Coccidioides immitis* spores in California, which resulted in widespread coccidioidomycosis outbreaks (173). In this 1977 event, a 160-km h^{-1} windstorm scoured 15 cm of *Coccidioides immitis*-contaminated topsoil from Kern County, located in the southernmost basin of California's San Joaquin Valley, carrying a resulting dust cloud to an altitude of 1,500 m (see the JPEG image [890 by 690 pixels] at https://geochange.er.usgs.gov/sw/impacts/geology/dust/desertdust.jpeg). The dust was transported northward and dispersed over an 87,000-km^2 area (150, 170, 173, 174), burying freeways and shutting down interstate transportation. There were 3 immediate storm-related fatalities, and 3 firefighters died in a forest fire spread by the strong winds. Sacramento, a low-endemicity area 500 km to the north, experienced a large coccidioidomycosis outbreak (115 cases and 6 fatalities reported versus a background incidence of 0 to 6 cases per year). Overall, 15 California counties northward in the dust cloud dispersion area reported a 10-fold increase in coccidioidomycosis cases, and 9 counties reported lesser increases (173). This 1977 *Coccidioides immitis* dispersion, with a total of more than 379 reported cases, serves as a historical benchmark for the potential magnitude of coccidioidomycosis cases from a significant dust storm (170). Integrated coccidioidomycosis case surveillance and dust storm forecasting are currently standard in U.S. areas of endemicity (175).

DISCUSSION

Historically, the importance of the airborne disease transmission pathway has been well recognized (11, 176–178), but more recently, work in this area has not been prioritized. Prior reviewers have suggested that the motivation to understand the airborne infectious disease transmission pathway has waned over time due to (i) the availability of antibiotic therapy and immunizations for key diseases of interest and (ii) the difficulty in detecting infectious pathogens in airborne particles relative to water, surfaces, or large-droplet sprays (179).

Regardless of the cause, the multiscale transmission of airborne disease is likely currently underappreciated, even though the cumulative body of literature across the scientific disciplines is large. Our experience is that it is quite difficult to locate all pertinent papers in the medical and public health literature, even for a single disease. A contributing cause may be the lack of standard indexing terms for airborne disease transmission. As an example, the U.S. National Library of Medicine's Medical Subjects Headings (MESH) indexing system lacks MESH terms for airborne disease transmission. For comparison, there are MESH terms for "fomite," "waterborne diseases," "vector-borne diseases," "sexually transmitted diseases," and "foodborne diseases." Currently, MESH terms in use to code airborne transmission articles are generic ones such as "air microbiology," "respiratory tract infections/diseases," and "inhalation exposure." To facilitate Internet searches in the future, we suggest that authors add the phrase "airborne disease transmission" or "airborne infection transmission" to article abstracts.

Most of the reports cited here are epidemiology studies where the airborne pathway is the predominant means of disease transmission and where researchers have excluded other disease transmission pathways, i.e., single-pathway outbreaks. There are relatively few published reports documenting airborne transmission as a secondary, contributory cause of disease, although important examples exist (e.g., see references 115, 119, and 180). For opportunistic pathogens, in which a disease can transmit through multiple pathways, not investigating or reporting instances of secondary airborne disease transmission may serve to reduce the number of airborne disease reports in the literature. Airborne transmission as a partial cause of disease outbreaks may be common, and more attention to this topic is warranted in the literature.

Our knowledge of the infectious disease population impacts is primarily based on surveillance systems that rely on reported, diagnosed cases. These systems are useful for monitoring trends over time and for identifying disease outbreaks. However, they can underreport population incidence and prevalence and so risk creating the impression that a particular disease is uncommon and lacks a significant population-level impact. This impression could be a disincentive to disease-specific research and airborne transmission pathway research in general.

As an example, Q fever is thought to be uncommon; however, U.S. nationally representative data show that 3% of the population have positive Q fever serology at any one time, which corresponds to an estimated 6 million adults (181). Similarly, Legionnaires' disease pneumonias are believed to be 10 times more common than what is currently being diagnosed (182). Notably, histoplasmosis, like coccidioidomycosis, has clear potential for airborne disease transmission and is widely endemic across the eastern, midwestern, and southern United States. We note that there have been no literature reports of longer-range airborne histoplasmosis outbreaks in the United States since the 1980s.

CONCLUSIONS

Airborne transmission of infectious disease has been demonstrated in multiple, independently conducted field experiments and observational epidemiology studies across distances ranging from meters to continental in scale. Furthermore, multiscale airborne disease transmission has been demonstrated for viruses, bacteria, and fungi across a wide range of relevant scientific disciplines, including plant biology, agricultural and veterinary biosafety, medicine, and public health. While historically, the importance of the airborne disease transmission pathway has been well recognized, this area has not been prioritized until the recent COVID-19 outbreak. Consequently, the scientific literature may underestimate the prevalence, importance, and key features of airborne disease transmission. Greater awareness of the potential for airborne disease transmission and dissemination of methodological guidelines for surveillance studies and disease outbreak investigations could help address this situation.

ACKNOWLEDGMENTS

M.B.D. was responsible for the study concept and design. Both M.B.D. and C.F.D. participated in literature searches, manuscript drafting, and revision.

Financial support was provided, in part, by the U.S. Department of Homeland Security for related early efforts. Research was supported, in part, by the DOE Office of Science through the National Virtual Biotechnology Laboratory, a consortium of DOE national laboratories focused on the response to COVID-19, with funding provided by the Coronavirus CARES Act. Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration, under contract DE-AC52-07NA27344.

The funders had no role in study design, data collection and interpretation, or the decision to submit the work for publication.

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REFERENCES

1. Burrows SM, Elbert W, Lawrence MG, Pöschl U. 2009. Bacteria in the global atmosphere—part 1: review and synthesis of literature data for different ecosystems. Atmos Chem Phys 9:9263–9280. https://doi.org/10.5194/acp-9-9263-2009.
2. Burrows SM, Butler T, Jöckel P, Tost H, Kerkweg A, Pöschl U, Lawrence MG. 2009. Bacteria in the global atmosphere—part 2: modeling of emissions and transport between different ecosystems. Atmos Chem Phys 9:9281–9297. https://doi.org/10.5194/acp-9-9281-2009.
3. Després VR, Huffman AJ, Burrows SM, Hoose C, Safatov AS, Buryak G, Fröhlich-Nowoisky J, Elbert W, Andreae MO, Pöschl U, Jaenicke R. 2012. Primary biological aerosol particles in the atmosphere: a review. Tellus B Chem Phys Meteorol 64:1.
4. Bowers RM, Sullivan AP, Costello EK, Collett JL, Knight R, Fierer N. 2011. Sources of bacteria in outdoor air across cities in the Midwestern United States. Appl Environ Microbiol 77:6350–6356. https://doi.org/10.1128/AEM.05498-11.
5. Muilenberg ML, Burge H (ed). 1996. Aerobiology: proceedings of the Pan-American Aerobiology Association. Lewis Publishers, Boca Raton, FL.
6. Salem H, Katz SA (ed). 2016. Aerobiology: the toxicology of airborne pathogens and toxins. Royal Society of Chemistry, Cambridge, United Kingdom.
7. Gregory PH. 1973. Microbiology of the atmosphere, 2nd ed. Leonard Hill Books, Aylesbury, United Kingdom.
8. Stilianakis NI, Drossinos Y. 2010. Dynamics of infectious disease transmission by inhalable respiratory droplets. J R Soc Interface 7:1355–1366. https://doi.org/10.1098/rsif.2010.0026.
9. Nicas M, Nazaroff WW, Hubbard A. 2005. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens. J Occup Environ Hyg 2:143–154. https://doi.org/10.1080/15459620590918466.
10. Riley RL, Mills CC, Nyka W, Weinstock N, Storey PB, Sultan LU, Riley MC, Wells WF. 1995. Aerial dissemination of pulmonary tuberculosis. A two-year study of contagion in a tuberculosis ward 1959. Am J Epidemiol 142:3–14. https://doi.org/10.1093/oxfordjournals.aje.a117542.
11. Langmuir AD. 1964. Airborne infection: how important for public health? I. A historical review. Am J Public Health Nations Health 54:1666–1668. https://doi.org/10.2105/ajph.54.10.1666.
12. Tang JW, Wilson P, Shetty N, Noakes CJ. 2015. Aerosol-transmitted infections—a new consideration for public health and infection control teams. Curr Treat Options Infect Dis 7:176–201. https://doi.org/10.1007/s40506-015-0057-1.
13. Hamborsky J, Kroeger A, Wolfe S (ed). 2015. The pink book: course textbook—epidemiology and prevention of vaccine-preventable diseases, 13th ed. Public Health Foundation, Washington, DC.
14. WHO. 2020. The top 10 causes of death. WHO, Geneva, Switzerland. https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death.
15. McLaughlin JM, Khan FL, Thoburn EA, Isturiz RE, Swerdlow DL. 2020. Rates of hospitalization for community-acquired pneumonia among US adults: a systematic review. Vaccine 38:741–751. https://doi.org/10.1016/j.vaccine.2019.10.101.
16. Killingley B, Nguyen-Van-Tam J. 2013. Routes of influenza transmission. Influenza Other Respir Viruses 7:42–51. https://doi.org/10.1111/irv.12080.
17. Kutter JS, Spronken MI, Fraaij PL, Fouchier RA, Herfst S. 2018. Transmission routes of respiratory viruses among humans. Curr Opin Virol 28:142–151. https://doi.org/10.1016/j.coviro.2018.01.001.
18. Bande F, Arshad SS, Omar AR, Hair-Bejo M, Mahmuda A, Nair V. 2017. Global distributions and strain diversity of avian infectious bronchitis virus: a review. Anim Health Res Rev 18:70–83. https://doi.org/10.1017/S1466252317000044.
19. Ignjatovic J, Sapats S. 2000. Avian infectious bronchitis virus. Rev Sci Tech 19:493–508. https://doi.org/10.20506/rst.19.2.1228.
20. Jordan B. 2017. Vaccination against infectious bronchitis virus: a continuous challenge. Vet Microbiol 206:137–143. https://doi.org/10.1016/j.vetmic.2017.01.002.

21. Miller LT, Yates VJ. 1968. Neutralization of infectious bronchitis virus by human sera. Am J Epidemiol 88:406–409. https://doi.org/10.1093/oxfordjournals.aje.a120901.
22. van der Hoek L. 2007. Human coronaviruses: what do they cause? Antivir Ther 12:651–658.
23. Walsh EE, Shin JH, Falsey AR. 2013. Clinical impact of human coronaviruses 229E and OC43 infection in diverse adult populations. J Infect Dis 208:1634–1642. https://doi.org/10.1093/infdis/jit393.
24. Talbot HK, Shepherd BE, Crowe JE, Jr, Griffin MR, Edwards KM, Podsiad AB, Tollefson SJ, Wright PF, Williams JV. 2009. The pediatric burden of human coronaviruses evaluated for twenty years. Pediatr Infect Dis J 28:682–687. https://doi.org/10.1097/INF.0b013e31819d0d27.
25. Pene F, Merlat A, Vabret A, Rozenberg F, Buzyn A, Dreyfus F, Cariou A, Freymuth F, Lebon P. 2003. Coronavirus 229E-related pneumonia in immunocompromised patients. Clin Infect Dis 37:929–932. https://doi.org/10.1086/377612.
26. Vassilara F, Spyridaki A, Pothitos G, Deliveliotou A, Papadopoulos A. 2018. A rare case of human coronavirus 229E associated with acute respiratory distress syndrome in a healthy adult. Case Rep Infect Dis 2018:6796839. https://doi.org/10.1155/2018/6796839.
27. McIntosh K, Chao RK, Krause HE, Wasil R, Mocega HE, Mufson MA. 1974. Coronavirus infection in acute lower respiratory tract disease of infants. J Infect Dis 130:502–507. https://doi.org/10.1093/infdis/130.5.502.
28. McIntosh K. 2004. Commentary: McIntosh K, Chao RK, Krause HE, Wasil R, Mocega HE, Mufson MA. Coronavirus infection in acute lower respiratory tract disease of infants. J Infect Dis 1974; 130:502-7. J Infect Dis 190:1033–1041. https://doi.org/10.1086/422851.
29. Ijaz MK, Brunner AH, Sattar SA, Nair RC, Johnson-Lussenburg CM. 1985. Survival characteristics of airborne human coronavirus 229E. J Gen Virol 66(Part 12):2743–2748. https://doi.org/10.1099/0022-1317-66-12-2743.
30. Monto AS. 1974. Medical reviews. Coronaviruses. Yale J Biol Med 47:234–251.
31. Cavallaro JJ, Monto AS. 1970. Community-wide outbreak of infection with a 229E-like coronavirus in Tecumseh, Michigan. J Infect Dis 122:272–279. https://doi.org/10.1093/infdis/122.4.272.
32. Riley EC, Murphy G, Riley RL. 1978. Airborne spread of measles in a suburban elementary school. Am J Epidemiol 107:421–432. https://doi.org/10.1093/oxfordjournals.aje.a112560.
33. Riley RL. 1979. Indoor spread of respiratory infection by recirculation of air. Bull Eur Physiopathol Respir 15:699–705.
34. Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin JZ, Lu JW, Nielsen PV, Niu J, Qian H, Sleigh AC, Su H-JJ, Sundell J, Wong TW, Yuen PL. 2007. Role of ventilation in airborne transmission of infectious agents in the built environment—a multidisciplinary systematic review. Indoor Air 17:2–18. https://doi.org/10.1111/j.1600-0668.2006.00445.x.
35. Eames I, Tang JW, Li Y, Wilson P. 2009. Airborne transmission of disease in hospitals. J R Soc Interface 6:S697–S702. https://doi.org/10.1098/rsif.2009.0407.focus.
36. Kowalski W. 2011. Hospital airborne infection control. CRC Press, Boca Raton, FL.
37. Riley RL, Mills CC, O'Grady F, Sultan LU, Wittstadt F, Shivpuri DN. 1961. Infectiousness of air from a tuberculosis ward. Am Rev Respir Dis 85:511–525.
38. Escombe AR, Oeser C, Gilman RH, Navincopa M, Ticona E, Martinez C, Caviedes L, Sheen P, Gonzalez A, Noakes C, Moore DAJ, Friedland JS, Evans CA. 2007. The detection of airborne transmission of tuberculosis from HIV-infected patients, using an in vivo air sampling model. Clin Infect Dis 44:1349–1357. https://doi.org/10.1086/515397.
39. Escombe AR, Moore DAJ, Gilman RH, Navincopa M, Ticona E, Mitchell B, Noakes C, Martínez C, Sheen P, Ramirez R, Quino W, Gonzalez A, Friedland JS, Evans CA. 2009. Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. PLoS Med 6: e1000043. https://doi.org/10.1371/journal.pmed.1000043.
40. Wehrle PF, Posch J, Richter KH, Henderson DA. 1970. An airborne outbreak of smallpox in a German hospital and its significance with respect to other recent outbreaks in Europe. Bull World Health Organ 43:669–679.
41. Gustafson TL, Lavely GB, Brawner ER, Hutcheson RH, Wright PF, Schaffner W. 1982. An outbreak of airborne nosocomial varicella. Pediatrics 70:550–556.
42. Siegel JD, Rhinehart E, Jackson M, Chirarello L. 2007. Guideline for isolation precautions: preventing transmission of infectious agents in healthcare settings (updated July 2019). Centers for Disease Control and Prevention Healthcare Infection Control Practices Advisory Committee, Atlanta, GA.
43. Hitchcock PJ, Mair M, Inglesby TV, Gross J, Henderson DA, O'Toole T, Ahern-Seronde J, Bahnfleth WP, Brennan T, Burroughs HEB, Davidson C, Delp W, Ensor DS, Gomory R, Olsiewski P, Samet JM, Smith WM, Streifel AJ, White RH, Woods JE. 2006. Improving performance of HVAC systems to reduce exposure to aerosolized infectious agents in buildings; recommendations to reduce risks posed by biological attacks. Biosecur Bioterror 4:41–54. https://doi.org/10.1089/bsp.2006.4.41.
44. Nielsen PV. 2009. Control of airborne infectious diseases in ventilated spaces. J R Soc Interface 6:S747–S755. https://doi.org/10.1098/rsif.2009.0228.focus.
45. Tang JW. 2009. The effect of environmental parameters on the survival of airborne infectious agents. J R Soc Interface 6:S737–S746. https://doi.org/10.1098/rsif.2009.0227.focus.
46. Memarzadeh F, Olmsted RN, Bartley JM. 2010. Applications of ultraviolet germicidal irradiation disinfection in health care facilities: effective adjunct, but not stand-alone technology. Am J Infect Control 38: S13–S24. https://doi.org/10.1016/j.ajic.2010.04.208.
47. Yu ITS, Wong TW, Chiu YL, Lee N, Li Y. 2005. Temporal-spatial analysis of severe acute respiratory syndrome among hospital inpatients. Clin Infect Dis 40:1237–1243. https://doi.org/10.1086/428735.
48. Wong T, Lee C, Tam W, Lau JT, Yu T, Lui S, Chan PKS, Li Y, Bresee JS, Sung JJY, Parashar UD, Outbreak Study Group. 2004. Cluster of SARS among medical students exposed to single patient, Hong Kong. Emerg Infect Dis 10:269–276. https://doi.org/10.3201/eid1002.030452.
49. Olsen SJ, Chang H-L, Cheung TY-Y, Tang AF-Y, Fisk TL, Ooi SP-L, Kuo H-W, Jiang DD-S, Chen K-T, Lando J, Hsu K-H, Chen T-J, Dowell SF. 2003. Transmission of the severe acute respiratory syndrome on aircraft. N Engl J Med 349:2416–2422. https://doi.org/10.1056/NEJMoa031349.
50. Li Y, Duan S, Yu ITS, Wong TW. 2005. Multi-zone modeling of probable SARS virus transmission by airflow between flats in Block E, Amoy Gardens. Indoor Air 15:96–111. https://doi.org/10.1111/j.1600-0668.2004.00318.x.
51. Yu ITS, Li Y, Wong TW, Tam W, Chan AT, Lee JHW, Leung DYC, Ho T. 2004. Evidence of airborne transmission of the severe acute respiratory syndrome virus. N Engl J Med 350:1731–1739. https://doi.org/10.1056/NEJMoa032867.
52. Xiao S, Li Y, Sung M, Wei J, Yang Z. 2018. A study of the probable transmission routes of MERS-CoV during the first hospital outbreak in the Republic of Korea. Indoor Air 28:51–63. https://doi.org/10.1111/ina.12430.
53. Vittoz P, Engler R. 2007. Seed dispersal distances: a typology based on dispersal modes and plant traits. Bot Helv 117:109–124. https://doi.org/10.1007/s00035-007-0797-8.
54. Wright SJ, Trakhtenbrot A, Bohrer G, Detto M, Katul GG, Horvitz N, Muller-Landau HC, Jones FA, Nathan R. 2008. Understanding strategies for seed dispersal by wind under contrasting atmospheric conditions. Proc Natl Acad Sci U S A 105:19084–19089. https://doi.org/10.1073/pnas.0802697105.
55. Soons MB, Nathan R, Katul GG. 2004. Human effects on long-distance wind dispersal and colonization by grassland plants. Ecology 85:3069–3079. https://doi.org/10.1890/03-0398.
56. Rieux A, Soubeyrand S, Bonnot F, Klein EK, Ngando JE, Mehl A, Ravigne V, Carlier J, de Lapeyre de Bellaire L. 2014. Long-distance wind-dispersal of spores in a fungal plant pathogen: estimation of anisotropic dispersal kernels from an extensive field experiment. PLoS One 9:e103225. https://doi.org/10.1371/journal.pone.0103225.
57. Severns PM, Sackett KE, Farber DH, Mundt CC. 2019. Consequences of long-distance dispersal for epidemic spread: patterns, scaling, and mitigation. Plant Dis 103:177–191. https://doi.org/10.1094/PDIS-03-18-0505-FE.
58. Brown CM, Nuorti PJ, Breiman RF, Hathcock AL, Fields BS, Lipman HB, Llewellyn GC, Hofmann J, Cetron M. 1999. A community outbreak of Legionnaires' disease linked to hospital cooling towers: an epidemiological method to calculate dose of exposure. Int J Epidemiol 28:353–359. https://doi.org/10.1093/ije/28.2.353.
59. Castilla J, Barricarte A, Aldaz J, García Cenoz M, Ferrer T, Pelaz C, Pineda S, Baladrón B, Martín I, Goñi B, Aratajo P, Chamorro J, Lameiro F, Torroba L, Dorronsoro I, Martínez-Artola V, Esparza MJ, Gastaminza MA, Fraile P, Aldaz P. 2008. A large Legionnaires' disease outbreak in Pamplona, Spain: early detection, rapid control and no case fatality. Epidemiol Infect 136:823–832. https://doi.org/10.1017/S0950268807009077.

60. Sabria M, Alvarez J, Dominguez A, Pedrol A, Sauca G, Salleras L, Lopez A, Garcia-Nuñez MA, Parron I, Barrufet MP. 2006. A community outbreak of Legionnaires' disease: evidence of a cooling tower as the source. Clin Microbiol Infect 12:642–647. https://doi.org/10.1111/j.1469-0691.2006.01447.x.
61. Phares CR, Russell E, Thigpen MC, Service W, Crist MB, Salyers M, Engel J, Benson RF, Fields B, Moore MR. 2007. Legionnaires' disease among residents of a long-term care facility: the sentinel event in a community outbreak. Am J Infect Control 35:319–323. https://doi.org/10.1016/j.ajic.2006.09.014.
62. García-Fulgueiras A, Navarro C, Fenoll D, García J, González-Diego P, Jiménez-Buñuales T, Rodriguez M, Lopez R, Pacheco F, Ruiz J, Segovia M, Balandrón B, Pelaz C. 2003. Legionnaires' disease outbreak in Murcia, Spain. Emerg Infect Dis 9:915–921. https://doi.org/10.3201/eid0908.030337.
63. Garrison LE, Kunz JM, Cooley LA, Moore MR, Lucas C, Schrag S, Sarisky J, Whitney CG. 2016. Vital signs: deficiencies in environmental control identified in outbreaks of Legionnaires' disease—North America, 2000–2014. MMWR Morb Mortal Wkly Rep 65:576–584. https://doi.org/10.15585/mmwr.mm6522e1.
64. Weiss D, Boyd C, Rakeman JL, Greene SK, Fitzhenry R, McProud T, Musser K, Huang L, Kornblum J, Nazarian EJ, Fine AD, Braunstein SL, Kass D, Landman K, Lapierre P, Hughes S, Tran A, Taylor J, Baker D, Jones L, Kornstein L, Liu B, Perez R, Lucero DE, Peterson E, Benowitz I, Lee KF, Ngai S, Stripling M, Varma JK, South Bronx Legionnaires' Disease Investigation Team. 2017. A large community outbreak of Legionnaires' disease associated with a cooling tower in New York City, 2015. Public Health Rep 132:241–250. https://doi.org/10.1177/0033354916689620.
65. Fitzhenry R, Weiss D, Cimini D, Balter S, Boyd C, Alleyne L, Stewart R, McIntosh N, Econome A, Lin Y, Rubinstein I, Passaretti T, Kidney A, Lapierre P, Kass D, Varma JK. 2017. Legionnaires' disease outbreaks and cooling towers, New York City, New York, USA. Emerg Infect Dis 23:1769–1776. https://doi.org/10.3201/eid2311.161584.
66. Chamberlain AT, Lehnert JD, Berkelman RL. 2017. The 2015 New York City Legionnaires' disease outbreak: a case study on a history-making outbreak. J Public Health Manag Pract 23:410–416. https://doi.org/10.1097/PHH.0000000000000558.
67. Gilsdorf A, Kroh C, Grimm S, Jensen E, Wagner-Wiening C, Alpers K. 2008. Large Q fever outbreak due to sheep farming near residential areas, Germany, 2005. Epidemiol Infect 136:1084–1087. https://doi.org/10.1017/S0950268807009533.
68. Sehulster L, Chinn RYW. 2003. Guidelines for environmental infection control in health-care facilities. Centers for Disease Control and Prevention Healthcare Infection Control Practices Advisory Committee, Atlanta, GA.
69. Lentino JR, Rosenkranz MA, Michaels JA, Kurup VP, Rose HD, Rytel MW. 1982. Nosocomial aspergillosis: a retrospective review of airborne disease secondary to road construction and contaminated air conditioners. Am J Epidemiol 116:430–437. https://doi.org/10.1093/oxfordjournals.aje.a113427.
70. Luby JP, Southern PM, Haley CE, Vahle KL, Munford RS, Haley RW. 2005. Recurrent exposure to Histoplasma capsulatum in modern air-conditioned buildings. Clin Infect Dis 41:170–176. https://doi.org/10.1086/430907.
71. Chamany S, Mirza SA, Fleming JW, Howell JF, Lenhart SW, Mortimer VD, Phelan MA, Lindsley MD, Iqbal NJ, Wheat LJ, Brandt ME, Warnock DW, Hajjeh RA. 2004. A large histoplasmosis outbreak among high school students in Indiana, 2001. Pediatr Infect Dis J 23:909–914. https://doi.org/10.1097/01.inf.0000141738.60845.da.
72. Benedict K, Mody RK. 2016. Epidemiology of histoplasmosis outbreaks, United States, 1938–2013. Emerg Infect Dis 22:370–378. https://doi.org/10.3201/eid2203.151117.
73. Brenier-Pinchart M-P, Lebeau B, Quesada J-L, Mallaret MR, Borel J-L, Mollard A, Garban F, Brion J-P, Molina L, Bosson J-L, Cahn J-Y, Grillot R, Pelloux H. 2009. Influence of internal and outdoor factors on filamentous fungal flora in hematology wards. Am J Infect Control 37:631–637. https://doi.org/10.1016/j.ajic.2009.03.013.
74. Vonberg R-P, Gastmeier P. 2006. Nosocomial aspergillosis in outbreak settings. J Hosp Infect 63:246–254. https://doi.org/10.1016/j.jhin.2006.02.014.
75. Chang CC, Ananda-Rajah M, Belcastro A, McMullan B, Reid A, Dempsey K, Athan E, Cheng AC, Slavin MA. 2014. Consensus guidelines for implementation of quality processes to prevent invasive fungal disease and enhanced surveillance measures during hospital building works, 2014: quality processes in prevention of IFD. Intern Med J 44:1389–1397. https://doi.org/10.1111/imj.12601.
76. Blair JE, Chang Y-HH, Ruiz Y, Duffy S, Heinrich BE, Lake DF. 2014. Distance from construction site and risk for coccidioidomycosis, Arizona, USA. Emerg Infect Dis 20:1464–1471. https://doi.org/10.3201/eid2009.131588.
77. Alexander DJ. 2000. Newcastle disease and other avian paramyxoviruses. Rev Sci Tech 19:443–462. https://doi.org/10.20506/rst.19.2.1231.
78. Alexander DJ, Aldous EW, Fuller CM. 2012. The long view: a selective review of 40 years of Newcastle disease research. Avian Pathol 41:329–335. https://doi.org/10.1080/03079457.2012.697991.
79. Swayne DE. 2009. Avian influenza vaccines and therapies for poultry. Comp Immunol Microbiol Infect Dis 32:351–363. https://doi.org/10.1016/j.cimid.2008.01.006.
80. Hugh-Jones M, Allan WH, Dark FA, Harper GJ. 1973. The evidence for the airborne spread of Newcastle disease. J Hyg (Lond) 71:325–339. https://doi.org/10.1017/s0022172400022786.
81. Mitchell BW, King DJ. 1994. Effect of negative air ionization on airborne transmission of Newcastle disease virus. Avian Dis 38:725–732. https://doi.org/10.2307/1592107.
82. Hakim H, Thammakarn C, Suguro A, Ishida Y, Nakajima K, Kitazawa M, Takehara K. 2015. Aerosol disinfection capacity of slightly acidic hypochlorous acid water towards Newcastle disease virus in the air: an in vivo experiment. Avian Dis 59:486–491. https://doi.org/10.1637/11107-042115-Reg.1.
83. Pileri E, Mateu E. 2016. Review on the transmission porcine reproductive and respiratory syndrome virus between pigs and farms and impact on vaccination. Vet Res 47:108. https://doi.org/10.1186/s13567-016-0391-4.
84. Dee S, Otake S, Deen J. 2010. Use of a production region model to assess the efficacy of various air filtration systems for preventing airborne transmission of porcine reproductive and respiratory syndrome virus and Mycoplasma hyopneumoniae: results from a 2-year study. Virus Res 154:177–184. https://doi.org/10.1016/j.virusres.2010.07.022.
85. Otake S, Dee SA, Jacobson L, Pijoan C, Torremorell M. 2002. Evaluation of aerosol transmission of porcine reproductive and respiratory syndrome virus under controlled field conditions. Vet Rec 150:804–808. https://doi.org/10.1136/vr.150.26.804.
86. Reicks DL. 2019. Effective biosecurity to protect North American studs and clients from emerging infectious disease. Theriogenology 137:82–87. https://doi.org/10.1016/j.theriogenology.2019.05.041.
87. Ferguson DD, Smith TC, Donham KJ, Hoff SJ. 2015. The efficiency of biofilters at mitigating airborne MRSA from a swine nursery. J Agric Saf Health 21:217–227. https://doi.org/10.13031/jash.21.10716.
88. Hardy R, Schilling K, Fromm J, Dai X, Cook M. 2006. Technical background document: microbial risk assessment and fate and transport modeling of aerosolized microorganisms at wastewater land application facilities in Idaho. Idaho Department of Environmental Quality, Boise, ID.
89. Dungan RS. 2014. Estimation of infectious risks in residential populations exposed to airborne pathogens during center pivot irrigation of dairy wastewaters. Environ Sci Technol 48:5033–5042. https://doi.org/10.1021/es405693v.
90. Dungan RS. 2010. Board-invited review: fate and transport of bioaerosols associated with livestock operations and manures. J Anim Sci 88:3693–3706. https://doi.org/10.2527/jas.2010-3094.
91. Wery N. 2014. Bioaerosols from composting facilities—a review. Front Cell Infect Microbiol 4:42. https://doi.org/10.3389/fcimb.2014.00042.
92. Berry ED, Wells JE, Bono JL, Woodbury BL, Kalchayanand N, Norman KN, Suslow TV, López-Velasco G, Millner PD. 2015. Effect of proximity to a cattle feedlot on Escherichia coli O157:H7 contamination of leafy greens and evaluation of the potential for airborne transmission. Appl Environ Microbiol 81:1101–1110. https://doi.org/10.1128/AEM.02998-14.
93. Douglas P, Hayes ET, Williams WB, Tyrrel SF, Kinnersley RP, Walsh K, O'Driscoll M, Longhurst PJ, Pollard SJT, Drew GH. 2017. Use of dispersion modelling for environmental impact assessment of biological air pollution from composting: progress, problems and prospects. Waste Manag 70:22–29. https://doi.org/10.1016/j.wasman.2017.08.023.
94. Douglas P, Tyrrel SF, Kinnersley RP, Whelan M, Longhurst PJ, Hansell AL, Walsh K, Pollard SJT, Drew GH. 2017. Predicting Aspergillus fumigatus exposure from composting facilities using a dispersion model: a conditional calibration and validation. Int J Hyg Environ Health 220:17–28. https://doi.org/10.1016/j.ijheh.2016.09.017.
95. Li Y, Zhang H, Qiu X, Zhang Y, Wang H. 2013. Dispersion and risk assessment of bacterial aerosols emitted from rotating-brush aerator during summer in a wastewater treatment plant of Xi'an, China. Aerosol Air Qual Res 13:1807–1814. https://doi.org/10.4209/aaqr.2012.09.0245.

96. Camann DE, Moore BE, Harding HJ, Sorber CA. 1988. Microorganism levels in air near spray irrigation of municipal wastewater: the Lubbock Infection Surveillance Study. J Water Pollut Control Fed 60:1960–1970.
97. Pearson C, Littlewood E, Douglas P, Robertson S, Gant TW, Hansell AL. 2015. Exposures and health outcomes in relation to bioaerosol emissions from composting facilities: a systematic review of occupational and community studies. J Toxicol Environ Health B Crit Rev 18:43–69. https://doi.org/10.1080/10937404.2015.1009961.
98. Brown JKM, Hovmøller MS. 2002. Aerial dispersal of pathogens on the global and continental scales and its impact on plant disease. Science 297:537–541. https://doi.org/10.1126/science.1072678.
99. Meyer M, Cox JA, Hitchings MDT, Burgin L, Hort MC, Hodson DP, Gilligan CA. 2017. Quantifying airborne dispersal routes of pathogens over continents to safeguard global wheat supply. Nat Plants 3:780–786. https://doi.org/10.1038/s41477-017-0017-5.
100. Cain ML, Milligan BG, Strand AE. 2000. Long-distance seed dispersal in plant populations. Am J Bot 87:1217–1227. https://doi.org/10.2307/2656714.
101. Nathan R. 2006. Long-distance dispersal of plants. Science 313:786–788. https://doi.org/10.1126/science.1124975.
102. Nathan R, Katul GG, Bohrer G, Kuparinen A, Soons MB, Thompson SE, Trakhtenbrot A, Horn HS. 2011. Mechanistic models of seed dispersal by wind. Theor Ecol 4:113–132. https://doi.org/10.1007/s12080-011-0115-3.
103. Aylor DE. 2003. Spread of plant disease on a continental scale: role of aerial dispersal of pathogens. Ecology 84:1989–1997. https://doi.org/10.1890/01-0619.
104. Spijkerboer HP, Beniers JE, Jaspers D, Schouten HJ, Goudriaan J, Rabbinge R, van der Werf W. 2002. Ability of the Gaussian plume model to predict and describe spore dispersal over a potato crop. Ecol Model 155:1–18. https://doi.org/10.1016/S0304-3800(01)00475-6.
105. Gloster J, Jones A, Redington A, Burgin L, Sørensen JH, Turner R, Dillon M, Hullinger P, Simpson M, Astrup P, Garner G, Stewart P, D'Amours R, Sellers R, Paton D. 2010. Airborne spread of foot-and-mouth disease—model intercomparison. Vet J 183:278–286. https://doi.org/10.1016/j.tvjl.2008.11.011.
106. Donaldson AI, Alexandersen S. 2002. Predicting the spread of foot and mouth disease by airborne virus. Rev Sci Tech 21:569–575. https://doi.org/10.20506/rst.21.3.1362.
107. Gloster J, Freshwater A, Sellers RF, Alexandersen S. 2005. Re-assessing the likelihood of airborne spread of foot-and-mouth disease at the start of the 1967–1968 UK foot-and-mouth disease epidemic. Epidemiol Infect 133:767–783. https://doi.org/10.1017/S0950268805004073.
108. Gloster J, Burgin L, Jones A, Sanson R. 2011. Atmospheric dispersion models and their use in the assessment of disease transmission. Rev Sci Tech 30:457–465. https://doi.org/10.20506/rst.30.2.2055.
109. Fisher MC, Henk DA, Briggs CJ, Brownstein JS, Madoff LC, McCraw SL, Gurr SJ. 2012. Emerging fungal threats to animal, plant and ecosystem health. Nature 484:186–194. https://doi.org/10.1038/nature10947.
110. Isard SA, Gage SH, Comtois P, Russo JM. 2005. Principles of the atmospheric pathway for invasive species applied to soybean rust. Bioscience 55:851–861. https://doi.org/10.1641/0006-3568(2005)055[0851:POTAPF]2.0.CO;2.
111. Skelsey P, Kessel GJT, Holtslag AAM, Moene AF, van der Werf W. 2009. Regional spore dispersal as a factor in disease risk warnings for potato late blight: a proof of concept. Agric For Meteorol 149:419–430. https://doi.org/10.1016/j.agrformet.2008.09.005.
112. Aylor DE, Taylor GS, Raynor GS. 1982. Long-range transport of tobacco blue mold spores. Agric Meteorol 27:217–232. https://doi.org/10.1016/0002-1571(82)90007-3.
113. Blanco-Meneses M, Carbone I, Ristaino JB. 2018. Population structure and migration of the tobacco blue mold pathogen, *Peronospora tabacina*, into North America and Europe. Mol Ecol 27:737–751. https://doi.org/10.1111/mec.14453.
114. Gloster J. 1983. Analysis of two outbreaks of Newcastle disease. Agric Meteorol 28:177–189. https://doi.org/10.1016/0002-1571(83)90006-7.
115. Ssematimba A, Hagenaars TJ, de Jong MCM. 2012. Modelling the wind-borne spread of highly pathogenic avian influenza virus between farms. PLoS One 7:e31114. https://doi.org/10.1371/journal.pone.0031114.
116. Ypma RJF, Jonges M, Bataille A, Stegeman A, Koch G, van Boven M, Koopmans M, van Ballegooijen WM, Wallinga J. 2013. Genetic data provide evidence for wind-mediated transmission of highly pathogenic avian influenza. J Infect Dis 207:730–735. https://doi.org/10.1093/infdis/jis757.
117. Dee S, Otake S, Oliveira S, Deen J. 2009. Evidence of long distance airborne transport of porcine reproductive and respiratory syndrome virus and *Mycoplasma hyopneumoniae*. Vet Res 40:39. https://doi.org/10.1051/vetres/2009022.
118. Otake S, Dee S, Corzo C, Oliveira S, Deen J. 2010. Long-distance airborne transport of infectious PRRSV and Mycoplasma hyopneumoniae from a swine population infected with multiple viral variants. Vet Microbiol 145:198–208. https://doi.org/10.1016/j.vetmic.2010.03.028.
119. Firestone SM, Cogger N, Ward MP, Toribio J-ALML, Moloney BJ, Dhand NK. 2012. The influence of meteorology on the spread of influenza: survival analysis of an equine influenza (A/H3N8) outbreak. PLoS One 7:e35284. https://doi.org/10.1371/journal.pone.0035284.
120. Gloster J. 1982. Risk of airborne spread of foot-and-mouth disease from the continent to England. Vet Rec 111:290–295. https://doi.org/10.1136/vr.111.13.290.
121. Gloster J, Sellers RF, Donaldson AI. 1982. Long distance transport of foot-and-mouth disease virus over the sea. Vet Rec 110:47–52. https://doi.org/10.1136/vr.110.3.47.
122. Gloster J, Blackall RM, Sellers RF, Donaldson AI. 1981. Forecasting the airborne spread of foot-and-mouth disease. Vet Rec 108:370–374. https://doi.org/10.1136/vr.108.17.370.
123. Christensen LS, Normann P, Thykier-Nielsen S, Sørensen JH, de Stricker K, Rosenørn S. 2005. Analysis of the epidemiological dynamics during the 1982-1983 epidemic of foot-and-mouth disease in Denmark based on molecular high-resolution strain identification. J Gen Virol 86:2577–2584. https://doi.org/10.1099/vir.0.80878-0.
124. Mikkelsen T, Alexandersen S, Astrup P, Champion HJ, Donaldson AI, Dunkerley FN, Gloster J, Sørensen JH, Thykier-Nielsen S. 2003. Investigation of airborne foot-and-mouth disease virus transmission during low-wind conditions in the early phase of the UK 2001 epidemic. Atmos Chem Phys 3:2101–2110. https://doi.org/10.5194/acp-3-2101-2003.
125. Sorensen JH, Mackay DKJ, Jensen CO, Donaldson AI. 2000. An integrated model to predict the atmospheric spread of foot-and-mouth disease virus. Epidemiol Infect 124:577–590. https://doi.org/10.1017/s095026889900401x.
126. Hagerman AD, South DD, Sondgerath TC, Patyk KA, Sanson RL, Schumacher RS, Delgado AH, Magzamen S. 2018. Temporal and geographic distribution of weather conditions favorable to airborne spread of foot-and-mouth disease in the coterminous United States. Prev Vet Med 161:41–49. https://doi.org/10.1016/j.prevetmed.2018.10.016.
127. Clark NJ, Soares Magalhães RJ. 2018. Airborne geographical dispersal of Q fever from livestock holdings to human communities: a systematic review and critical appraisal of evidence. BMC Infect Dis 18:218. https://doi.org/10.1186/s12879-018-3135-4.
128. Hawker JI, Ayres JG, Blair I, Evans MR, Smith DL, Smith EG, Burge PS, Carpenter MJ, Caul EO, Coupland B, Desselberger U, Farrell ID, Saunders PJ, Wood MJ. 1998. A large outbreak of Q fever in the West Midlands: windborne spread into a metropolitan area? Commun Dis Public Health 1:180–187.
129. Tissot-Dupont H, Amadei M-A, Nezri M, Raoult D. 2004. Wind in November, Q fever in December. Emerg Infect Dis 10:1264–1269. https://doi.org/10.3201/eid1007.030724.
130. Tissot-Dupont H, Torres S, Nezri M, Raoult D. 1999. Hyperendemic focus of Q fever related to sheep and wind. Am J Epidemiol 150:67–74. https://doi.org/10.1093/oxfordjournals.aje.a009920.
131. Dupuis G, Petite J, Péter O, Vouilloz M. 1987. An important outbreak of human Q fever in a Swiss alpine valley. Int J Epidemiol 16:282–287. https://doi.org/10.1093/ije/16.2.282.
132. Brooke RJ, Mutters NT, Péter O, Kretzschmar MEE, Teunis PFM. 2015. Exposure to low doses of Coxiella burnetii caused high illness attack rates: insights from combining human challenge and outbreak data. Epidemics 11:1–6. https://doi.org/10.1016/j.epidem.2014.12.004.
133. Schimmer B, ter Schegget R, Wegdam M, Züchner L, de Bruin A, Schneeberger PM, Veenstra T, Vellema P, van der Hoek W. 2010. The use of a geographic information system to identify a dairy goat farm as the most likely source of an urban Q-fever outbreak. BMC Infect Dis 10:69. https://doi.org/10.1186/1471-2334-10-69.
134. van Leuken JPG, van de Kassteele J, Sauter FJ, van der Hoek W, Heederik D, Havelaar AH, Swart AN. 2015. Improved correlation of human Q fever incidence to modelled C. burnetii concentrations by means of an atmospheric dispersion model. Int J Health Geogr 14:14. https://doi.org/10.1186/s12942-015-0003-y.
135. Hackert VH, van der Hoek W, Dukers-Muijrers N, de Bruin A, Al Dahouk S, Neubauer H, Bruggeman CA, Hoebe CJPA. 2012. Q fever: single-point source outbreak with high attack rates and massive numbers of

undetected infections across an entire region. Clin Infect Dis 55:1591–1599. https://doi.org/10.1093/cid/cis734.
136. Schneeberger PM, Wintenberger C, van der Hoek W, Stahl JP. 2014. Q fever in the Netherlands—2007–2010: what we learned from the largest outbreak ever. Med Mal Infect 44:339–353. https://doi.org/10.1016/j.medmal.2014.02.006.
137. van der Hoek W, Dijkstra F, Schimmer B, Schneeberger PM, Vellema P, Wijkmans C, ter Schegget R, Hackert V, van Duynhoven Y. 2010. Q fever in the Netherlands: an update on the epidemiology and control measures. Euro Surveill 15:19520. https://www.eurosurveillance.org/content/10.2807/ese.15.12.19520-en.
138. Hackert VH, Hoebe CJPA, Dukers-Muijrers N, Krafft T, Kauhl B, Henning K, Karges W, Sprague L, Neubauer H, Al Dahouk S. 2020. Q fever: evidence of a massive yet undetected cross-border outbreak, with ongoing risk of extra mortality, in a Dutch-German border region. Transbound Emerg Dis 67:1660–1670. https://doi.org/10.1111/tbed.13505.
139. Parr A, Whitney EA, Berkelman RL. 2015. Legionellosis on the rise: a review of guidelines for prevention in the United States. J Public Health Manag Pract 21:E17–E26. https://doi.org/10.1097/PHH.0000000000000123.
140. Nygard K, Werner-Johansen O, Ronsen S, Caugant DA, Simonsen O, Kanestrom A, Ask E, Ringstad J, Odegard R, Jensen T, Krogh T, Hoiby EA, Ragnhildstveit E, Aaberge IS, Aavitsland P. 2008. An outbreak of Legionnaires disease caused by long-distance spread from an industrial air scrubber in Sarpsborg, Norway. Clin Infect Dis 46:61–69. https://doi.org/10.1086/524016.
141. Nguyen TMN, Ilef D, Jarraud S, Rouil L, Campese C, Che D, Haeghebaert S, Ganiayre F, Marcel F, Etienne J, Desenclos J-C. 2006. A community-wide outbreak of Legionnaires disease linked to industrial cooling towers—how far can contaminated aerosols spread? J Infect Dis 193:102–111. https://doi.org/10.1086/498575.
142. Ulleryd P, Hugosson A, Allestam G, Bernander S, Claesson BE, Eilertz I, Hagaeus A-C, Hjorth M, Johansson A, de Jong B, Lindqvist A, Nolskog P, Svensson N. 2012. Legionnaires' disease from a cooling tower in a community outbreak in Lidköping, Sweden—epidemiological, environmental and microbiological investigation supported by meteorological modelling. BMC Infect Dis 12:313. https://doi.org/10.1186/1471-2334-12-313.
143. Wedege E, Bergdal T, Bolstad K, Caugant DA, Efskind J, Heier HE, Kanestrom A, Strand BH, Aaberge IS. 2009. Seroepidemiological study after a long-distance industrial outbreak of Legionnaires' disease. Clin Vaccine Immunol 16:528–534. https://doi.org/10.1128/CVI.00458-08.
144. Russo A, Gouveia CM, Soares PMM, Cardoso RM, Mendes MT, Trigo RM. 2018. The unprecedented 2014 Legionnaires' disease outbreak in Portugal: atmospheric driving mechanisms. Int J Biometeorol 62:1167–1179. https://doi.org/10.1007/s00484-018-1520-8.
145. Nguyen C, Barker BM, Hoover S, Nix DE, Ampel NM, Frelinger JA, Orbach MJ, Galgiani JN. 2013. Recent advances in our understanding of the environmental, epidemiological, immunological, and clinical dimensions of coccidioidomycosis. Clin Microbiol Rev 26:505–525. https://doi.org/10.1128/CMR.00005-13.
146. D'Alessio DJ, Heeren RH, Hendricks SL, Ogilvie P, Furcolow ML. 1965. A starling roost as the source of urban epidemic histoplasmosis in an area of low incidence. Am Rev Respir Dis 92:725–731.
147. Tosh FE, Doto IL, D'Alessio DJ, Medeiros AA, Hendricks SL, Chin TD. 1966. The second of two epidemics of histoplasmosis resulting from work on the same starling roost. Am Rev Respir Dis 94:406–413. https://doi.org/10.1164/arrd.1966.94.3.406.
148. Sellers TF, Price WN, Newberry WM. 1965. An epidemic of erythema multiforme and erythema nodosum caused by histoplasmosis. Ann Intern Med 62:1244–1262. https://doi.org/10.7326/0003-4819-62-6-1244.
149. Schlech WF, Wheat LJ, Ho JL, French ML, Weeks RJ, Kohler RB, Deane CE, Eitzen HE, Band JD. 1983. Recurrent urban histoplasmosis, Indianapolis, Indiana, 1980-1981. Am J Epidemiol 118:301–312. https://doi.org/10.1093/oxfordjournals.aje.a113637.
150. Drutz DJ. 1979. Urban coccidioidomycosis and histoplasmosis: Sacramento and Indianapolis. N Engl J Med 301:381–382. https://doi.org/10.1056/NEJM197908163010711.
151. Wheat LJ, Slama TG, Eitzen HE, Kohler RB, French ML, Biesecker JL. 1981. A large urban outbreak of histoplasmosis: clinical features. Ann Intern Med 94:331–337. https://doi.org/10.7326/0003-4819-94-3-331.
152. Lauer A, Talamantes J, Castañón Olivares LR, Medina LJ, Baal JDH, Casimiro K, Shroff N, Emery KW. 2014. Combining forces—the use of Landsat TM satellite imagery, soil parameter information, and multiplex PCR to detect Coccidioides immitis growth sites in Kern County, California. PLoS One 9:e111921. https://doi.org/10.1371/journal.pone.0111921.
153. Harris WJ, Roffers PD. 2010. Assessing erosion potential and Coccidioides immitis probability using existing geologic and soils data, p 75–80. *In* Soller DR (ed), Digital mapping techniques '10—workshop proceedings. U.S. Geological Survey open-file report 2012–1171. US Geological Survey, Sacramento, CA.
154. Brown J, Benedict K, Park BJ, Thompson GR, III. 2013. Coccidioidomycosis: epidemiology. Clin Epidemiol 5:185–197. https://doi.org/10.2147/CLEP.S34434.
155. Sondermeyer G, Lee L, Gilliss D, Tabnak F, Vugia D. 2013. Coccidioidomycosis-associated hospitalizations, California, USA, 2000–2011. Emerg Infect Dis 19:1590–1597. https://doi.org/10.3201/eid1910.130427.
156. Wheeler C, Lucas KD, Mohle-Boetani JC. 2015. Rates and risk factors for coccidioidomycosis among prison inmates, California, USA, 2011. Emerg Infect Dis 21:70–75. https://doi.org/10.3201/eid2101.140836.
157. Benedict K, Park BJ. 2014. Invasive fungal infections after natural disasters. Emerg Infect Dis 20:349–355. https://doi.org/10.3201/eid2003.131230.
158. Schneider E, Hajjeh RA, Spiegel RA, Jibson RW, Harp EL, Marshall GA, Gunn RA, McNeil MM, Pinner RW, Baron RC, Burger RC, Hutwagner LC, Crump C, Kaufman L, Reef SE, Feldman GM, Pappagianis D, Werner SB. 1997. A coccidioidomycosis outbreak following the Northridge, Calif, earthquake. JAMA 277:904–908. https://doi.org/10.1001/jama.1997.03540350054033.
159. Jibson RW. 2002. A public health issue related to collateral seismic hazards: the valley fever outbreak triggered by the 1994 Northridge, California earthquake. Surv Geophys 23:511–528. https://doi.org/10.1023/A:1021226827679.
160. Jibson RW, Harp EL, Schneider E, Hajjeh RA, Spiegel RA. 1998. An outbreak of coccidioidomycosis (valley fever) caused by landslides triggered by the 1994 Northridge, California, earthquake. Geol Soc Rev Eng Geol 12:53–61. https://doi.org/10.1130/REG12-p53.
161. Thompson SE, Katul GG. 2013. Implications of nonrandom seed abscission and global stilling for migration of wind-dispersed plant species. Glob Chang Biol 19:1720–1735. https://doi.org/10.1111/gcb.12173.
162. Smith DJ, Timonen HJ, Jaffe DA, Griffin DW, Birmele MN, Perry KD, Ward PD, Roberts MS. 2013. Intercontinental dispersal of bacteria and archaea by Transpacific winds. Appl Environ Microbiol 79:1134–1139. https://doi.org/10.1128/AEM.03029-12.
163. Mazar Y, Cytryn E, Erel Y, Rudich Y. 2016. Effect of dust storms on the atmospheric microbiome in the Eastern Mediterranean. Environ Sci Technol 50:4194–4202. https://doi.org/10.1021/acs.est.5b06348.
164. Behzad H, Mineta K, Gojobori T. 2018. Global ramifications of dust and sandstorm microbiota. Genome Biol Evol 10:1970–1987. https://doi.org/10.1093/gbe/evy134.
165. Weil T, De Filippo C, Albanese D, Donati C, Pindo M, Pavarini L, Carotenuto F, Pasqui M, Poto L, Gabrieli J, Barbante C, Sattler B, Cavalieri D, Miglietta F. 2017. Legal immigrants: invasion of alien microbial communities during winter occurring desert dust storms. Microbiome 5:32. https://doi.org/10.1186/s40168-017-0249-7.
166. Peter H, Hörtnagl P, Reche I, Sommaruga R. 2014. Bacterial diversity and composition during rain events with and without Saharan dust influence reaching a high mountain lake in the Alps. Environ Microbiol Rep 6:618–624. https://doi.org/10.1111/1758-2229.12175.
167. Kellogg CA, Griffin DW, Garrison VH, Peak KK, Royall N, Smith RR, Shinn EA. 2004. Characterization of aerosolized bacteria and fungi from desert dust events in Mali, West Africa. Aerobiologia 20:99–110. https://doi.org/10.1023/B:AERO.0000032947.88335.bb.
168. Griffin DW. 2007. Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. Clin Microbiol Rev 20:459–477. https://doi.org/10.1128/CMR.00039-06.
169. Polymenakou PN. 2012. Atmosphere: a source of pathogenic or beneficial microbes? Atmosphere 3:87–102. https://doi.org/10.3390/atmos3010087.
170. Pappagianis D, Einstein H. 1978. Tempest from Tehachapi takes toll or Coccidioides conveyed aloft and afar. West J Med 129:527–530.
171. Hermansen JE, Torp U, Prahm LP. 1978. Studies of transport of live spores of cereal mildew and rust fungi across the North Sea. Grana 17:41–46. https://doi.org/10.1080/00173137809428851.
172. Mundt CC, Wallace LD, Allen TW, Hollier CA, Kemerait RC, Sikora EJ. 2013. Initial epidemic area is strongly associated with the yearly extent of soybean rust spread in North America. Biol Invasions 15:1431–1438. https://doi.org/10.1007/s10530-012-0381-z.

173. Flynn NM, Hoeprich PD, Kawachi MM, Lee KK, Lawrence RM, Goldstein E, Jordan GW, Kundargi RS, Wong GA. 1979. An unusual outbreak of windborne coccidioidomycosis. N Engl J Med 301:358–361. https://doi.org/10.1056/NEJM197908163010705.
174. Williams PL, Sable DL, Mendez P, Smyth LT. 1979. Symptomatic coccidioidomycosis following a severe natural dust storm. Chest 76:566–570. https://doi.org/10.1378/chest.76.5.566.
175. Sprigg WA, Nickovic S, Galgiani JN, Pejanovic G, Petkovic S, Vujadinovic M, Vukovic A, Dacic M, DiBiase S, Prasad A, El-Askary H. 2014. Regional dust storm modeling for health services: the case of valley fever. Aeolian Res 14:53–73. https://doi.org/10.1016/j.aeolia.2014.03.001.
176. Perkins WA, Vaughan LM. 1961. Public health implications of airborne infection: physical aspects. Bacteriol Rev 25:347–355. https://doi.org/10.1128/MMBR.25.3.347-355.1961.
177. Jones AM, Harrison RM. 2004. The effects of meteorological factors on atmospheric bioaerosol concentrations—a review. Sci Total Environ 326:151–180. https://doi.org/10.1016/j.scitotenv.2003.11.021.
178. Langmuir AD. 1961. Public health implications of airborne infection: medical aspects. Bacteriol Rev 25:356–358. https://doi.org/10.1128/MMBR.25.3.356-358.1961.
179. Roy CJ, Milton DK. 2004. Airborne transmission of communicable infection—the elusive pathway. N Engl J Med 350:1710–1712. https://doi.org/10.1056/NEJMp048051.
180. Pandit P, Hoch T, Ezanno P, Beaudeau F, Vergu E. 2016. Spread of Coxiella burnetii between dairy cattle herds in an enzootic region: modelling contributions of airborne transmission and trade. Vet Res 47:48. https://doi.org/10.1186/s13567-016-0330-4.
181. Anderson AD, Kruszon-Moran D, Loftis AD, McQuillan G, Nicholson WL, Priestley RA, Candee AJ, Patterson NE, Massung RF. 2009. Seroprevalence of Q fever in the United States, 2003–2004. Am J Trop Med Hyg 81:691–694. https://doi.org/10.4269/ajtmh.2009.09-0168.
182. Cassell K, Gacek P, Rabatsky-Ehr T, Petit S, Cartter M, Weinberger DM. 2019. Estimating the true burden of Legionnaires' disease. Am J Epidemiol 188:1686–1694. https://doi.org/10.1093/aje/kwz142.

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