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Editorial

From commensalism to mutualism: integrating the microbial ecology, building science, and indoor air communities to advance research on the indoor microbiome

People throughout the world spend most of their time indoors, cohabitating with diverse microbial communities both on material surfaces and suspended in the indoor air. Advances in DNA sequencing techniques that allow rapid, high-throughput characterization of taxonomic marker genes (e.g., bacterial 16S rRNA and fungal ITS) and metagenomic DNA from environmental samples have enabled a sharp increase in the number of studies exploring various aspects of microbial diversity and abundance in indoor environments (Kelley and Gilbert, 2013; Konya and Scott, 2014; Peccia et al., 2011; Ramos and Stephens, 2014). Compared to culturing or chemical-marker based techniques, the new DNA-based methods provide a deeper insight into the structure (i.e., relative proportions of rare and abundant organisms) and composition (i.e., the phylogenetic structure of taxa) of microbial communities in environmental samples. Recent investigations in indoor environments—many of which have been initiated with research funding from the Alfred P. Sloan Foundation's program on the Microbiology of the Built Environment (MoBE)—have characterized microbial communities on surfaces and in air within the spaces in which we live and work, emphasizing buildings without obvious mold or moisture problems. Environments investigated include offices and other commercial buildings, university classrooms, healthcare facilities, homes, public restrooms and transportation settings.

Several key findings have resulted from this group of studies:

- Culture-based methods vastly underestimate the abundance, diversity, and functional potential of microbial communities in indoor air (e.g., Tringe et al., 2008);
- Bacterial communities in occupied environments show a strong influence from human and animal inhabitants and are influenced by patterns of occupancy (Hewitt et al., 2013; Hospodsky et al., 2012; Qian et al., 2012). Correspondingly, the microbiome of human inhabitants may show an environmental fingerprint (Brooks et al., 2014; Lax et al., 2014);
- In buildings without a history of moisture problems, fungal communities appear to originate primarily from local outdoor environments, though human activities may influence their dynamics (e.g., resuspension) indoors (e.g., Adams et al., 2013a,b; Amend et al., 2010; Qian et al., 2012);
- Building characteristics, such as surface materials and outdoor air ventilation strategies, also influence the diversity and abundance of microbial communities found indoors (e.g., Frankel et al., 2012; Kembel et al., 2012, 2014; Meadow et al., 2014).

The built environment as a set of distinct ecological habitats is a nascent but increasingly appreciated concept. Emerging research is helping us understand how basic ecological processes such as dispersal and selection pressures can structure indoor microbial communities. But to a large degree, in studies that have focused on ecological-oriented questions about the 'indoor microbiome,' the building science and indoor air communities have played only supporting roles. For example, many recent studies have insufficiently characterized operational and environmental characteristics that are important for building function and that could also influence microbial communities, such as air-exchange rates, temperature, humidity, surface moisture, and human occupancy (Ramos and Stephens, 2014). Insufficiently documented building characteristics limit our ability to generalize findings or to apply results to design strategies for controlling indoor microbial communities (Corsi et al., 2012). As such, the relevance of the information from these studies has not been immediately clear or translatable to those in the building science and indoor air communities. While the microbial ecology field has benefited from increased understanding of fundamental processes, the indoor air community has remained largely unaffected. In ecological terms, this relationship may be described as 'commensalism'—where one organism benefits without affecting the other.

We propose that the relationship between microbial ecology and building/indoor air sciences needs to move toward 'mutualism'—a relationship in which both entities benefit. To help achieve progress toward this goal, we held a Sloan-funded workshop, *Building science to advance research in the microbiology of the built environment*, in May 2014 at the Illinois Institute of Technology in Chicago, IL. The goals were to engage the building science and indoor air communities in this growing field and facilitate discussions with a small group of molecular biologists. Our specific aims were, first, to identify gaps in current studies, and, second, to inform a research agenda for future studies of the indoor microbiome that stems from deep knowledge of how buildings are constructed, operated, and occupied. The details of the workshop are described in full in a workshop report and meeting transcript (Stephens, 2014). In summary, the workshop identified target areas in which MoBE research can improve to become more directly informative for those in the building science and indoor air communities. Here are some key goals identified through this process:

- Increase the use and/or development of methods for microbial *quantification* and other quantitative *metrics*, particularly those that may be more relevant to human exposure and health than relative abundance (e.g., absolute abundance, viability, metabolic activity, allergenicity, etc.).
- Conduct longitudinal *intervention and controlled environment studies* that focus on *fundamental processes* familiar to those in the indoor air sciences (e.g., emission, survival, fate, and transport). Examples include investigations into the influence of built environment factors (e.g., air exchange, indoor environmental conditions, filtration, and occupancy characteristics) on microbial community characteristics or measurements of microbial community progressions over building-relevant time scales.
- Engage a *broader funding base*. The general consensus was that study questions must be broadened to include health and/or energy efficiency goals to successfully engage a wider variety of funding sources and partners, including:
  - Industries involved in the building design, construction, operation, and occupational fields.
  - Governmental sources focused on various aspects of public and environmental health.

  Efforts should include partnering with existing health, building science, or indoor air studies where appropriate and advantageous.
- Continue and enhance efforts to *communicate* and *transfer knowledge* between microbiology and building science communities, and begin integrating *health scientists* into the research agenda. Relatedly, more interdisciplinary workshops should be pursued, including, for instance, a cross-disciplinary, hands-on workshop where researchers experience and learn each other's methods, terminology, and tools, or where a wider variety of stakeholders (including practitioners) engage more closely with each other's methods.
- Continue efforts to *improve standardization and evaluation of sampling methods*.
  - Includes both air and surface sampling methods for microbial characterization and built environment data collection.
  - Standardization must include flexibility for study design and future method developments and applications.
- Explore connections between *indoor microbiology and chemistry*.

This list is not exhaustive. However, addressing these broad priority areas is expected to improve our understanding of the complex connections between building design, operation, and occupancy, indoor microbiomes, and human exposure and health. Active participation by the indoor air and building science communities in a mutualistic relationship with microbial ecology at this stage of the burgeoning research agenda is crucial to meeting this goal!

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