Annual Review of Public Health

Building Evidence for Health: Green Buildings, Current Science, and Future Challenges

J.G. Cedeño-Laurent, A. Williams, P. MacNaughton, X. Cao, E. Eitland, J. Spengler, and J. Allen

Environmental Health Department, Harvard T.H. Chan School of Public Health, Boston, Massachusetts 02215, USA; email: memocedeno@mail.harvard.edu

Annu. Rev. Public Health 2018. 39:291–308

First published as a Review in Advance on January 12, 2018

The *Annual Review of Public Health* is online at publhealth.annualreviews.org

https://doi.org/10.1146/annurev-publhealth-031816-044420

Keywords

health, indoor environmental quality, green buildings, sustainability, human rights, built environment

Abstract

Civilizational challenges have questioned the status quo of energy and material consumption by humans. From the built environment perspective, a response to these challenges was the creation of green buildings. Although the revolutionary capacity of the green building movement has elevated the expectations of new commercial construction, its rate of implementation has secluded the majority of the population from its benefits. Beyond reductions in energy usage and increases in market value, the main strength of green buildings may be the procurement of healthier building environments. Further pursuing the right to healthy indoor environments could help the green building movement to attain its full potential as a transformational public health tool. On the basis of 40 years of research on indoor environmental quality, we present a summary of nine environment elements that are foundational to human health. We posit the role of green buildings as a critical research platform within a novel sustainability framework based on social-environmental capital assets.

INTRODUCTION

The relationship between habitation and human health dates back to the Middle Pleistocene (781–126 kya). Early evidence of exposure to microcharcoal and soot in Lower Paleolithic hominis from indoor cave smoke suggests that humans were affected by indoor environmental exposures resulting from activities that were critical to civilization (e.g., control of fire) (53, 132). Since then, we have faced unexpected consequences from modifying our interactions with the built environment and buildings, such as the sanitation crisis at the end of the nineteenth century (75) or the energy crisis in the 1970s and the subsequent onset of sick building syndrome (SBS) cases (11, 46, 62). More recently, rapid urbanization and population growth have led to the extensive use of natural resources for construction, adding to the significant greenhouse gas emissions from existing and new buildings. This practice has made significant impacts on the health of ecosystems and a changing climate. In response, ecological sustainability was developed as a field of study to stop, and revert to the extent possible, the damages inflicted on planetary health by human activities.

In buildings, sustainability has been driven primarily by green building rating systems (RSs). The presence of green buildings now extends to more than 160 countries, assessed with more than 40 building RSs as reported by the World Green Building Council. In principle, RSs share a similar approach: a performance evaluation of a building based mostly on design parameters, according to consensus-based criteria on domains such as energy and water consumption, use of natural resources, and indoor environmental quality (IEQ). Similar to sustainability, RSs focused initially on the reduction of energy and water use and waste. Green buildings have so successfully galvanized a market transformation by offering sustainable solutions that, although the concepts were initially considered cutting edge, many of these criteria are now standard and expected minimum design criteria for new buildings in major real estate markets, regardless of whether the buildings pursue RS credits.

This significant shift in building practices has resulted in benefits to human health at different scales (84). At the societal level, green buildings may reduce pollutant emissions by consuming less energy. Although the benefits of green buildings to the broader society are a compelling argument for certification and government mandates for their use, return on investment for property owners as well as improvements in occupants' health, satisfaction, and productivity are presumably the most tangible benefits and are therefore the greatest motivation for building owners and tenants to pursue green building certification. As green building elements that promote energy efficiency have become the norm, we have seen a shift in the market toward designing, operating, and maintaining "healthy buildings."

In this review, we focus on this last aspect—human health, satisfaction, and productivity—and aim to provide a brief summary of the scientific evidence related to buildings and health. We divide this review into nine foundational elements that constitute a healthy building (indoor air quality, ventilation, thermal health, water quality, dampness and mold, dust and pests, noise, light and views, and safety and security), which were chosen on the basis of evidence of a causal or strongly suggestive relationship between each foundational element and health outcomes. Studies from all types of buildings (green and conventional) were considered, allowing us to draw on reliable study designs from four decades of IEQ research and larger samples of buildings and study participants rather than exclusively relying on green buildings. As a result, the nine foundational elements are not particular to any specific rating system; rather, they represent the foundational components of any healthy, green building. Finally, we present our views on how green buildings should evolve to become an effective public health tool to address current and future challenges of indoor environments and human health.

FOUNDATIONAL ELEMENTS OF A HEALTHY BUILDING

Indoor Air Quality

Indoor air quality (IAQ) is a simplified term that is used to describe the complex topic that explores how the air in indoor environments impacts human health, comfort, and productivity. The term IAQ includes all the chemical, radiological, biological, and physical pollutants to which we are exposed via indoor air (131). Therefore, it is a subset of overall IEQ, which includes water, dust, and lighting, among others. IAQ is too broad of a topic to be adequately described within the scope of this paper. Here we present a succinct description of IAQ for readers unfamiliar with the topic, and we direct readers to the many excellent and thorough reviews that cover by now well-established exposure-response functions for common pollutants (3, 95, 117, 122).

IAQ is influenced by three primary factors: pollutants generated indoors, for example from building products (e.g., formaldehyde), consumer products [e.g., volatile organic compounds (VOCs)], animals (e.g., human bioeffluent, animal allergens), and human activity (e.g., cooking, spraying pesticides); pollutants generated outdoors that penetrate indoors (e.g., radon, diesel exhaust); and the building systems and conditions that can act to mitigate or exacerbate these exposures (e.g., ventilation, filtration, moisture). Poor IAQ has been associated with both acute effects such as asthma, fatigue, irritation, and headache, as well as chronic effects such as cancer, depending on the pollutant, pollutant concentration, and exposure duration.

Quantifying the economic costs and benefits of IAQ remains a critical research area because these types of analyses influence government policy and policy makers, as well as building owners and designers who are often making trade-offs to save building costs without accounting for the health ramifications of those decisions. Poor IAQ is associated with increased absenteeism (93), increased sick building symptoms (119), and increases in infectious disease transmission (44, 58, 70), all of which have associated economic impacts. A 2008 meta-analysis evaluated the monetary and societal costs of indoor air pollutant–related damages and observed a range of reported damages associated with poor IAQ, including productivity loss, health care costs, and building damages (from moist air and mold development). Each study estimated upwards of $10 million in annual "air pollution costs" (101). There are also significant economic benefits from cleaner indoor environments. In the United States alone, the cost savings and productivity gains from improved indoor environments have been estimated at $25 billion to $150 billion per year (47).

IAQ is a multidisciplinary phenomenon and serves as the basis and cross-point for all the foundational elements reviewed in this article. Singular strategies may not be effective in responding to the deterioration of IAQ by climate change (CC), energy conservation, and social developments. Rather, holistic solutions geared toward a better IAQ are preferable, including innovations in air distribution, air cleaning, and indoor environmental devices/systems, and should leverage smart technologies and sensing systems with user management that optimizes IAQ on the basis of real-time health performance indicators (122).

Ventilation

Ventilation plays a crucial role in creating healthy IAQ by regulating the air velocity, temperature, relative humidity, and airborne contaminant concentrations (33). Ventilation in buildings brings in fresh air from outside and dilutes occupant-generated pollutants (e.g., CO_2, odors) and product-generated pollutants (e.g., VOCs) (77). Although a mechanically ventilated building system filters outdoor air, outdoor pollutants such as $PM_{2.5}$ can penetrate indoors if the mechanical system does not properly filter the air stream. Because people spend approximately 90% of their time indoors, the main exposure to outdoor air pollution may occur indoors (31, 79). Even with proper ventilation, the concentration of pollutants indoors can be higher than concentrations found outdoors (116).

Occupants in poorly ventilated spaces often report symptoms such as headache, fatigue, shortness of breath, sinus congestion, cough, sneezing, dizziness, and nausea, as well as eye, nose, throat, and skin irritation (91). Lower indoor ventilation rates are associated with higher rates of short-term sick leave, asthma, and respiratory infection (120). This collection of symptoms stemming from extended exposure to poorly ventilated spaces has been deemed sick building syndrome (SBS) (39, 128). Studies have also found an association between the ventilation of buildings and the transmission of airborne infections (77, 83, 111). Ventilation has also shown strong associations with cognitive function; a 400-ppm increase in indoor CO_2 levels has been associated with a 21% decrease in performance on a cognitive task (4, 84, 85). In primary schools, low classroom ventilation rates resulted in significant decreases in academic achievement (54). Many studies have suggested that green buildings with increased ventilation generally have lower levels of pollutants (e.g., VOCs, nitrogen dioxide, particulate matter) (64, 98) and that occupants have reported the perception of improved IAQ and fewer health problems (34, 86).

To ensure better IAQ in building spaces, current ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) standards require a minimum ventilation of 20 cubic feet per minute per person (12) and recommend regular maintenance of heating, ventilation, and air conditioning (HVAC) systems, as substandard ventilation often occurs in buildings where HVAC systems are either neglected or inadequately maintained (52). The current ventilation standard, by definition, is a minimum standard designed to provide merely "acceptable" IAQ, despite decades of research showing benefits of higher outdoor air ventilation rates. Doubling ventilation rates resulted in an increase in productivity that offset the associated energy costs (84). However, changes in ventilation raise concerns about the size and capacity of ventilation ducts, so decisions must involve all relevant stakeholders.

These health-promoting ventilation findings should be considered in future standards for all building types. As society prioritizes reducing energy use to mitigate future global challenges, such as CC and rapid urbanization, additional research on advanced ventilation systems with high outdoor air pollution filtration rates (i.e., increased global ambient CO_2 levels, increased ambient pollution from energy sources in developing countries) will be necessary to lower ventilation energy costs for zero–low-energy designs (28). Areas that rely on natural ventilation will need to be considered in relation to changing climates [e.g., increased temperatures, increased humidity (45)] because buildings in these areas must still meet adaptive thermal comfort standards as well as mitigate further health and environmental damages (34).

Thermal Health

Traditionally, thermal comfort has been defined as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (13, p. 3) and is influenced by air temperature, mean radiant temperature, air speed, humidity, personal metabolic activity, and clothing-induced thermal insulation (41). Thermal health, a new term that goes beyond just comfort, encompasses effects on health, performance, and well-being.

Unfavorable heat, humidity, and ventilation conditions in the workplace have been associated with increased reports of itchy, watery eyes, headaches, throat irritation, respiratory symptoms, increased heart rate, negative mood, SBS symptoms, and fatigue (23, 73). Low humidity and low temperatures alter the disease transmission of infectious disease particles, such as the influenza virus (81). Alternatively, warm and humid indoor environments encourage mold and fungal growth

(117). Thermal conditions of indoor environments can also impact performance and learning, such that task and cognitive performance is reduced under high temperatures in office workers, college students, and schoolchildren (55, 72, 73, 134). Furthermore, higher overnight temperatures have been associated with insufficient sleep, especially during summer periods (99), which has implications for health and performance on the subsequent day.

Heat waves are the largest source of mortality of all meteorological phenomena and cause thousands of deaths annually. The built environment can exacerbate or mitigate the exposure to high indoor temperatures during heat waves. Air conditioned spaces can provide thermally stable environments. Recent research has demonstrated a 3–4% increase in electricity generation per degree Celsius increase of summer temperatures, which is associated with increases in sulfur dioxide and nitrogen oxides, as well as the greenhouse gas CO_2 (1). During heat waves, indoor temperatures of non–air conditioned spaces can exceed outdoor temperatures owing to the thermal mass of the building, and these high temperatures extend even after outdoor temperatures drop, creating indoor heat waves.

CC has increased the frequency, duration, and intensity of heat waves (113). Consequently, indoor heat waves will present widespread challenges for the built environment, especially in climates where buildings were designed to harness heat to endure cold winters. As air conditioning usage increases to tolerate warmer climates, cooling demand during heat waves is expected to strain the electricity grid, increasing the risk of power outages (113) and threatening the limited passive habitability of the current built environment (59, 104). Future research can address these challenges by analyzing the adaptation mechanisms for different climate types, air conditioning use patterns, and the implications of air conditioning usage under different energy generation mix scenarios.

Water Quality

The large diversity in water quality and composition globally may result in a mixture of inorganic, organic, or microbial substances within the water supply. Water infrastructure is critical for more than 4 billion people who rely on water through a piped connection and 2.4 billion who use improved sources such as public taps, protected wells, and boreholes (50). Although the United States has one of the safest public drinking water supplies in the world, problems persist. Water infrastructure in the United States has significantly deteriorated and is approaching the end of its useful life as many water pipes and mains are more than 100 years old (19). A 2017 assessment found water infrastructure in the United States to be in "poor to fair condition and mostly below standard" with "strong risk of failure," brought to national attention by the Flint water crisis in Michigan (11a). Lead and copper water service pipes have been associated with reductions in cognitive function, hypertension, and reproductive problems in children and adults (26). In 2016, elevated lead levels were detected in the drinking water of many US public schools across the country, owing to an aging school building infrastructure that predates the Lead and Copper Rule (22, 94, 97). *Legionella* bacteria in building water systems accounted for two-thirds of waterborne illness outbreaks in the United States, 26% of reported illnesses, and all 14 reported deaths—12 of which were associated with health care facilities (19). *Legionella* thrive in building plumbing systems with stagnating water (plumbing system dead legs or areas with infrequent water use), with warm water, and when residual disinfectant concentrations are low.

There are two key challenges facing water consumption in buildings: water access and water quality. The green building movement addresses the first challenge by conserving water through technology and behavior changes that improve efficiency. Strategies include reducing flow rate, using alternative water sources, or reducing plant watering. This approach can, however, negatively impact water quality; the longer that water sits in service pipes, the greater the uptake of heavy metals and formation of disinfection by-products (109). Chlorination of drinking water has been used in the United States since 1908 and has allowed for widespread disinfection of water. However, cell culture, animal, and human epidemiological and toxicological studies show potentially carcinogenic, reproductive complications and endocrine-disrupting properties of disinfection by-products (8, 50, 74, 96).

CC, rapid urbanization, and population growth will exacerbate deficiencies in the global water systems and demand holistic, innovative solutions that consider water composition, process, delivery, and conservation. Water quality improvements rely on the exploration of novel, cost-effective filtration methodologies, including solar light catalytic ozonation, electrochemical separation, sand filtration, and other types of solid catalysts (49). Owing to uneven spatial distribution of water stress, assuring global water resources for the building, irrigation, energy generation, and industrial sectors will require tailored delivery and conservation solutions. Ensuring consistent, contaminant-free water delivery will be a challenge for the 5 billion people who will be living in water-stressed areas by 2050 (114).

Moisture

Water and moisture can enter buildings through many routes: leaks from plumbing, building envelope openings, condensation on cold surfaces, poorly maintained drain pans, and inadequate ventilation of kitchens, showers, and combustion appliances. This moisture creates favorable conditions for mold growth, which can destroy the surfaces on which the mold grows, such as wallboards, ceiling tiles, insulation, and carpeting. The introduction of moisture into buildings has been previously identified by the Occupational Safety and Health Administration (OSHA) as the primary source of building-related illness (100). Studies from Europe, Canada, and the United States have found mold, mildew, or water damage in 36% of homes (35). This exposure is also problematic in office buildings, as 85% of office buildings in the United States had water damage and 45% had active leaks at the time of a US Environmental Protection Agency (EPA) survey (124).

The most prevalent health effect caused by moisture-induced mold formation is asthma; 21% of the 21.8 million cases of asthma annually are attributable to residential dampness and mold (68). Other health impacts that are consistently associated with mold exposure include allergic symptoms, respiratory effects (e.g., cough, wheeze, chest tightness, hoarseness), and vocal cord dysfunction (24, 38, 90, 92, 103). Additionally, mold can produce irritating and health-harmful substances, including VOCs (102). Increased water damage and mold have been found to negatively impact workplace productivity, job performance, quality of life, absenteeism, and classroom learning for office workers, teachers, and schoolchildren (9, 24, 48). Despite strong evidence that mold is an asthmagen and an allergen, not all metrics used to measure indoor dampness and mold exposures are adequate for practical and widespread use in indoor environments because some are too complex, do not scale for widespread use, or are not health protective (90).

Synthetic materials in newer buildings present a future challenge with higher risk for mold growth because humidity cannot be dissipated as easily with more hydrophilic materials. CC will also impact the prevalence of indoor moisture because regions with more frequent heavy precipitation or severe weather events (i.e., floods, tropical storms), which introduce moisture into buildings through infrastructure damage (127), will be at an increased risk for mold growth, as was documented following Hurricanes Katrina and Rita (15). Changes in humidity levels, which determine indoor humidity, will also have implications for indoor moisture as global climates change (127).

Safety and Security

Our search for safety and security originates from the endogenous responses to stimuli perceived as threats. When our sense of security is threatened, our bodies elicit a cascade of biological fight-or-flight responses that alter our physical and psychological functioning (115). Perceived threats to safety flood our bodies with stress-induced hormones, including adrenaline and cortisol, which elevate heart rate and increase blood pressure (10). Over time, these responses can take their toll both psychologically and physiologically. Chronically elevated stress hormones suppress immunity, which can exacerbate autoimmune diseases and other inflammatory conditions, whereas elevated blood pressure levels can eventually lead to damaged arteries and plaque formation, putting stressed individuals at greater risk of hypertension and cardiovascular disease (87, 118). Buildings, by function, are designed to serve as safe havens from environmental and security risks; in practice, however, they deploy a wide range of features that in some cases exacerbate threats to safety and security.

Emergency preparedness is considered an essential feature of modern buildings. Fire and life safety systems are integrated into buildings systems, drawing notice only when inadequate systems or failures lead to catastrophic consequences. In terms of security features, well-designed measures such as fences, locks, or secure entry systems have the potential to reduce fear of crime, whereas evidence is limited for closed-circuit television (CCTV), multicomponent environmental crime prevention programs, or regeneration programs (80). Perception of safety may be influenced by the presence of uniformed security guards but only in situations when safety is perceived to be inadequate without them (43). After enhanced security measures were introduced into Liverpool, tower block buildings in the United Kingdom, fear of domestic crime was reported as being much lower among residents relative to the greater population of Britain. These examples highlight the efficacy of several safety features in buildings; however, research remains limited.

As CC continues to increase the risk of severe weather events (61), the built environment will be subject to increasing environmental threats. Buildings with limited capacity to adapt during extreme weather events impose a great risk of post-traumatic stress disorder and depressive, panic, and anxiety disorders on their occupants (6).

Lighting and Views

Light exposure has visual and nonvisual effects on human health. The nonvisual effects of light pertain to its role as the main environmental cue that directs biological circadian rhythms to the 24-hour light–dark cycle. These circadian rhythms synchronize the physiological and behavioral processes in our body to the cyclic nature of environmental stimuli. With the advent of electrical light, however, we have significantly altered the timing, intensity, and spectrum of light exposure relative to available outdoor daylight. The phase-shifting effect of light can lead to circadian misalignment, as observed in shift workers, and has been associated with an increased risk for accidents, metabolic disorders, cardiovascular disease, and some cancer types (17, 18, 21, 107). Conversely, selective light exposure timing, duration, spectrum, and intensity have been studied to enhance alertness, increase productivity, and treat seasonal affective disorder and sleep disorders (7, 69, 78, 126). Experimental light interventions have suggested moderate effects in slowing the progression of neurodegenerative conditions and improving quality of life among the elderly (110).

Visually induced health impacts include visual strain, eye irritation, and blurred vision from uncomfortable glare, direct light input, high illuminance, and high-contrast conditions from lighting fixtures and computer screens (25). Photosensitive individuals (e.g., migraineurs) report light intensity and flickering as nociceptive stimuli, even during nonepisodic migraine periods (121).

Flickering at frequencies lower than 100 Hz has also been associated with impacts on visual search performance and reading accuracy (65, 71). Furthermore, environmental psychology research has been focusing on the restorative effects of aesthetic aspects of visual environments with biophilic elements. Studies of classrooms with views of nature report that students experience faster recovery from stress and mental fatigue, along with improved performance in attentional functioning tests, when compared with windowless classrooms or classrooms with outer urban views (76).

Novel modeling tools have been developed to predict the visual and nonvisual lighting properties of a space (66). Thus developers in contemporary architecture seek to design buildings that minimize the trade-offs between daylight penetration, glare, and excessive solar thermal heat gains (7). Progress in solid-state LEDs (light-emitting diode light sources) has reduced costs and incorporated tunable spectrum features, facilitating the manipulation of light to promote desirable circadian phase shifting. In addition, light manufacturers, professional societies, and health-oriented RSs are incorporating melanopic lux or melanopic/photopic lux ratios as new metrics to inform decisions on lighting systems on the basis of the visual and nonvisual effects of indoor light. Given the potential conflicting effects of lighting, choosing between enhancing alertness at the expense of the melatonin-suppression-related health outcomes is a conundrum that will not be solved by issuing simple recommendations (82).

Noise

In occupational settings, prolonged exposure to high noise intensity [>85 dBA (A-weighted decibels)] is associated with hearing loss (16). Approximately 24% of Americans present with symptoms of noise-induced hearing loss. Buildings act as structures that mitigate noise propagation from outdoor sources. Still, low-frequency noises can penetrate through structural elements. Even at low noise levels, the nonauditory effects of noise include cardiovascular disease and sleep disruption. Physiologic arousal in the autonomic, motor, and cortical systems has been observed from nighttime exposures to sound levels as low as 33 dBA (16).

Nocturnal noise is associated with shorter proportion of deep sleep and a higher propensity for wakefulness. Additionally, it has a stronger association with cardiovascular disease than does daytime noise exposure. The World Health Organization (WHO) estimates that sleep disturbance constitutes the single most important cause of disability associated with environmental noise exposure in highly urbanized societies. An annual increase of 1.6% is expected in the number of people exposed to average noise levels from aircrafts exceeding 55 dBA (20). A 10-dBA increase in noise levels from aircrafts increased cardiovascular-related hospital admissions in 3.5% (36). These effects have major societal implications because estimates indicate that 145.5 million people in the United States may be exposed chronically to levels higher than 55 dBA (51). Open windows and bedrooms oriented toward the road have shown to increase cardiovascular and hypertension risk (14). In office buildings, white noise generators are used to mask other noise sources to increase concentration, under the hypothesis that a moderate arousal decreases one's attention to cues peripheral to the task in question (60). In schools, however, masking noise has shown contradictory effects, affecting high-performance students at the expense of benefiting the lowest-performing students (56).

Dust and Pests

Dust acts as a reservoir for a variety of harmful agents (27): outdoor particles that penetrate indoors, viruses, bacteria, chemicals, allergens, building materials, dander, fabric fibers, and flakes of paint with lead. Indoor exposures to contaminants residing in dust rely on three main pathways:

(*a*) inhalation of resuspended dust, (*b*) direct dermal absorption, and (*c*) ingestion from hand-to-mouth behaviors. In fact, occupants are surrounded by a cloud of resuspended dust as they go about daily activities. This mass of dust that enters the body each day is relevant to human health. Studies have documented that the amount of chemical that is present in indoor dust can be directly correlated with the amount of chemical found in the blood of people who live and work in these environments (135). Some of these agents (such as viruses) may exist in dust for only a few hours, whereas others may remain in the dust for decades. Indoor dust is the primary route of exposure for lead (129), which can accumulate in dust from flaked paint or lead-contaminated dirt tracked in from outdoors. Unlike chemicals in the air, chemicals in dust, known as persistent organic pollutants (POPs), can continue to expose occupants long after the sources have been removed; examples include flame retardants, stain repellent, and plasticizers. For example, flame-retardant chemicals can be found in many common furnishings and building materials used in schools. Flame-retardant chemicals that are used in consumer products migrate out of those products into air and dust (5). Many flame-retardant chemicals are endocrine-disrupting chemicals that interfere with the reproductive system and are associated with thyroid disease (42).

Indoor allergens are typically harmless substances that we encounter every day. Common household allergen sources include pet dander, pollen, mold, and pest and rodent excrement. Particles containing these allergens commonly settle into carpets, drapes, soft furnishings, and other locations where settled dust collects (40). A survey of 851 homes across the United States found that more than half of the homes had at least 6 detectable allergens (112). When allergens are inhaled or come into contact with eyes, they can trigger an immune response that leads to an allergic reaction. Allergens can assist in the development and the exacerbation of asthma and nasal allergies. In the United States, asthma causes 439,000 hospitalizations, 1.8 million emergency room visits, and 3,600 deaths annually (29). Young children, the elderly, those who are genetically predisposed, and low-income individuals are most vulnerable (2, 88). Poor IAQ can also aggregate domestic allergen load (40, 105).

Pesticides are chemical or biological agents that kill or control common household pests (e.g., cockroaches, mice), microbial contamination (e.g., viruses, bacteria, protozoans), disease-carrying outdoor pests (e.g., mosquitos, ticks, rodents), and other bacteria. Widespread pesticide use in modern society makes it difficult to avoid exposure. The EPA reported that 75% of households use pesticides in their homes, usually in the form of insecticides or disinfectants. They also found that 80% of most people's exposures to pesticides were indoors and that significant levels of more than one dozen pesticides had been measured in the air inside homes (125). Pest control chemicals such as pyrethroids and organophosphates are toxic substances that have the potential to cause long-lasting effects, even in low doses (32, 67). Pesticides have been linked to a wide range of human health and environmental impacts but most often affect the nervous system. Symptoms may range from mild (e.g., headache, dizziness, nausea, sweating) to moderate (e.g., excessive salivation, blurred vision, muscular incoordination), to severe (i.e., inability to breathe, loss of reflexes, unconsciousness, death) (123). In particular, long-term pesticide exposures have been associated with a number of cancers (57, 133). Adequate ventilation, nonchemical methods of pest control, and integrated pest management are suggested pathways to reduce indoor pesticide exposure.

GREEN BUILDINGS AND THE HUMAN RIGHT TO HEALTHY INDOOR ENVIRONMENTS

Concurrent with the origin of the green building movement, the WHO issued a document recognizing that access to a healthy indoor environment is a human right (130; see the sidebar titled Principles of Healthy Indoor Air). The document is intended to inform decision makers, public

PRINCIPLES OF HEALTHY INDOOR AIR

P1. Everyone has the right to breathe healthy indoor air.
P2. Everyone has the right to adequate information about potentially harmful exposures and to be provided with effective means for controlling their indoor exposures.
P3. No agent at a concentration that exposes any occupant to an unnecessary health risk should be introduced into indoor air.
P4. Everyone associated with a building bears responsibility to advocate or work for acceptable air quality.
P5. Socioeconomic status should have no bearing on people's access to healthy indoor air, but health status may determine special needs for some groups.
P6. All relevant organizations should establish explicit criteria for evaluating and assessing building air quality and its impact on health.
P7. Where there is a risk of harmful indoor air exposure, the presence of uncertainty shall not be used as a reason for postponing cost-effective measures to prevent such exposure.
P8. The polluter is accountable for any harm to health and/or welfare resulting from unhealthy indoor air exposures.
P9. Health and environmental concerns cannot be separated, and the provision of healthy indoor air should not compromise global or local ecological integrity or the rights of future generations.

Source: Adapted from Reference 130

health officials, landlords, property managers, architects, lawyers, individuals, and organizations to ensure that healthy indoor environments are a human right for all. However, this report, along with the literature documented in the summary of the nine foundational elements, has not been enough to completely transform the building sector to design and manage buildings that promote healthy indoor environments.

Transforming the building sector requires action for all classes of real estate. In this review, we have focused predominantly on high-end real estate in developed countries. We should be mindful that exposure to indoor pollution is still one of the most significant contributors to the global burden of disease, primarily in the developing world (30). Massive attention is now being given to the respiratory effects associated with the use of biomass for heating and cooking (e.g., China's 100 Million Clean Cook Stove Program), and international aid organizations have been working to improve combustion, incorporate exhaust ductwork, and introduce cleaner fuels. However, more than 1.5 billion people are still being exposed to dangerously high levels of particulate matter and carbon monoxide on a daily basis (106).

We face challenges in providing healthy IEQ while also confronting rapid urbanization (new structures) and the renovation of the existing building stocks. Is it even reasonable to expect that certification of green buildings, which has a limited niche of high-end buildings, and new construction will make much of an impact? In 16 years, Leadership in Energy and Environmental Design (LEED), the most prevalent green building RS in the United States, has certified 29,000 commercial buildings out of ~5.5 million buildings (63). For green buildings to spearhead the attainment of health in the built environment, their foundational elements must be within the reach of all buildings.

Unfortunately, most of the examples in which many individuals have benefited from improved indoor environments have come through banning a substance, setting product standards, or engaging in wide-scale public education on such hazards as asbestos, radon, polychlorinated biphenyls

(PCBs), lead paint, urea formaldehyde, and chlorinated pesticides. Smoking has been the one indoor air hazard that has seen broad and substantial societal change: After 30 years of accumulating evidence and two US Surgeon General reports, secondhand smoke was unequivocally recognized as a public health risk. Public health evidence finally shifted the civic debate to guarantee the right to smoke-free indoor environments.

Perhaps there is an opportunity to frame health-promoting indoor environments and expand the green building movement in the context of sustainability, instead of the outdated version of the three-legged stool of economy, environment, and society. A more relevant sustainability framework posits that sustainability, inclusive of social well-being, is determined by the accessibility to the planet's capital assets (89). The authors suggest that society's pursuit of sustainable development since the first Rio World Conference in 1992 has been misguided by the myopic examination of material and energy flows. Companies, cities, countries, and individuals wishing to be responsible have established inventories, set goals, and managed the flows of water, waste, energy, and resources. This effort has proven to be insufficient, considering that populations are increasing, economies are expanding, and resources are diminishing. We will be resilient against future disruptions only if we grow our human, natural, material, social, and knowledge capitals.

We reframe the purpose for green buildings as a transformational process to develop a healthier built environment. Within this framework, green buildings have demonstrated their ability to contribute to the natural and manufactured capital assets (**Figure 1**). However, the greatest

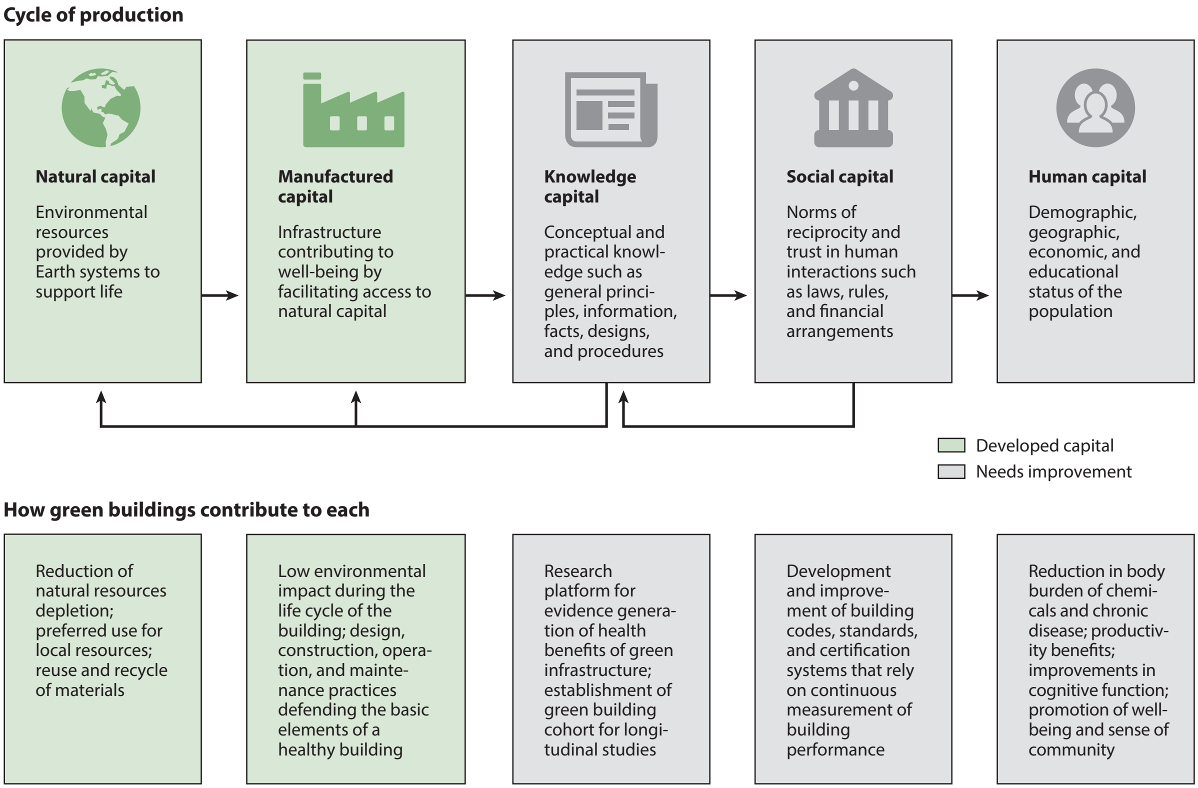

Figure 1

Role of green buildings in the social-environmental sustainability framework. Adapted from Matson et al. (89).

pending contribution of green buildings is expected to occur in the knowledge capital domain, positively influencing the human and social capital assets.

With respect to knowledge capital, we consider that green buildings could become an evidence-generating platform on which to conduct longitudinal cohort studies that support the epidemiology of building-related health outcomes. In green buildings, the adoption of pollution source control beyond the enforceable requirements directly appeals to two principles of *The Right to Healthy Indoor Air*, the principle of nonmaleficence (avoiding chemical compounds that pose unnecessary health risks) and the precautionary principle (delaying the introduction of chemicals with uncertain health risks, until proven safe) (130). This approach constitutes a natural intervention adequate to study the long-term effects of indoor environmental exposures on outcomes with a long latency period, from which we know little at this time. Moreover, the shift from design- to performance-oriented rating criteria would enable environmental exposure data collection at an unprecedented level. Given the amount of time that individuals in modern societies spend indoors, these data could inform a significant portion of the lifetime personal environmental exposures (i.e., exposome).

Strengthening the knowledge capital should inform decisions about how we interact with the natural and manufactured capitals in the face of civilizational challenges, such as CC. As experienced with the public health successes of the past (e.g., control of radon, lead, and secondhand smoke), knowledge capital could catalyze changes in legislation (social capital) that foster the well-being of the population (human capital).

CONCLUSION

Green buildings are a necessary, but not sufficient, component of the future of sustainable urbanization. Building for health is the paradigm of the future that includes a focus on ecosystem health (green buildings) and indoor health (healthy buildings). The evidence presented here is but a small fraction of the overwhelming evidence generated over the past 40 years that demonstrates how buildings influence human health.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

1. Abel D, Holloway T, Kladar RM, Meier P, Ahl D, et al. 2017. Response of power plant emissions to ambient temperature in the eastern United States. *Environ. Sci. Technol.* 51:5838–46
2. Ahluwalia S, Matsui EC. 2011. The indoor environment and its effects on childhood asthma. *Curr. Opin. Allergy Clin. Immunol.* 11:137–43
3. Allen JG, MacIntosh DL, Saltzman LE, Baker BJ, Matheson JM, et al. 2012. Elevated corrosion rates and hydrogen sulfide in homes with 'Chinese drywall'. *Sci. Total Environ.* 426:113–19
4. Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. *Environ. Health Perspect.* 124:805–12
5. Allen JG, McClean MD, Stapleton HM, Webster TF. 2008. Critical factors in assessing exposure to PBDEs via house dust. *Environ. Int.* 34:1085–91
6. Amstadter AB, Acierno R, Richardson L, Kilpatrick DG, Gros DF, et al. 2009. Post-typhoon prevalence of post-traumatic stress disorder, major depressive disorder, panic disorder and generalized anxiety disorder in a Vietnamese sample. *J. Trauma. Stress* 22:180–88

7. Andersen M. 2015. Unweaving the human response in daylighting design. *Build. Environ.* 91:101–17
8. Andra SS, Charisiadis P, Arora M, van Vliet-Ostaptchouk JV, Makris KC. 2015. Biomonitoring of human exposures to chlorinated derivatives and structural analogs of bisphenol A. *Environ. Int.* 85:352–79
9. Angelon-Gaetz KA, Richardson DB, Marshall SW, Hernandez ML. 2016. Exploration of the effects of classroom humidity levels on teachers' respiratory symptoms. *Int. Arch. Occup. Environ. Health* 89:729–37
10. APA (Am. Psychol. Assoc.). 2013. *How stress affects your health*. APA, Washington, DC. **http://www.apa.org/helpcenter/stress.aspx**
11. Apte MG, Fisk WJ, Daisey JM. 2000. Associations between indoor CO_2 concentrations and sick building syndrome symptoms in US office buildings: an analysis of the 1994–1996 BASE study data. *Indoor Air* 10:246–57

11a. ASCE (Am. Soc. Civ. Eng.). 2017. *2017 infrastructure report card: drinking water*. ASCE, Reston, VA. **https://www.infrastructurereportcard.org/wp-content/uploads/2017/01/Drinking-Water-Final.pdf**

12. ASHRAE (Am. Soc. Heat. Refrig. Air-Cond. Eng.). 2013. *ANSI/ASHRAE Standard 62.1–2013. Ventilation for Acceptable Indoor Air Quality*. Atlanta: ASHRAE
13. ASHRAE (Am. Soc. Heat. Refrig. Air-Cond. Eng.). 2016. *ANSI/ASHRAE Standard 55–2016. Thermal Environmental Conditions for Human Occupancy*. Atlanta: ASHRAE
14. Babisch W. 2006. Transportation noise and cardiovascular risk: updated review and synthesis of epidemiological studies indicate that the evidence has increased. *Noise Health* 8:1–29
15. Barbeau DN, Grimsley LF, White LE, El-Dahr JM, Lichtveld M, et al. 2010. Mold exposure and health effects following hurricanes Katrina and Rita. *Annu. Rev. Public Health* 31:165–78
16. Basner M, Brink M, Bristow A, de Kluizenaar Y, Finegold L, et al. 2015. ICBEN review of research on the biological effects of noise 2011–2014. *Noise Health* 17:57–82
17. Beauchemin KM, Hays P. 1998. Dying in the dark: sunshine, gender, and outcomes in myocardial infarction. *J. R. Soc. Med.* 91:352–54
18. Bedrosian TA, Fonken LK, Nelson RJ. 2016. Endocrine effects of circadian disruption. *Annu. Rev. Physiol.* 78:109–31
19. Beer KD, Gargano JW, Roberts VA, Hill VR, Garrison LE, et al. 2015. Surveillance for waterborne disease outbreaks associated with drinking water—United States, 2011–2012. *MMWR* 64:842–48
20. Berglund B, Lindvall T, Schwela DH, eds. 1999. *Guidelines for Community Noise*. Geneva: WHO. **http://apps.who.int/iris/handle/10665/66217**
21. Blask DE. 2009. Melatonin, sleep disturbance and cancer risk. *Sleep Med. Rev.* 13:257–64
22. Bloom M. 2016. Elevated lead levels found at half of Atlanta schools tested. *myAJC*, June 30. **http://www.myajc.com/news/local-education/elevated-lead-levels-found-half-atlanta-schools-tested/lpxRF60YOlXdF1W2etlHDK/**
23. Bluyssen P, Roda C, Mandin C, Fossati S, Carrer P, et al. 2016. Self-reported health and comfort in 'modern' office buildings: first results from the European OFFICAIR study. *Indoor Air* 26:298–317
24. Bornehag C, Sundell J, Sigsgaard T. 2004. Dampness in buildings and health (DBH): report from an ongoing epidemiological investigation on the association between indoor environmental factors and health effects among children in Sweden. *Indoor Air* 14:59–66
25. Boyce PR. 2010. Review: The impact of light in buildings on human health. *Indoor Built Environ*. 19:8–20
26. Brown MJ, Margolis S. 2012. Lead in drinking water and human blood lead levels in the United States. *MMWR Suppl*. 61:1–9
27. Butte W, Heinzow B. 2002. Pollutants in house dust as indicators of indoor contamination. *Rev. Environ. Contam. Toxicol.* 175:1–46
28. Cao X, Dai X, Liu J. 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build*. 128:198–213
29. CDC (Cent. Dis. Control Prev.). 2017. *Most recent asthma data*. Updated June, CDC, Atlanta. **https://www.cdc.gov/asthma/most_recent_data.htm**
30. Chafe ZA, Brauer M, Klimont Z, Van Dingenen R, Mehta S, et al. 2014. Household cooking with solid fuels contributes to ambient $PM_{2.5}$ air pollution and the burden of disease. *Environ. Health Perspect.* 122:1314

31. Chen C, Zhao B. 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmos. Environ.* 45:275–88
32. Chen M, Chang C-H, Tao L, Lu C. 2015. Residential exposure to pesticide during childhood and childhood cancers: a meta-analysis. *Pediatrics* 136:719–29
33. Chen Q. 2009. Ventilation performance prediction for buildings: a method overview and recent applications. *Build. Environ.* 44:848–58
34. Chenari B, Carrilho JD, da Silva MG. 2016. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review. *Renew. Sustain. Energy Rev.* 59:1426–47
35. Cho S-H, Reponen T, LeMasters G, Levin L, Huang J, et al. 2006. Mold damage in homes and wheezing in infants. *Ann. Allergy Asthma Immunol.* 97:539–45
36. Correia AW, Peters JL, Levy JI, Melly S, Dominici F. 2013. Residential exposure to aircraft noise and hospital admissions for cardiovascular diseases: multi-airport retrospective study. *BMJ* 347:f5561
37. Crimmins A, Balbus J, Gamble JL, Beard CB, Bell JE, et al., eds. 2016. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Washington, DC: US Glob. Change Res. Prog.
38. Cummings K, Fink J, Vasudev M, Piacitelli C, Kreiss K. 2013. Vocal cord dysfunction related to water-damaged buildings. *J. Allergy Clin. Immunol. Pract.* 1:46–50
39. Daisey JM, Angell WJ, Apte MG. 2003. Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Indoor Air* 13:53–64
40. Dales R, Liu L, Wheeler AJ, Gilbert NL. 2008. Quality of indoor residential air and health. *Can. Med. Assoc. J.* 179:147–52
41. de Dear R. 2004. Thermal comfort in practice. *Indoor Air* 14:32–39
42. de Wit CA. 2002. An overview of brominated flame retardants in the environment. *Chemosphere* 46:583–624
43. Doyle M, Frogner L, Andershed H, Andershed A-K. 2016. Feelings of safety in the presence of the police, security guards, and police volunteers. *Eur. J. Crim. Policy Res.* 22:19–40
44. Drinka PJ, Krause P, Schilling M, Miller BA, Shult P, Gravenstein S. 1996. Report of an outbreak: nursing home architecture and influenza-A attack rates. *J. Am. Geriatr. Soc.* 44:910–13
45. Fann N, Brennan T, Dolwick P, Gamble J, Ilacqua V, et al. 2016. Air quality impacts. See Ref. 37, pp. 69–98
46. Fisk WJ, Mirer AG, Mendell MJ. 2009. Quantitative relationship of sick building syndrome symptoms with ventilation rates. *Indoor Air* 19:159–65
47. Fisk WJ, Rosenfeld AH. 1997. Estimates of improved productivity and health from better indoor environments. *Indoor Air* 7:158–72
48. Fletcher AM, London MA, Gelberg KH, Grey AJ. 2006. Characteristics of patients with work-related asthma seen in the New York State occupational health clinics. *J. Occup. Environ. Med.* 48:1203–11
49. Gomes J, Costa R, Quinta-Ferreira RM, Martins RC. 2017. Application of ozonation for pharmaceuticals and personal care products removal from water. *Sci. Total Environ.* 586:265–83
50. Grellier J, Rushton L, Briggs DJ, Nieuwenhuijsen MJ. 2015. Assessing the human health impacts of exposure to disinfection by-products—a critical review of concepts and methods. *Environ. Int.* 78:61–81
51. Hammer MS, Swinburn TK, Neitzel RL. 2014. Environmental noise pollution in the United States: developing an effective public health response. *Environ. Health Perspect.* 122:115
52. Hanssen SO. 2004. HVAC—the importance of clean intake section and dry air filter in cold climate. *Indoor Air* 14:195–201
53. Hardy K, Radini A, Buckley S, Sarig R, Copeland L, et al. 2016. Dental calculus reveals potential respiratory irritants and ingestion of essential plant-based nutrients at Lower Palaeolithic Qesem Cave Israel. *Quat. Int.* 398:129–35
54. Haverinen-Shaughnessy U, Moschandreas DJ, Shaughnessy RJ. 2011. Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air* 21:121–31
55. Haverinen-Shaughnessy U, Shaughnessy R. 2015. Effects of classroom ventilation rate and temperature on students' test scores. *PLOS ONE* 10:e0136165
56. Helps SK, Bamford S, Sonuga-Barke EJ, Söderlund GB. 2014. Different effects of adding white noise on cognitive performance of sub-, normal and super-attentive school children. *PLOS ONE* 9:e112768

57. Hernández A, Menéndez P. 2016. Linking pesticide exposure with pediatric leukemia: potential underlying mechanisms. *Int. J. Mol. Sci.* 17:461
58. Hoge CW, Reichler MR, Dominguez EA, Bremer JC, Mastro TD, et al. 1994. An epidemic of pneumococcal disease in an overcrowded, inadequately ventilated jail. *N. Engl. J. Med.* 331:643–48
59. Holmes SH, Phillips T, Wilson A. 2016. Overheating and passive habitability: indoor health and heat indices. *Build. Res. Inf.* 44:1–19
60. Houston BK. 1969. Noise, task difficulty, and Stroop color-word performance. *J. Exp. Psychol.* 82:403–4
61. IPCC (Intergov. Panel Clim. Change). 2013. *IPCC: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. TF Stocker, D Qin, G-K Plattner, MMB Tignor, SK Allen, et al. Cambridge, UK: Cambridge Univ. Press
62. Jaakkola JJK. 1998. The office environment model: a conceptual analysis of the sick building syndrome. *Indoor Air* 8:7–16
63. Jackson J. 2009. How risky are sustainable real estate projects? An evaluation of LEED and ENERGY STAR development options. *J. Sustain. Real Estate* 1:91–106
64. Jacobs DE, Ahonen E, Dixon SL, Dorevitch S, Breysse J, et al. 2015. Moving into green healthy housing. *J. Public Health Manag. Pract.* 21:345–54
65. Jaén EM, Colombo EM, Kirschbaum CF. 2011. A simple visual task to assess flicker effects on visual performance. *Light. Res. Technol.* 43:457–71
66. Jakubiec JA, Reinhart CF. 2012. The 'adaptive zone'—a concept for assessing discomfort glare throughout daylit spaces. *Light. Res. Technol.* 44:149–70
67. Jokanović M, Kosanović M. 2010. Neurotoxic effects in patients poisoned with organophosphorus pesticides. *Environ. Toxicol. Pharmacol.* 29:195–201
68. Kanchongkittiphon W, Mendell MJ, Gaffin JM, Wang G, Phipatanakul W. 2015. Indoor environmental exposures and exacerbation of asthma: an update to the 2000 review by the Institute of Medicine. *Environ. Health Perspect.* 123:6–20
69. Keis O, Helbig H, Streb J, Hille K. 2014. Influence of blue-enriched classroom lighting on students' cognitive performance. *Trends Neurosci. Educ.* 3:86–92
70. Knibbs LD, Morawska L, Bell SC, Grzybowski P. 2011. Room ventilation and the risk of airborne infection transmission in 3 health care settings within a large teaching hospital. *Am. J. Infect. Control* 39:866–72
71. Kuller R, Laike T. 1998. The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal. *Ergonomics* 41:433–47
72. Lan L, Wargocki P, Lian Z. 2011. Quantitative measurement of productivity loss due to thermal discomfort. *Energy Build.* 43:1057–62
73. Lan L, Wargocki P, Wyon DP, Lian Z. 2011. Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance. *Indoor Air* 21:376–90
74. Legay C, Rodriguez MJ, Sérodes JB, Levallois P. 2010. Estimation of chlorination by-products presence in drinking water in epidemiological studies on adverse reproductive outcomes: a review. *Sci. Total Environ.* 408:456–72
75. Leon D. 2008. Cities, urbanization and health. *Int. J. Epidemiol.* 37:4–8
76. Li D, Sullivan WC. 2016. Impact of views to school landscapes on recovery from stress and mental fatigue. *Landsc. Urban Plann.* 148:149–58
77. Li Y, Leung GM, Tang JW, Yang X, Chao CYH, et al. 2007. Role of ventilation in airborne transmission of infectious agents in the built environment—a multidisciplinary systematic review. *Indoor Air* 17:2–18
78. Lockley SW, Evans EE, Scheer F, Brainard GC, Czeisler CA, Aeschbach D. 2006. Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep* 29:161–68
79. Logue JM, McKone TE, Sherman MH, Singer BC. 2011. Hazard assessment of chemical air contaminants measured in residences. *Indoor Air* 21(2):92–109; corrigendum 21(4):351–52
80. Lorenc T, Petticrew M, Whitehead M, Neary D, Clayton S, et al. 2013. Environmental interventions to reduce fear of crime: systematic review of effectiveness. *Syst. Rev.* 2:30

81. Lowen A, Mubareka S, Steel J, Palese P. 2007. Influenza virus transmission is dependent on relative humidity and temperature. *PLOS Pathog*. 3:1470–76
82. Lucas RJ, Peirson S, Berson DM, Brown TM, Cooper HM, et al. 2014. Measuring and using light in the melanopsin age. *Trends Neurosci*. 37:1–9
83. Luongo JC, Fennelly KP, Keen JA, Zhai ZJ, Jones BW, Miller SL. 2016. Role of mechanical ventilation in the airborne transmission of infectious agents in buildings. *Indoor Air* 26:666–78
84. MacNaughton P, Pegues J, Satish U, Santanam S, Spengler J, Allen J. 2015. Economic, environmental and health implications of enhanced ventilation in office buildings. *Int. J. Environ. Res. Public Health* 12:14709–22
85. MacNaughton P, Satish U, Laurent JGC, Flanigan S, Vallarino J, et al. 2017. The impact of working in a green certified building on cognitive function and health. *Build. Environ.* 114:178–86
86. Maddalena R, Mendell MJ, Eliseeva K, Chan WR, Sullivan DP, et al. 2015. Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making. *Indoor Air* 25:362–70
87. Marsland A, Bachen E, Cohen S, Rabin B, Manuck S. 2002. Stress, immune reactivity and susceptibility to infectious disease. *Physiol. Behav.* 77:711–16
88. Mathur SK. 2010. Allergy and asthma in the elderly. *Semin. Respir. Crit. Care Med.* 31:587–95
89. Matson P, Clark WC, Andersson K. 2016. *Pursuing Sustainability: A Guide to the Science and Practice*. Princeton, NJ: Princeton Univ. Press
90. Mendell MJ, Kumagai K. 2017. Observation-based metrics for residential dampness and mold with dose–response relationships to health: a review. *Indoor Air* 27:506–17
91. Mendell MJ, Lei-Gomez Q, Mirer AG, Seppänen O, Brunner G. 2008. Risk factors in heating, ventilating, and air-conditioning systems for occupant symptoms in US office buildings: the US EPA BASE study. *Indoor Air* 18:301–16
92. Mendell MJ, Mirer AG, Cheung K, Tong M, Douwes J. 2011. Respiratory and allergic health effects of dampness, mold, and dampness-related agents: a review of the epidemiologic evidence. *Environ. Health Perspect.* 119:748–56
93. Milton DK, Glencross PM, Walters MD. 2000. Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints. *Indoor Air* 10:212–21
94. Natl. Inst. Environ. Health Sci. (NIEHS). 2013. *Lead and your health*. Oct., NIEHS, Durham, NC. **https://www.niehs.nih.gov/health/materials/lead_and_your_health_508.pdf**
95. Nazaroff W, Weschler CJ, Little JC, Hubal EA. 2012. Intake to production ratio: a measure of exposure intimacy for manufactured chemicals. *Environ. Health Perspect.* 120:1678–83
96. Nieuwenhuijsen MJ, Toledano MB, Eaton NE, Fawell J, Elliott P. 2000. Chlorination disinfection byproducts in water and their association with adverse reproductive outcomes: a review. *Occup. Environ. Med.* 57:73–85
97. Nitkin A. 2016. 26 CPS schools have lead in their water: What does this mean for kids? *DNAInfo*, June 20. **https://www.dnainfo.com/chicago/20160620/downtown/do-chicago-schools-have-lead-problem-heres-what-you-need-know**
98. Noris F, Adamkiewicz G, Delp WW, Hotchi T, Russell M, et al. 2013. Indoor environmental quality benefits of apartment energy retrofits. *Build. Environ.* 68:170–78
99. Obradovich N. 2017. Climate change may speed democratic turnover. *Climat. Change* 140:135–47
100. OSHA (Occup. Saf. Health Adm.). 2006. *Preventing Mold-Related Problems in the Indoor Workplace: A Guide for Building Owners, Managers and Occupants*. Washington, DC: US Dep. Labor. **https://www.osha.gov/Publications/preventing_mold.pdf**
101. Pervin T, Gerdtham U-G, Lyttkens CH. 2008. Societal costs of air pollution–related health hazards: a review of methods and results. *Cost Eff. Resour. Alloc.* 6:19
102. Pettigrew H, Selmi C, Teuber S, Gershwin M. 2010. Mold and human health: separating the wheat from the chaff. *Clin. Rev. Allergy Immunol.* 38:148–55
103. Quansah R, Jaakkola MS, Hugg TT, Heikkinen SAM, Jaakkola JJK. 2014. Residential dampness and molds and the risk of developing asthma: a systematic review and meta-analysis. *PLOS ONE* 9:e93454
104. Quinn A, Tamerius JD, Perzanowski M, Jacobson JS, Goldstein I, et al. 2014. Predicting indoor heat exposure risk during extreme heat events. *Sci. Total Environ.* 490:686–93

105. Raulf M, Klimek L. 2015. Mites and other indoor allergens. *Allergologie* 38:45–46
106. Rehfuess E, Corvalan C, Neira M. 2006. Indoor air pollution: 4000 deaths a day must no longer be ignored. *Bull. World Health Organ.* 84:508
107. Reid KJ, Santostasi G, Baron KG, Wilson J, Kang J, Zee PC. 2014. Timing and intensity of light correlate with body weight in adults. *PLOS ONE* 9:e92251
108. Deleted in proof
109. Rhoads WJ, Pruden A, Edwards MA. 2016. Survey of green building water systems reveals elevated water age and water quality concerns. *Environ. Sci. Water Res. Technol.* 2:164–73
110. Riemersma-van der Lek RF, Swaab DF, Twisk J, Hol EM, Hoogendijk WJ, Van Someren EJ. 2008. Effect of bright light and melatonin on cognitive and noncognitive function in elderly residents of group care facilities: a randomized controlled trial. *JAMA* 299:2642–55
111. Rudnick SN, Milton DK. 2003. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* 13:237–45
112. Salo PM, Arbes SJ Jr., Crockett PW, Thorne PS, Cohn RD, Zeldin DC. 2008. Exposure to multiple indoor allergens in US homes and its relationship to asthma. *J. Allergy Clin. Immunol.* 121:678–84
113. Sarofim MC, Saha S, Hawkins MD, Mills DM, Hess J, et al. 2016. Temperature-related Death and Illness. See Ref. 37, pp. 43–68
114. Schlosser CA, Strzepek K, Gao X, Fant C, Blanc E, et al. 2014. The future of global water stress: an integrated assessment. *Earth's Future* 2:341–61
115. Schneiderman N, Ironson G, Siegel SD. 2005. Stress and health: psychological, behavioral, and biological determinants. *Annu. Rev. Clin. Psychol.* 1:607–28
116. Shendell DG, Winer AM, Weker R, Colome SD. 2004. Evidence of inadequate ventilation in portable classrooms: results of a pilot study in Los Angeles County. *Indoor Air* 14:154–58
117. Spengler JD, Samet JM, McCarthy JF. 2001. *Indoor Air Quality Handbook*. New York: McGraw-Hill
118. Stafford M, Chandola T, Marmot M. 2007. Association between fear of crime and mental health and physical functioning. *Am. J. Public Health* 97:2076–81
119. Stenberg B, Eriksson N, Höög J, Sundell J, Wall S. 1994. The sick building syndrome (SBS) in office workers. A case-referent study of personal, psychosocial and building-related risk indicators. *Int. J. Epidemiol.* 23:1190–97
120. Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, et al. 2011. Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air* 21:191–204
121. Thabet M, Wilkinson F, Wilson HR, Karanovic O. 2013. The locus of flicker adaptation in the migraine visual system: a dichoptic study. *Cephalalgia* 33:5–19
122. Tham KW, Wargocki P, Tan YF. 2015. Indoor environmental quality, occupant perception, prevalence of sick building syndrome symptoms, and sick leave in a Green Mark Platinum-rated versus a non-Green Mark-rated building: a case study. *Sci. Technol. Built Envir.* 21:35–44
123. Thundiyil JG, Stober J, Besbelli N, Pronczuk J. 2008. Acute pesticide poisoning: a proposed classification tool. *Bull. World Health Organ.* 86:205–9
124. US EPA (Environ. Prot. Agency). 2013. *Moisture Control Guidance for Building Design, Construction and Maintenance*. Washington, DC: US EPA. **https://www.epa.gov/sites/production/files/2014-08/documents/moisture-control.pdf**
125. US EPA (Environ. Prot. Agency). 2017. *Pesticides' impact on indoor air quality*. Updated May 10. US EPA, Washington, DC. **http://www.epa.gov/indoor-air-quality-iaq/pesticides-impact-indoor-air-quality**
126. Viola A, James L, Schlangen L, Dijk D. 2008. Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. *Scand. J. Work Environ. Health* 34:297–306
127. Voorhees AS, Fann N, Fulcher C, Dolwick P, Hubbell B, et al. 2011. Climate change-related temperature impacts on warm season heat mortality: a proof-of-concept methodology using BenMAP. *Environ. Sci. Technol.* 45:1450–57
128. Wargocki P, Wyon DP, Sundell J, Clausen G, Fanger PO. 2000. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air* 10:222–36

129. Whitehead TP, Metayer C, Ward MH, Colt JS, Gunier RB, et al. 2014. Persistent organic pollutants in dust from older homes: learning from lead. *Am. J. Public Health* 104:1320–26
130. WHO (World Health Organ.). 2000. *The Right to Healthy Indoor Air*. Rep. from WHO Meet. from the Eur. Cent. Environ. Health, May 15–17, Bilthoven, Neth. Copenhagen: WHO Reg. Off. Eur. **http://www.euro.who.int/__data/assets/pdf_file/0019/117316/E69828.pdf?ua=1**
131. WHO (World Health Organ.). 2010. *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Geneva: WHO
132. Wiessner PW. 2014. Embers of society: firelight talk among the Ju/'hoansi Bushmen. *PNAS* 111:14027–35
133. Zeng F, Lerro C, Lavoué J, Huang H, Siemiatycki J, et al. 2017. Occupational exposure to pesticides and other biocides and risk of thyroid cancer. *Occup. Environ. Med.* 74:502–10
134. Zhang F, de Dear R. 2017. University students' cognitive performance under temperature cycles induced by direct load control events. *Indoor Air* 27:78–93
135. Zota AR, Rudel RA, Morello-Frosch RA, Brody JG. 2008. Elevated house dust and serum concentrations of PBDEs in California: unintended consequences of furniture flammability standards? *Environ. Sci. Technol.* 42:8158–64