ASSESSMENT OF BUILDING INTERVENTIONS ON STUDENT HEALTH

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ABSTRACT

For more than thirty years, epidemiological and exposure assessment studies have documented the relationship between indoor environmental quality and student health. However, there is an outstanding need to address immediate and long-term building-related environmental challenges. For this reason, this dissertation provides a quantitative evaluation of strategies that could mitigate current harmful indoor exposures and promote investments in healthy environmental quality in schools. It addresses knowledge gaps around a specific set of current strategies across various scales and settings to mitigate indoor environmental exposures including emerging technologies, building and construction policies, and school-related data collection efforts.

First, we examined the effectiveness of 'smart', dynamic purifiers compared to continuously running purification in a randomized crossover study. We compared changes in indoor particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs) concentrations across three intervention arms: no air purification; dynamic purification responsive to elevated $PM_{2.5}$ and/or VOC concentrations; and continuous purification with fan speed set to half the purifier's full capability. Both purification types resulted in significant reductions of VOCs, with higher reductions from a continuous system. Dynamic purification can effectively reduce peak exposures to $PM_{2.5}$ from indoor sources, but continuous purification may better reduce daily $PM_{2.5}$ and VOC concentrations.

Second, using a cross-sectional analysis, we examined the association between school building conditions and chronic absenteeism in Massachusetts. A systematic assessment of public school buildings provided categorical building quality measures across health-related building and site characteristics. Schools with the greatest need for repair were disproportionately attended by disadvantaged and minority students, and associated with high absenteeism. When analyzing specific building systems, schools needing major repairs or replacement of school *roofs*, *building envelope*, and *site-related* features were significantly associated with higher chronic absenteeism compared to schools in need of general maintenance. Addressing building disrepair may provide another strategy for reducing chronic absenteeism.

Lastly, in a multi-year study, we characterized building quality at baseline and evaluated school-level associations between acquiring green building certification (Leadership in Energy and Environmental Design and Collaborative for High Performance Schools) and standardized test performance. No association was observed for green buildings because at baseline, future green-certified schools were already higher-performing and the study population of green-certified buildings did not acquire all indoor environmental quality credits available. Allocation of green-certified schools should account for prior academic performance, health, and building quality with greater prioritization of indoor environmental quality credits.

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"No young doctor nowadays can hope for work as exciting and rewarding"

- Alice Hamilton

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CHAPTER 1: INTRODUCTION

More than 30 years of research shows that indoor environmental quality (IEQ) is associated with physiological impacts on respiratory, neurological, and cardiovascular systems as well as cognitive function and worker productivity (Samet, Marbury et al. 1987, Jones 1999, Allen, MacNaughton et al. 2015, Colton, Laurent et al. 2015). In the next 30 years, climate change will have serious implications on indoor environments, specifically settings in which humans live and learn (Spengler 2012). It is expected there will be an increased concentration and distribution of poor air quality, higher temperatures, moisture, and allergens, resulting in increased air pollution penetration indoors, diminished thermal comfort, and increased mold and pest growth (Kinney 2008, Barnes, Alexis et al. 2013). Furthermore, global demographics will dynamically change as our population rapidly ages and urbanizes (Sherbinin, Carr et al. 2007, PRB 2016, WHO 2017). The majority of buildings in today's society will continue to be occupied in the coming decades, so they must be able to accommodate these environmental and social shifts.

The design of school buildings is particularly important, as these buildings can be a significant determinant of health, cognitive function, and scholastic ability ultimately influencing the allocation of performance-based school funding, health in adulthood, and national gross domestic product. School building occupants, children aged 5-18 years old, are also among the most vulnerable to adverse indoor environmental quality because of their higher respiratory rates, thinner skin, faster metabolisms, immature immune systems and blood/brain barriers, and larger body surface area relative to body weight compared to adults (Schwartz 2004). Aside from time spent in the home, the longest indoor exposure for 51 million American students is in their public-school buildings, where each child spends 15,600 hours by the time they graduate 12th grade. Children are more susceptible to school-based environmental stressors than adults; students of low socioeconomic status are especially vulnerable due to limited primary care access and environmental exposures associated with poor school siting (Mohai, Kweon et al. 2011) and housing quality (Adamkiewicz, Zota et al. 2011).

Despite the robust and granular characterization of indoor environmental problems students face (Eitland 2017), reducing adverse school building exposures has largely been overlooked by school stakeholders and policymakers. Yet, it may serve as a part of a multifaceted approach to promote the social, physiological, and academic well-being of children. These environmental challenges are exacerbated by 1) the lack of enforceable regulations for indoor environments, 2) limited consistent investment, and 3) the uneven distribution or monitoring of learning facilities.

First, the National Ambient Air Quality Standards (NAAQS) sets standards for primary and secondary outdoor air pollutants across the United States. However, there is no indoor air quality standard despite evidence that outdoor pollutant concentrations affect indoor levels conditional on atmospheric conditions, proximity to sources, airflow, and occupant and building factors including window use, mechanical ventilation, filtration use, location of air intake, building geometry and urban street canyons (Yuan, Ng et al. 2014, Tong, Chen et al. 2016, Nosek, Fuka et al. 2018). Furthermore, activities producing indoor environmental exposures (e.g. smoking, air conditioning and heating) can lead to average particulate matter and volatile organic compound concentrations two to five times higher indoors than outdoors (Rumchev, Spickett et al. 2004, Bruno, Caselli et al. 2008, Paciência, Madureira et al. 2016, EPA 2019).

Second, school infrastructure is rapidly deteriorating due to an estimated $271 billion in deferred building maintenance and repairs in the United States (U.S. Green Building Council, 21st Century School Fund et al. 2016) and a decline in federal funding for school building construction and alterations between 2000-2016 (NCES 2019). U.S. public school buildings are on average more than 50 years old, and schools in urban districts or attended by a high percentage of students on free and reduced-price lunch are even older, with an average age that may be as high as 70-80 years old (NCES 2019). Between disinvestment, poor maintenance, and a high proportion of schools predating significant environmental regulations, school building occupants are increasingly exposed to legacy pollutants that negatively impact learning and teaching such as PCBs in old light ballasts and caulking (Herrick, McClean et al. 2004), lead in flaking paint and corroding water pipes (GAO 2018), and asbestos fibers (U. S. Congress Senate 2015).

Third, despite schools being the second largest sector of public infrastructure in the United States after roads and highways, school conditions are not monitored annually (ASCE 2017). Due to limited school funding, schools are in dire need of targeted, health-centered investment. A universal, systematic assessment of school buildings may serve as a diagnostic tool to inform prioritization of maintenance needs, ensure proper allocation of resources, and support healthy learning environments.

Dissertation Goal

The goal of this dissertation is to provide a quantitative evaluation of strategies that could mitigate current harmful indoor exposures and promote investments in healthy environmental quality in schools. This dissertation addresses knowledge gaps around a specific set of current strategies across various settings to mitigate indoor environmental exposures including emerging technologies, building and construction policies, and school-related data collection efforts.

To address the dissertation goal, we first evaluated an intervention designed to reduce indoor air pollutants in an individual room (Chapter 2). Sensor-activated portable room air-cleaners (PRACs) were compared to traditional, continuously running PRAC technology. Continuous use of air purifiers has been positively associated with respiratory and cardiovascular health benefits in diverse populations including healthy adults, asthmatic children, pregnant or recent mothers and the elderly (Bräuner, Forchhammer et al. 2008, Xu, Raja et al. 2010, Allen, Carlsten et al. 2011, Sublett 2011, Chin, Godwin et al. 2014, Rice, Brigham et al. 2018). While many studies have shown that continuous purification can mitigate exposures (Fisk 2013, Fisk and Chan 2017, McNamara, Thornburg et al. 2017, Cox, Isiugo et al. 2018, Zhan, Johnson et al. 2018), none have examined whether sensor-activated air purifiers are more effective than continuously running PRACs at a set fan speed, especially during peak pollution events. Chapter 2 compares the effectiveness of particulate matter ($PM_{2.5}$) and total volatile organic compound (TVOC) sensor-activated portable air purification and continuously-running purification in urban residences in Boston. A crossover study of 32 residents provides a real-world evaluation of portable air purifiers. Continuous and integrated environmental exposures were measured in the living room and bedroom over the summer of 2017. Findings suggest sensor-activated portable air purification can address temporal variation in indoor pollutant levels associated with occupancy (e.g. cleaning, cooking, personal care product use) and outdoor traffic.

Second, the dissertation examined the relationship between school building conditions and chronic absenteeism in Massachusetts (Chapter 3). Massachusetts conducted three statewide school building assessments since 2006, yet has not evaluated the association with academic performance. Simultaneously, the state has developed chronic absenteeism reduction policies and programs to prioritize chronically low-performing schools, with an emphasis on low-income students (MA DESE 2017). To date, the state has largely focused on social-emotional efforts (e.g. reduce disciplinary actions, improve school culture) (MA DESE 2018); this analysis suggests ways to reduce chronic absenteeism by improving school IEQ. Chapter 3 examines the association between school building conditions and chronic absenteeism in a cross-sectional analysis during the 2016-2017 academic year in Massachusetts' kindergarten to 12th grade (K-12) schools. This chapter uses a statewide school building assessment to examine how overall building disrepair and specific building systems may be associated with chronic student absenteeism. The goal of this chapter is to identify school-level building factors and socioeconomic characteristics to target future state-funded investment and repair.

Lastly, the dissertation investigated the association between school building quality and academic performance using a subset of energy-efficient, green-certified schools in Massachusetts (Chapter 4). This effort builds upon the longitudinal multidisciplinary school database, Massachusetts' School Metrics and Research Tools (MA SMART) (MacNaughton, Eitland et al. 2017), using data from schools that were newly renovated or built with support from the High Efficiency Green School Program, which is sponsored by the Massachusetts School Building Authority. This statewide financial incentive program promotes energy efficiency and IEQ through green school certification (MSBA 2019). Green schools are designated as such by earning either of two main certifications 1) Leadership in Energy and Environmental Design for Schools (LEED)(USGBC 2007), and 2) The Northeast Collaborative for High Performance Schools (CHPS 2019). Studies have examined academic performance outcomes in LEED schools in other states (Thombs 2015, Thombs and Prindle 2018) as well as other building types (Allen, MacNaughton et al. 2015, Macnaughton, Satish et al. 2017) (Colton, MacNaughton et al. 2014) but have not examined the relationship between green school building occupancy and standardized test performance in Massachusetts. Chapter 4 compares Massachusetts school building conditions, academic performance, and demographics between schools that received green certification and those that did not during academic years 2010-2011and 2015-2016. This chapter identifies potential social and environmental mechanisms for why green school buildings may not be significantly associated with improvements in standardized test performance.

It is my hope that the data, methods, and results presented in this dissertation reinforce the need for just, equitable, and urgent investment in student occupied spaces. From dormitory housing to K-12 classrooms, the different scales of analyses employed in this dissertation provide school stakeholders and public health practitioners with methods for evaluating environmental interventions in their own communities. This dissertation also provides a rich discussion about how these findings could be translated into policies that promote quantifiable and equitable improvements in student outcomes. Specifically, increasing our understanding of the environmental and health effects of emerging technologies, school-related policies, and school building conditions can allow us to effectively, efficiently, and equitably improve student health and well-being.

CHAPTER 2: Evaluation of Dynamic-Response and Continuous Portable Air Purifiers for Reducing Residential PM2.5 and VOCs Exposures

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Abstract

Sensor-activated portable room air purifiers are a part of a growing market of smart home technologies aimed at improving health by responding to poor environmental quality. However, the effectiveness of ‘smart’ purifiers compared to continuously running purification has not been evaluated in a real-world setting. In 2017, we conducted a randomized crossover study in urban residences (n=32) and compared changes in indoor $PM_{2.5}$ and volatile organic compounds (VOCs) concentrations across three intervention arms: 1) Baseline: no air purification, 2) Smart, dynamic purification (SDP): purification responsive to elevated $PM_{2.5}$ and/or VOC concentrations 3) Continuous purification (CP): fan speed set to half the purifier’s full capability. Compared to baseline, CP and SDP reduced the daily geometric mean concentration of $PM_{2.5}$ by 29% and 19%, respectively. During peak events, SDP led to lower peak $PM_{2.5}$ concentrations and shorter durations compared to CP and Baseline. Both purification types resulted in significant reductions of VOCs, with higher reductions from CP. SDP can effectively reduce peak exposures to $PM_{2.5}$ from indoor sources, but CP may better reduce daily $PM_{2.5}$ and VOC concentrations from outdoor sources. These findings suggest a combination of CP supplemented by SDP that activates at lower thresholds may optimize public health benefits.

Introduction

The World Health Organization estimated over seven million deaths were due to air pollution, with 3.8 million deaths related to indoor air pollutants per year, largely driven by dirty fuels and biomass cooking (Amegah and Jaakkola 2016, WHO 2018). However, the issue of household air pollution is not limited to families in developing countries. Over 600,000 low-income Americans are exposed to household air pollutants from burning solid fuels for heating (Rogalsky, Mendola et al. 2014). In recent decades, indoor air quality has gained attention in the

United States with the number of publications on ‘indoor air pollution’ increasing fifteen-fold since 1990 (Corlan 2019).

Two ubiquitous indoor pollutants are particles 2.5 microns in diameter or smaller ($PM_{2.5}$) and volatile organic compounds (VOCs). Residential sources of $PM_{2.5}$ include cooking, heaters, candles, cigarette smoke and other combustion activities that result in discrete pollution events. VOC sources include personal care products, cleaners, air fresheners, furniture and paint (Shah and Singh 1988). Personal activities and behaviors (e.g. smoking, air conditioning and heating) can lead to average $PM_{2.5}$ and VOC concentrations two to five times higher indoors than outdoors (Rumchev, Spickett et al. 2004, Bruno, Caselli et al. 2008, Paciência, Madureira et al. 2016, EPA 2019). Furthermore, gaseous pollutants can also oxidize to form harmful secondary products including ozone and formaldehyde (Carslaw and Shaw 2019).

Air quality within homes is also influenced by outdoor pollution. Fossil fuel burning, point sources (e.g. bus depots, airports, construction sites), roadways, and other traffic-related combustion (Polidori, Kwon et al. 2009, Vette, Burke et al. 2013) can penetrate indoors (Morawska, Ayoko et al. 2017). The extent to which outdoor concentration effects indoor levels will depend on atmospheric conditions, proximity to sources, airflow, occupant and building factors including window use, mechanical ventilation, filtration use, location of air intake, building geometry and urban street canyons (Yuan, Ng et al. 2014, Tong, Chen et al. 2016, Nosek, Fuka et al. 2018).

Acute and chronic exposures to $PM_{2.5}$ are associated with increased risk of adverse cardiovascular, respiratory, reproductive, and mortality outcomes (Miller, Siscovick et al. 2007, Hoffmann, Moebus et al. 2009, Fleisch, Gold et al. 2014, Thurston, Ahn et al. 2016, Mahalingaiah 2018). Similarly, exposure to VOCs has been associated with an increased risk of asthma in young children, increased cancer risk, nausea, cognitive impairments and eye, nose, and throat irritation (Kilburn 2000, Guo, Lee et al. 2004, Rumchev, Spickett et al. 2004, Zhu, Wong et al. 2013, Kponee, Nwanaji-Enwerem et al. 2018). In addition to particles and gaseous pollutants, semi-volatile compounds commonly used as flame retardants, pesticides, and stain repellents have been associated with allergic reactions, asthma, neurological toxicity and reproductive development problems (Hu, Chen et al. 2013, Weschler and Nazaroff 2014, Allen, Gale et al. 2016, Dallongeville, Costet et al. 2016, Sunderland, Hu et al. 2019).

Portable room air-cleaning (PRAC) technology is now in more than 30% of U.S. homes (Shaughnessy and Sextro 2006) and is suggested to be part of a multi-faceted approach to reducing household air pollution exposure (e.g. behavioral modifications, resident education, green cleaning, testing for radon) (Fisk 2013). The efficacy of PRAC devices has been studied extensively. For example, high-efficiency particulate air (HEPA) filters have been shown to reduce $PM_{2.5}$ concentrations by 60% in wood smoke effected homes over a 1-week period, and reduce the $PM_{2.5}$ geometric mean by 63% in healthy non-smoking homes over a 2-day period (Bräuner, Forchhammer et al. 2008, Allen, Carlsten et al. 2011). Continuous use of air purifiers has been positively associated with respiratory and cardiovascular health benefits in diverse populations including healthy adults, asthmatic children, pregnant or recent mothers and the elderly (Bräuner, Forchhammer et al. 2008, Xu, Raja et al. 2010, Allen, Carlsten et al. 2011, Sublett 2011, Chin, Godwin et al. 2014, Rice, Brigham et al. 2018).

However, as HEPA filters combined with activated carbon filters are newer to the commercial market, there is limited evidence of whether this combination lowers both $PM_{2.5}$ exposures and VOC concentrations. While many studies have shown that continuous purification can mitigate exposures (Fisk 2013, Fisk and Chan 2017, McNamara, Thornburg et al. 2017, Cox, Isiugo et al. 2018, Zhan, Johnson et al. 2018), none have examined whether sensor-activated air purifiers are more effective than continuously running PRACs at a set fan speed, especially during peak pollution events. We investigate the effectiveness of PRACs on reducing average $PM_{2.5}$, peak $PM_{2.5}$, and VOCs in student dormitories using a randomized crossover intervention study design. Specifically, the three aims of our study were to 1) compare the effectiveness of portable air purification to reduce $PM_{2.5}$ and VOC concentrations in dorms compared to those without purification, 2) quantify the impact of smart and continuous purification on the magnitude and duration of high $PM_{2.5}$ events from both outdoor and indoor sources, 3) evaluate the effectiveness of purification to reduce 1-week integrated VOC concentrations.

Methods

Study Population

From July to August 2017, we conducted a crossover study in a naturally-ventilated residential building in Boston, MA. The 70-unit, 85-bed apartment building has one and two bedroom units ranging from 300 to 735 square feet. It is heated with hot water, has operable windows and has no forced ventilation or exhaust. Kitchens have exhaust hoods that pass exhaust through a filter and return into the space.

Two cohorts of 16 participants underwent a three-week monitoring study (n = 32), the first cohort in July and the second cohort in August. Limited by the number of available PRACs, the two cohorts only differed by the timing of their sampling. The study population occupied the same residence for three consecutive weeks. Participants were recruited as a convenience sample through the institution's Office for Student Affairs' email list and recruitment flyers. Participants were included if they directly rented housing in the residence hall and were aged 18 years or older. Individuals were excluded if they were away from their residence for more than 3 days during the study period. Participants completed a baseline survey on personal demographics and received financial compensation at the end of each week. The study was approved by the Harvard T.H. Chan School of Public Health Institutional Review Board and informed consent was received by all participants.

Air Purification Intervention

Baseline concentrations were obtained during the first week. In week two, each participant received two identical PRACs capable of being operated either on a continuous airflow or dynamic airflow. A PRAC was placed in the bedroom and the living room of each residence. The cohort was divided in half and participants were randomly assigned to receive one of the two purification settings (Figure 2-1). Eight participants (50%) had their PRAC filters set to continuous purification (CP) at a moderate fan speed setting with a constant flow rate of 30 ft^3/min for minimal noise disruption (below 55 decibels). The PRACs for the other eight participants were set to a $PM_{2.5}$ and TVOC sensor-activated air filtration setting (SDP: smart, dynamic-response purification), which adjusts fan speed according to the air quality detected by the PRAC itself (flow rate range: 20 ft^3/min – 80 ft^3/min). During week three, researchers changed the purifier setting so participants received the opposing purification condition from the week prior.

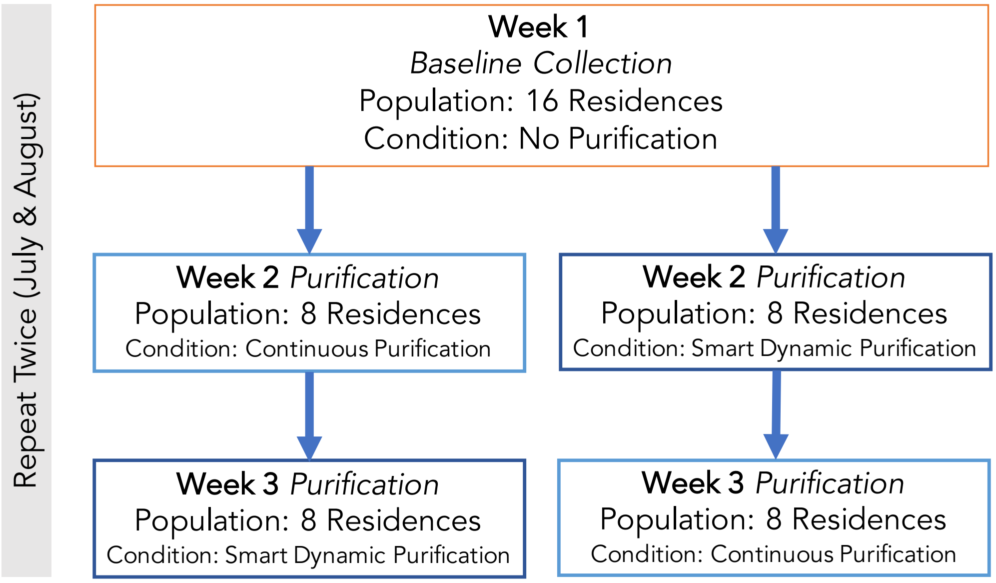

Figure 2-1: Experimental Study Design

Portable Room Air Cleaner Specifications

The PRAC used in this study was a Dyson Pure Cool Link Tower, Dyson Ltd, containing an oscillating cooling fan, a filter comprised of 20 feet of H-13 HEPA borosilicate microfiber, and an activated carbon filter. We performed chamber studies to estimate when SDP would automatically increase the air flow. This chamber study included two Awair Omni Indoor Air Quality Monitors, which continuously measured $PM_{2.5}$, VOCs, CO_2, temperature and relative humidity. The monitoring devices were placed inside a sealed 10-gallon aquarium with the PRAC base. PM and VOCs were introduced into the aquarium using a small pump. $PM_{2.5}$ was introduced into the aquarium using a sonic particle generation system consisting of a speaker, latex diaphragm and elutriator cylinder, which separated the larger particles (PM_{10}) from the fine particles ($PM_{2.5}$) that remain suspended. The $PM_{2.5}$ material used was finely ground black charcoal. VOCs were introduced into the aquarium by spraying consumer air fresheners near the inlet of the pump. The Awair's $PM_{2.5}$ value was normalized to a $PM_{2.5}$ gravimetric measurement by adding an air sampling pump equipped with a $PM_{2.5}$ size selective inlet and pre-weighed Teflon filter. The correction factor is 2.11. The Awair monitors and the filter sample ran for two days to have enough mass on the filter to weigh reliably. In these chamber conditions, the SDP activated once $PM_{2.5}$ concentrations exceeded $53\mu g/m^3$. When corrected, SDP activated when $PM_{2.5}$ concentrations were above $133\mu g/m^3$ or total volatile organic compound (TVOC) concentration exceeded 2,500ppb. This assessment revealed SDP exceeded the CP fan speed (constant flow rate of $30ft^3/min$).

Air Quality Monitoring

Indoor concentrations of $PM_{2.5}$, VOCs, and other environmental conditions were measured using multiple instruments housed in a sampling apparatus placed in the living room of each home during the 3-week study. A Netatmo weather station measured temperature, carbon dioxide (CO_2), noise, relative humidity and barometric pressure in the participants' bedroom and living room (Netatmo 2017). Netatmo weather stations were calibrated to 0 and 3,000ppm CO_2 using calibration gases (Allen, MacNaughton et al. 2015). An Alphasense Optical Particle Monitor (OPC-N2) continuously measured PM size counts (0.38 to 17-micron diameter) and mass concentrations for PM_1, $PM_{2.5}$, and PM_{10} every approximately 1.4 seconds (Alphasense Air 2017). A one-week gravimetric particle sample was collected at a nominal flow rate of 0.8 L/min using a Harvard mini PEM that consisted of a $PM_{2.5}$ impactor (Chang, Sarnat et al. 1999), Schwarzer Precision (Essen Germany) SP140 pump, and a Teflon filter (37mm, Pall Life Sciences, Port Washington, NY). The actual flow rates were recorded at 1-minute intervals using Omron D6F-P0010A2 flow sensor. Filters were weighed after 48-hour conditioning at the Harvard Chan School of Public Health using a Mettler MT5 microbalance (Mettler-Toledo, Columbus, OH) housed in a temperature and humidity-controlled room. The gravimetrically determined $PM_{2.5}$ concentrations were used to normalize the $PM_{2.5}$ readings by OPC-N2. Sensors selected have been previously validated and calibrated for use in residential spaces (Gillooly, Zhou et al. 2019).

In the July cohort, a Tenax TA thermal desorption (TD) tube (Model C1-AXXX-5003, Markes International, Sacramento, CA) was deployed in each home (n=48, 3 weeks/16 participants) for the study week to passively collect an integrated sample. For quality assurance and quality control purposes, blank and duplicate VOC samples were administered for 25% of the samples (n=12). Samples were then analyzed on a TD (ULTRA 2 + UNITY 2, Markes International, Llantrisant, UK) gas chromatography/mass spectrometry (GC/MS, Agilent 7890A/5975C, Agilent, Santa Clara, CA, USA) system for 75 target compounds following an established protocol (Jia and Fu 2017). The detection limits were 0.01 - 0.05μg/m^3 at 25°C for 7-day sampling, depending on the physiochemical properties of chemicals.

Covariates

We calculated air exchange rates (AER) for each participant-day of the study using CO_2 data. We used an algorithmic detection of CO_2 decay periods that were analyzed using the tracer gas method described in ASTM Standard E741-11 for single-zone spaces. The rate of decay of occupant generated CO_2 can be used to estimate air exchange rates using the validated methodology set forth by ASTM. Specifically, our algorithm assumes decay periods when the end-of-decay concentration approximates 400ppm (i.e., near outdoor concentrations), which corresponds to changes in space occupancy from occupied to vacant. A limitation of this method is that air from other zones with higher CO_2 levels can bias air exchange rate calculations, as well as incorrect occupant CO_2 generation rates leading to inaccuracies.

Hourly outdoor $PM_{2.5}$ and PM_{10} concentrations were measured at a permanent air quality monitoring site on the rooftop of a building located 0.5 miles away from the study residences. The ambient air monitoring station has a Beta Attenuation Monitor (BAM1020, Met One

Instruments, Inc., Grants Pass, OR) and the $PM_{2.5}$ values derive from the BAM are seasonally corrected by the Harvard Impactor integrated sampler.

Every morning of the 3-week study, participants received a 10-minute survey via email asking about occupancy, daily exposures and health symptoms for the previous day. Participants reported daily the number of meals cooked, cleaning, use of candles and among other activities. The duration and start time of cooking and cleaning events was not consistently recorded by all participants, and was not considered for this study.

Statistical Analysis

For each intervention arm, we collected seven days of $PM_{2.5}$ aggregated to 5-minute averages and daily averages. The $PM_{2.5}$ data had a right skewed distribution and was log transformed to meet the assumption of normal distribution for statistical modeling. Our exclusion criteria for daily mean data were incomplete environmental information including, indoor and outdoor $PM_{2.5}$, temperature, humidity, AER and CO_2; daily mean $PM_{2.5}$ values below $1 \mu g/m^3$ due to suspected sensor failure; and when two purification settings were used during a single 24-hour period. Of 32 homes, one sensor malfunctioned for an entire monitoring period; those results were excluded from our analysis.

To quantify the overall daily effectiveness of purification, our first outcome of interest was the difference in daily geometric mean $PM_{2.5}$ concentration between participants' baseline and PRAC intervention using a generalized additive multilevel model with a random intercept for participant.

To examine periods of high $PM_{2.5}$, our second outcome was participants' time and average concentration above the National Ambient Air Quality Standards (NAAQS). Due to no enforceable indoor standard for residential indoor air quality, we used the daily and yearly outdoor NAAQS threshold as a proxy for health-relevant exposures. The data was subset to those concentrations exceeding the yearly and 24-hour thresholds of 12μg/m^3 and 35μg/m^3, respectively. We calculated the total time above these thresholds and geometric mean concentration for each participant. Models were adjusted for relative humidity, air exchange rate, and outdoor $PM_{2.5}$ concentration.

Third, to determine purifier responsiveness and reduce high indoor $PM_{2.5}$ events, we identified $PM_{2.5}$ peaks and examined the differences in peak concentration, duration of decay, and decay rate across the three purification conditions. Peak $PM_{2.5}$ events were detected from the continuous time-series data. Each 'event' starts at the peak $PM_{2.5}$ concentration and ends when the decay has reached steady state. Decay events were considered a sustained decrease in concentrations, and ended either when the slope of the decay approached 0 (asymptote) or when the next time period had a sudden increase in $PM_{2.5}$. Peak concentrations (C_{time}) were detected when the following condition was met: $C_{time-1} < C_{time} > C_{time+1}$ (C_{time-1}: concentration of prior observation; C_{time+1}: concentration of following observation). Summary statistics including the peak concentration, end concentration, rate of change, and peak duration were calculated for each decay event (Table 6-1 in Supplementary Materials).

The identified peaks (n=1107) were classified into three categories: 1) minor peaks, where the starting $PM_{2.5}$ concentration was below 12μg/m^3; 2) moderate peaks, where the starting $PM_{2.5}$ concentration was above 12μg/m^3 but below 35μg/m^3; and 3) major peaks, where the starting $PM_{2.5}$ concentration was above 35μg/m^3. We had statistical power to look at peaks per study week (n >30). We used an Analysis of Variance (ANOVA) test to test for differences in peak characteristics across each intervention arm. We tested the association between purifier setting and peak duration, starting concentration and decay rate using generalized additive mixed models. Participant ID was included as a random intercept to account for measurements clustered within participants' homes. All models were adjusted for relative humidity (%), outdoor $PM_{2.5}$ ($\mu g/m^3$), and occupancy (space occupied/vacant) (Equation 1). We explored effect modification by peak magnitude (Minor Peak: $<12\mu g/m^3$; Moderate Peak: $12\text{-}35\mu g/m^3$; Major Peak: $>35\mu g/m^3$) (Table 2-2). We conducted a sensitivity analysis with apartment-specific characteristics including unit floor (1-4), number of occupants and occupancy (determined by increasing CO_2 concentrations in the residence). Baseline was used as the reference group. All analyses were performed using the open source statistical software RStudio Version 1.0.143.

$$Peak\ Characteristic = \beta_1 + \beta_2(Purifier\ Setting) + \beta_3(Relative\ Humidity) + \beta_4(Hourly\ Outdoor\ PM_{2.5}) + \beta_5(Occupancy) + \beta_6(Magnitude\ of\ Peak) + \beta_7(Magnitude\ of\ Peak\ x\ Purifier\ Setting) + e_i \qquad (1)$$

Fourth, we evaluated changes in one-week integrated VOC concentrations between baseline and purification settings. The mean VOC concentration and standard deviation across the 30 VOCs measured in homes are reported in Supplementary Materials in Table 6-2. Common groups of VOCs were identified using factor analysis. Factor analyses were performed using log-transformed concentrations of frequently detected VOCs (detection frequency >50%) and a Varimax rotation to obtain clear factor patterns. A factor was retained if its Eigenvalue was >1 and a VOC was included in the final factor pattern if it had at least one factor loading >0.5. Multiple factor analyses were tried until all the above conditions were met and the factor pattern could be reasonably interpreted with prior knowledge. Factor analyses were performed using PROC FACTOR in SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Using the factor loadings, the factor score was calculated and a univariate multilevel model was generated with a random intercept for study participant i (Equation 2). β_1 is the fixed intercept and β_2 is the fixed effect for the dummy variable of purifier setting, purification types compared to baseline.

$$VOC\ Factor\ Weighted\ Sum = \beta_1 + \beta_2(Purifier\ Setting) + e_i \qquad (2)$$

Results

Demographics

We completed 128 home visits for 32 participants across two cohorts over a six-week study period, three weeks in July and three in August 2017. Baseline participant demographics are summarized in Table 6-3 and the population demographics were balanced between the two cohorts (p>0.10), which were determined by Fisher's Exact Test for categorical variables and standardized mean difference test for continuous variables. Participants were predominately female (62.5%), and had lived in other countries prior to their current apartment (69%). Nearly half the population had lived in the residence for fewer than 3 months (46.9%). Baseline self-reported surveys revealed that the population was comprised of healthy adults in moderately good to extremely good health (6.3 on a scale of 1-7, with 7 being extremely good), who did not have allergies (65%) and did not take daily asthma medication (100%). Participants did not see any mice or rats in the apartments, but 41% reported seeing cockroaches. Twenty-five participants (78%) stated they cleaned their homes every day, and 22% had used an air purifier in their past homes.

Summary of Environmental Measures

The geometric means and standard deviations of indoor and outdoor environmental conditions are reported in Table 2-1. The indoor geometric mean $PM_{2.5}$ concentrations were considerably lower than the outdoor $PM_{2.5}$ concentrations during the study period. However, despite the low mean daily $PM_{2.5}$ concentrations at baseline (3.82μg/m^3), purification weeks were associated with reductions in the geometric mean of $PM_{2.5}$ (SDP: 3.35μg/m^3; CP: 2.84μg/m^3).

Temperature and relative humidity remained consistent and within acceptable ranges for the duration of the study. Median air exchange rates (0.71-0.82) in our study were slightly higher than, but generally consistent with median air exchange rates in U.S. homes (0.55 ACH). There were no significant differences for these environmental variables across study arms.

Table 2-1: Summary of Environmental Characteristics by Purifier Setting: Mean (Standard Deviation)

	Baseline	Dynamic (SDP)	Continuous (CP)
$PM_{2.5}$ μg/m^3			
Arithmetic Mean	7.00 (25.29)	3.93(2.46)	3.61(3.11)
*Geometric Mean**	3.82 (2.21)	3.35(1.74)	2.84 (1.93)
*Apartments Reporting A/C Use**	2.80 (4.50)	2.97 (2.66)	2.75 (3.95)
Outdoor	16.30 (3.61)	16.35 (3.01)	16.49 (3.25)
I/O Ratio	0.39 (1.15)	0.24 (0.14)	0.22 (0.16)
Temperature °C	27.49 (1.97)	27.63(2.00)	28.03 (2.13)
Relative Humidity %	55.06 (6.00)	55.05 (5.14)	54.18 (6.49)
Carbon Dioxide ppm	733.15 (282)	685.31 (257)	651.12 (215)
Time Unit Occupied %	50% (18)	52% (17)	52% (16)
Noise dB	56.33 (4.77)	56.24 (3.62)	56.19 (4.19)
AER Air Changes per Hour	0.71 (0.48)	0.82(0.61)	0.71 (0.44)
TVOC μg/m^3	37.15 (44.83)	30.33 (37.01)	25.68 (32.48)
Above Outdoor National Ambient Air Quality Standards			
Mean Concentration* $PM_{2.5}$ >12 μg/m^3*	23.56 (2.09)	19.12 (1.72)	19.82 (1.71)
Mean Duration $PM_{2.5}$ >12 μg/m^3 per Participant	2.2 hours	1.9 hours	2.3 hours
Mean Concentration $PM_{2.5}$ >35 μg/m^3*	76.24 (1.95)	63.60 (1.77)	63.16 (1.79)
Mean Duration $PM_{2.5}$>35 μg/m^3 per Participant	4 hours	2.4 hours	3.5 hours

Note: *GM: Geometric Mean; GSD: Geometric Standard Deviation

Average Daily $PM_{2.5}$ Analysis

Statistical modeling examining differences in daily $PM_{2.5}$ concentrations between baseline and intervention weeks showed that purification resulted in reductions of 29% during CP and 19% during SDP compared to baseline measurements in the same home.

Peak Event Decay Analysis

There were no statistically significant differences in the number of peaks across the baseline and the two interventions (ANOVA; $p=0.486$). Stratification by 'peak type' allowed us to determine PRAC effectiveness at different $PM_{2.5}$ peak magnitudes. Results for the generalized additive mixed effect model, which includes a term for effect modification between decay peak type and purifier setting, revealed that both purification interventions were most effective at peaks above $35 \mu g/m^3$ compared to baseline and minor peaks (Table 2-2). We evaluated the impact of the interventions on peak exposures across three variables: duration of exposure, peak concentration, and decay rate.

Duration

The duration of a peak event was significantly lower for both purifier settings relative to baseline ($p<0.05$). The average duration of a peak event in the baseline condition was 96.3 minutes compared to 70.5 minutes for SDP and 74.6 minutes for CP. In the generalized additive mixed effect model in Table 2-2, purification was most effective at reducing the decay duration when the peak concentration is above $35 \mu g/m^3$. Specifically, SDP use during major peaks was associated with the greatest peak duration reductions. Compared to major peaks during baseline (93.7 minutes), the model estimated that major peaks lasted for 9 minutes with SDP and 40 minutes with CP.

Peak Concentration

Peak concentration was significantly reduced with the use of purification. For major peaks, the peak concentration with SDP was estimated to be 87.6μg/m³ and CP was estimated to be 95.7μg/m³ compared to baseline (128.1μg/m³). Use of purification during moderate peaks did not lead to statistically significant differences in peak concentration.

Decay Rate

In the regression model, only CP use during major peaks was associated with statistically different decay rates compared to baseline. However, the model shows that SDP had a faster decay rate (1.29μg/m³/min) compared to CP (0.892μg/m³/min) during major peaks, as expected due to the higher fan speed at high concentrations.

Table 2-2: Peak Event Characteristics Regression Model Results

	Duration (mins)		**Peak Concentration (μg/m³)**		**Decay Rate (μg/m³/min)**	
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI
Baseline Reference						
SDP	-15.61**	(-25.98, -5.23)	0.030	(-8.81, 8.87)	0.033	(-0.09, 0.16)
CP	-7.12	(-17.21, 2.96)	-0.65	(-9.14, 7.84)	0.012	(-0.11, 0.13)
Moderate Peaks	-0.47	(-13.41, 12.45)	11.88*	(0.73, 23.03)	0.14	(-0.013, 0.30)
Major Peaks	93.73***	(76.69, 110.77)	128.1***	(113.5, 142.7)	1.30***	(1.10, 1.50)
SDP*Moderate Peaks	9.18	(-8.192, 26.54)	-0.13	(-15.19, 14.92)	0.016	(-0.19, 0.22)
CP*Moderate Peaks	-1.68	(-18.19, 14.84)	0.88	(-13.38, 15.14)	0.011	(-0.19, 0.21)
SDP * Major Peaks	-68.88***	(-91.91, -45.85)	-40.42***	(-60.36, -20.48)	-0.043	(-0.32, 0.23)
CP * Major Peaks	-46.60***	(-70.10, -23.09)	-31.66**	(-51.92, -11.39)	-0.42**	(-0.70, -0.14)
R^2	0.181		0.383		0.272	

Note: Significance denotes * p-value <0.05, ** p-value<0.01, *** p-value <0.001
Models adjusted for average humidity, occupancy, and outdoor $PM_{2.5}$ concentration during the peak event

VOC Analysis

Factor analyses revealed five common sources that explained 84.5% of the total variance of 23 VOCs (Table S4). Factor 1 included aromatic compounds and light alkanes (C8 and C9), which are likely emitted by gasoline vapor and vehicle exhaust. Factor 2 contained terpenes, naphthalene and C13 alkane, reflecting cleaning agents and pesticides. Factor 3 was notably correlated with CO_2 level, indicating these chemicals are associated with presence and activities of occupants. Thus, styrene may be emitted by food packings, chloroform from tap water use, and C10 and C12 alkanes are from air fresheners and personal care products. The heavy alkanes in Factor 4 were mainly emitted from paints, coating, and adhesives. Factor 5 included aromatic compounds and C11 alkane, possibly from combustion processes. It should be noted any one VOC has multiple sources and a typical indoor source emits multiple chemicals. Thus, these groupings roughly reflect common sources, but they are not exclusive.

Using the factor loadings, the weighted sum for each factor was calculated and a univariate multilevel model was generated with a random intercept for study participant. Across the five factors, purification consistently reduced the weighted sum (Table 2-3 & Figure 2-2). Notably, both purification types were associated with statistically significant reductions in traffic-related aromatic compounds and light alkanes (Factor 1), occupancy-related compounds (Factor 3), and aromatic compounds and C11 alkane (Factor 5). Across the five factors, the CP had greater reductions in weighted VOC sums except in Factor 2, where SDP was associated with a statistically significant 30% reduction in the weighted sum of compounds associated with cleaning and pesticides (Factor 2). CP was associated with a 43.6% reduction in compounds found in paints, coating, and adhesives (Factor 4) compared to SDP.

Table 2-3: VOC ($\mu g/m^3$) and CO_2 (ppm) Factor Regression Results (Standard Error)

	Factor 1 Traffic Outdoor	**Factor 2** Cleaning Pesticide	**Factor 3** Occupancy	**Factor 4** Adhesives Paints	**Factor 5** Combustion
Reference: Baseline					
Intercept	4.79 ***	18.49 **	1.77***	2.32***	0.68***
	(0.24)	(5.65)	(0.21)	(0.27)	(0.06)
Continuous	-2.16 ***	-6.85	-0.74**	-0.71**	-0.34***
	(0.39)	(3.96)	(0.23)	(0.28)	(0.08)
Dynamic	-1.15 **	-9.78*	-0.65**	-0.40	-0.22**
	(0.39)	(3.96)	(0.23)	(0.28)	(0.08)

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

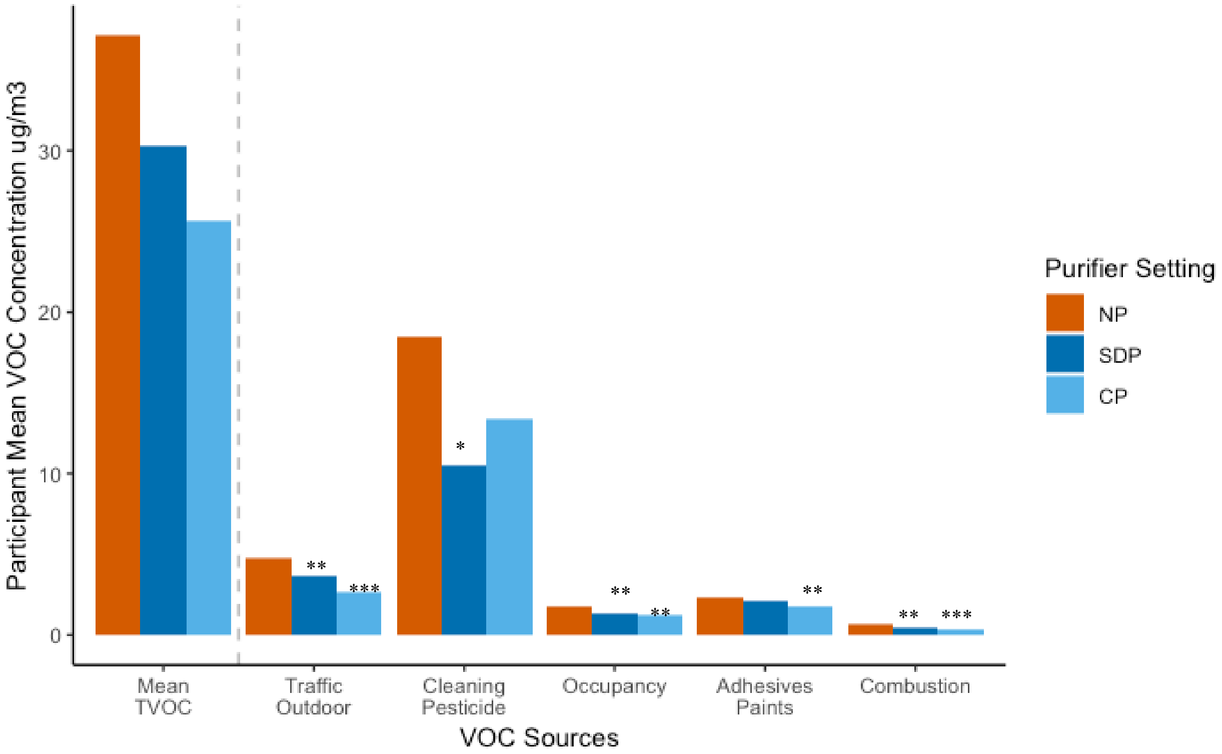

Figure 2-2: Mean participant VOC concentration during study period using factor weighting

Note: Mean TVOC: average total volatile organic compounds during each sampling week. Dashed vertical line separates total VOC and Factor-associated VOC concentrations. Traffic/Outdoor: Includes compounds found in Factor 1, Cleaning/Pesticide includes Factor 2, Occupancy include Factor 3, Adhesives/Paints includes Factor 4, and Combustion includes Factor 5. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Discussion

This crossover intervention provides real-world evidence about dynamic-response PRAC use and the effectiveness within and across participants. We assessed differences in $PM_{2.5}$ and

VOC concentrations in apartments across three treatment arms: 1) no air purification (baseline), 2) continuous PRAC use (CP), and 3) smart, dynamic-response PRAC use (SDP). Overall, the apartments had low baseline concentrations of $PM_{2.5}$ and VOCs. However, consistent with other residential research on high efficiency portable filter use (Bräuner, Forchhammer et al. 2008, Allen, Carlsten et al. 2011, Weichenthal 2012), we observed reductions in weekly $PM_{2.5}$ concentrations when purification was used.

Regression results of daily averages suggest that CP with a fixed flow rate may result in greater reductions for residential $PM_{2.5}$ concentrations compared to SDP, if SDP trigger thresholds are high. However, the results also show that SDP is very effective at minimizing the impact of peak events. For example, restricting our analysis to periods of high $PM_{2.5}$ concentrations, SDP was more effective than CP. Specifically, the duration above the NAAQS $PM_{2.5}$ thresholds were shorter for SDP compared to CP, suggesting reduced exposure to potential harmful $PM_{2.5}$ concentrations. In mixed models looking at the effects of purification on peak $PM_{2.5}$ events, we found SDP significantly reduced the duration and peak concentration compared to Baseline. CP was also useful for shortening the duration, lowering the peak concentration, and increasing the decay rate of major peaks compared to Baseline, but less effective than SDP. We conclude that SDP is more effective than traditional CP approaches at reducing high $PM_{2.5}$ concentrations because it is responsive to peak events by increasing air flow.

The factor analysis of VOC composition revealed five distinct factors. Across these factors, univariate analysis showed purification consistently reduced the weighted sum of these compounds. This suggests purification is an effective method of reducing benzene, toluene, ethylbenzene and xylene (BTEX) compounds (Factor 1). This exposure is known to be associated with endocrine disruption, respiratory, reproductive and cardiovascular outcomes at ambient, non-occupational levels (Bolden, Kwiatkowski et al. 2015). Except for cleaning and pest management agents (Factor 2), CP was associated with greater reductions in weighted VOC sums compared to SDP. Known for their favorable smell, terpenes in Factor 2 (e.g. limonene, pinene) may be associated with acute cleaning events that would trigger a dynamic response. Terpenes can oxidize and form secondary pollutants known to be probable carcinogens (e.g. formaldehyde) and contact allergens (Nazaroff and Weschler 2004); therefore, responsive purification may reduce exposure to other pollutants not monitored in this study. This suggests SDP may be responsive to indoor VOC events associated with cleaning and pesticide use compared to CP.

Acute, Event-Specific Application for PRACs

There are broad applications for SDP use in areas with acute and chronic high ambient air pollution. Acute natural events that result in high $PM_{2.5}$ concentrations such as nocturnal radiation inversions, temperature inversions (Hien, Bac et al. 2002, Wallace and Kanaroglou 2009), and wild fires may benefit from responsive purification (Fisk and Chan 2017). In Ontario, Canada, nighttime inversion events resulted in a 54% increase in $PM_{2.5}$ concentrations (6.8 to 10.5 $\mu g/m^3$) compared to daytime (Wallace and Kanaroglou 2009). These fluctuations would typically occur when a resident was sleeping, but SDP could respond to these variations if the activation threshold was sensitive at lower $PM_{2.5}$ concentrations. Due to the effectiveness of removing fine particles, continuously running air purifiers have been highlighted as a primary intervention during wildfires, which lead to short-term, far-reaching pollution events that are associated with increased VOC, carbon monoxide, nitric oxides, and polycyclic hydrocarbon concentrations (Barn, Elliott et al. 2016) and are associated with increased hospital admissions, respiratory complications, and mortality (Fisk and Chan 2017). In July 2013, smoke from

Canadian wildfires resulted in sharp local increases in $PM_{2.5}$ concentrations (max concentration of 90 $\mu g/m^3$) lasting 12-18 hours (Sofowote and Dempsey 2015). Previous studies showed Canadian wildfires may influence air quality across the United States (Ara Begum, Kim et al. 2005). Therefore, SDP use may be effective at reducing risk during high pollutant events even when there is not a perceived risk due to distance. Similarly, the state of California is experiencing a growing number of wildfires with more than 7,400 wildfires in 2018 (Cal Fire 2018). In a study of air filtration interventions during the 2003 wildfire season, Fisk & Chan found that continuous portable air filtration with a high efficiency filter had the greatest reduction in predicted mean $PM_{2.5}$ concentrations compared to central air heating and cooling systems and baseline conditions (Fisk and Chan 2017). The concentrations reported from these events exceed 35 $\mu g/m^3$ (Fisk and Chan 2017), which is when SDP has shown to be associated with the greatest reductions in peak duration and magnitude. SDP could independently prevent accumulation of particles and gaseous material as indoor levels increase by increasing air flow and filtration capacity.

Daily, Chronic Exposure Application for PRACs

In homes of healthy adults with residential wood combustion, daily chronic use of CP was associated with improved endothelial function, decreased concentrations and a 60% reduction in fine particle concentrations (Allen, Carlsten et al. 2011). Temporal variation in occupancy and wood combustion use, may provide a reason for a dynamic air flow response. However, in homes of healthy older adults proximal to roadways and without a strong indoor pollutant source, cardiovascular health benefits were observed after 48 hours of filtration use (Bräuner, Forchhammer et al. 2008). SDP has the potential to intervene on diurnal variations in

$PM_{2.5}$ concentrations generated by heating, cooking events, and outdoor traffic that would repeatedly exceed 12µg/m^3 of $PM_{2.5}$ and contribute to intermittent VOC formation.

Ambient air quality standards in the United States have resulted in low outdoor daily and annual $PM_{2.5}$ concentrations, which may explain the limited triggering of the internal PM sensor within the SDP PRAC over the course of this study. However, in a study conducted among adults with active asthma, symptoms increased in prevalence at $PM_{2.5}$ levels as low as 4.00–7.06µg/m^3 (Mirabelli, Vaidyanathan et al. 2016), which were found in the residences included in our study. In a low-income senior housing building in Phoenix, Arizona, researchers documented mean and median $PM_{2.5}$ concentrations in the living room at 62 µg/m^3 and 13µg/m^3, respectively, with 36% of samples exceeding 40ppb for formaldehyde (Frey, Destaillats et al. 2014), suggesting SDP could be useful at reducing particulate and gaseous pollutants at lower levels.

Previous international studies support the use of CP due to high outdoor pollutant concentrations that require continual air cleaning indoors. In a study of seven buildings in Beijing, outdoor $PM_{2.5}$ strongly contributed to indoor levels, with an average residential indoor/outdoor (I/O) ratio of 0.94 (Deng, Li et al. 2017). They report that 40.6% of residential homes had I/O ratios less than 0.8 and concluded that naturally ventilated buildings could be more effective at reducing indoor $PM_{2.5}$ concentrations, especially when influenced by outdoor sources. Based on our study findings, CP may be an effective supplement to reduce $PM_{2.5}$ and VOCs levels for naturally ventilated residences with low I/O ratios.

This study has several limitations. First, baseline indoor $PM_{2.5}$ concentrations were low due to predominately single person units and short term leases (3-months), which may not be reflective of cooking, product use, or cleaning behaviors found in typical homes. The study was conducted during the summer. Consequently, seasonality may impact the composition and concentration of indoor pollutants and allergen levels, along with altering ventilation patterns. Second, this study was limited to apartments of non-smoking residents. Higher concentrations of $PM_{2.5}$ and VOC pollution are expected to exist in houses with attached garages or smoking activities (Breysse, Buckley et al. 2005, Héroux, Clark et al. 2010, Wheeler, Wong et al. 2013, Semple, Apsley et al. 2015). Also, the student participants studied healthcare and may be more aware of the importance of a hygienic indoor environment compared to the general population. Third, baseline measurements were collected prior to purification weeks, therefore we cannot compare to purification weeks because outdoor conditions (e.g. precipitation, construction, traffic patterns) could be different across the testing period and the occupants might have behaved differently during baseline compared to other weeks. Fourth, the VOC and $PM_{2.5}$ concentration activation threshold is proprietary information and we cannot determine which pollutant triggered the device. However, our chamber studies estimated that to exceed the CP fan speed, $PM_{2.5}$ must exceed $133\mu g/m^3$ in a low VOC environment, and TVOC concentrations must exceed 2500ppb in a $PM_{2.5}$-free environment. We hypothesize that the concentration rate of change contributes to the fan speed response. Lastly, research shows that air pollution data from a single monitoring station may not be able to capture local traffic, surrounding greenness, and construction impacts (Dionisio, Isakov et al. 2013). This limited our ability to control for short-term changes that may have affected the activation and effectiveness of SDP PRACs.

This study is the first assessment, to our knowledge, of smart purification effectiveness in a real-world residential setting. The outdoor conditions remained consistent for all study participants because they lived in the same residence and all participants were exposed to the same traffic patterns, pest management, and green space. Also, the low $PM_{2.5}$ concentrations during inactivity allowed for clear identification of minor, moderate, and major peaks during occupied periods. Additionally, due to the crossover design, we did not need to control for personal characteristics (e.g. age, BMI, no smoking) because we compared participants to themselves.

These findings are generalizable to this type of purifier and residential configuration. With other PRACs on the market and in single family homes, we expect to see different results across PRACs, geographies, building types, and occupant behaviors. In areas with higher pollution, we expect greater PRAC effectiveness, especially in communities of lower socioeconomic status, which have been shown to be at increased risk of indoor and outdoor air pollution (Samet and White 2004, Rogalsky, Mendola et al. 2014). Therefore, further research is needed in more environmentally and temporally diverse settings, including residences with higher $PM_{2.5}$ concentrations, real-time VOC monitoring, greater variation in daily indoor and outdoor peak exposure, longer term use, and seasonal variation.

Conclusions

The results of this study indicate that purifiers are associated with an overall reduction in daily $PM_{2.5}$ and VOC concentrations. During periods of high $PM_{2.5}$ or acute peak events, dynamic-response purifiers can further reduce the duration of peak events and maximum concentrations further. Also, dynamic-response purifiers reduce VOC concentrations associated with cleaning events and occupancy. Observing $PM_{2.5}$ and VOC reductions in low-pollutant environments suggest promising implications for dynamic-response, ‘smart’ purifiers in homes. Portable room air cleaners continuously running at a set fan speed supplemented by a low trigger threshold dynamic response may provide a promising public health intervention that reduces individuals’ exposure to $PM_{2.5}$ and VOCs.

CHAPTER 3: Association between school building disrepair and chronic absenteeism: A case study of K-12 Schools in Massachusetts

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Abstract

Seven million K-12 students are chronically absent every year in the United States. Growing evidence suggests that poor physical condition of school buildings may contribute to student absenteeism. This cross-sectional analysis examined the association between school building conditions and chronic absenteeism for the 2016-2017 academic year in Massachusetts' kindergarten to 12th grade (K-12) schools (N = 1,379). A systematic assessment of K-12 schools provided categorical building quality measures of building and site characteristics, 16 of which might affect health. Poisson regression analyses, stratified by Title 1 eligibility and school type (elementary, middle, high) and controlled for sociodemographic characteristics, revealed that chronic absenteeism is positively associated with schools that require a higher number of building repairs, especially for low socioeconomic schools (Title 1 eligible). In an analysis of specific building systems, schools needing major repairs or replacement of school *roofs*, *building envelope*, and *site-related* features were significantly associated with higher chronic absenteeism compared to schools in need of general maintenance. Schools with the greatest need for repair are disproportionately attended by disadvantaged and minority students, and associated with high absenteeism. Addressing building disrepair may provide another strategy for reducing chronic absenteeism and environmental inequalities.

Introduction

In the United States, 16% out of 7 million students are chronically absent every year (U.S. Department of Education 2019), which means they miss at least 10% of the academic year due to absence. In response to the implementation of the Every Student Succeeds Act (ESSA), more than thirty states, including Massachusetts (MA) (MA DESE 2017), have begun to track chronic absenteeism. Asthma is the primary health condition responsible for student absenteeism nationally (Moonie, Sterling et al. 2006, Hsu, Qin et al. 2016, Lary, Allsopp et al. 2019), especially for younger children and for schools with a high concentration of low-income students (Meng, Babey et al. 2012). However, non-respiratory health conditions, communicable diseases (Koep, Enders et al. 2013), and sick building syndrome symptoms including fatigue (Turunen, Toyinbo et al. 2014) and headaches (Rousseau-Salvador, Amouroux et al. 2014), may also influence student attendance.

There is growing evidence that deleterious physiological and psychological health (Mohai, Kweon et al. 2011) and learning outcomes (Shendell, Prill et al. 2004, Haverinen-Shaughnessy, Moschandreas et al. 2011, Hsu, Qin et al. 2016, Berman, McCormack et al. 2018, U.S. Department of Education 2019) are associated with exposure to poor indoor and outdoor school building quality—characterized by low ventilation rates (Fisk, Paulson et al. 2016), excessive moisture, improper siting (Mohai, Kweon et al. 2011, Grineski and Collins 2018), exposure to indoor pollutants (e.g. volatile organic compounds, dust and particles, pests, asbestos, radon) (Shendell, Barnett et al. 2004), inadequate temperature control (Mendell and Heath 2005) and lighting (Mott, Robinson et al. 2012, Mott, Robinson et al. 2014). In response to a Congressional request, in 1995 the U.S. Government Accounting Office reported that one-third of schools needed major repair or replacement, and another 40% required repair or replacement of key building systems, including roofs and plumbing (United States General Accounting Office 1995). In a follow-up study in 2013, the National Center for Education Statistics surveyed a nationally representative sample of school buildings and found more than half of U.S. schools still needed corrective maintenance and repairs to put them in "good" overall condition (meaning the building meets the reasonable needs of the school) (Alexander and Lewis 2014). Yet, the role of improvements to physical school environments in reducing chronic absenteeism has been largely overlooked by government due to a lack of regulatory oversight and consistent school facilities evaluations (Sampson 2012). Studies in other parts of the country show positive associations between attendance metrics and health-related building and site systems quality (e.g. six or more building problems, poor ventilation) (Simons, Lin et al. 2009, MacNaughton, Eitland et al. 2017, Berman, McCormack et al. 2018). However, none of these studies examined statewide associations between K-12 school buildings quality and annual measures of chronic absenteeism after the 2008 recession, with a policy-relevant marker for socioeconomic status of schools.

To address infrastructure needs and chronic absenteeism, MA has improved upon these national efforts. First, they have conducted three statewide school building assessments since 2006. Second, the MA Department of Elementary and Secondary Education developed policies and programs to prioritize chronically low-performing schools, with an emphasis on Title I schools, which are eligible for supplemental federal funding to assist their large concentrations of low-income students (MA DESE 2017). To date, the state has largely focused on social-emotional efforts that reduce disciplinary actions, provide additional student support, and improve school culture (MA DESE 2018), but has yet to focus on the physical building.

To address this research gap, we used MA data on chronic absenteeism by school in conjunction with the state's 2016 statewide building assessment to evaluate the association between school building disrepair and chronic absenteeism in MA K-12 schools in the 2016-2017 academic year. Our two main research questions were 1) how is total building disrepair associated with chronic absenteeism, and 2) how is disrepair of specific building systems (e.g. lighting, water, roof) associated with chronic absenteeism.

Methods

This cross-sectional analysis examined the association between school building conditions and school-level rates of chronic absenteeism for the 2016-2017 academic year across kindergarten to 12th grade (K-12) MA schools. In 2016, the Massachusetts School Building Authority (MSBA) commissioned an independent evaluation of the conditions of K-12 school buildings.

In 2016-2017, there were 1,859 public schools in MA, with 1,697 schools eligible for MSBA funding. Of the 1,419 schools assessed in the MSBA School Survey, our final study population included 1,379 (97%) public K-12 schools open during the 2016-2017 academic year. These schools occupied a total of 2,239 buildings (MSBA 2017). We excluded 40 schools from our analysis due to non-traditional building use and/or educational practices, including: vocational schools due to the large number of non-classroom buildings including barns, workshops, and annex spaces; schools designated as charter or alternative education due to their non-traditional teaching methodology and incomplete information about student demographics; and schools with 25 or fewer students because smaller schools may indicate the use of non-traditional pedagogical practices occurring in public schools.

School Building Condition

Our independent variable was a measure of building quality derived from the MSBA 2016 School Survey. This survey was conducted by independent assessors comprised of design and engineering professionals who evaluated K-12 schools (MSBA 2017). Assessors and district representatives examined all major spaces and systems at each facility and evaluated the quality of 14 building systems (Roof; Boilers; Heating, Ventilation and Air Conditioning [HVAC]; Exterior Walls; Exterior Windows; Interior Ceiling; Interior Floors; Interior Other; Structural

Soundness; Electrical Services and Distribution; Electrical Lighting; Fire and Life Safety; Fire Suppression; Plumbing) and 7 site-specific features (Parking Lot; Walkways and Drop Areas; Drainage; Lighting; Water Supply; Septic, Sewage, and Waste Water Disposal; Playgrounds). Other systems evaluated but not included in this analysis were elevators/lifts and specialties (e.g. lockers, toilet partitions). Each building system or site feature was assigned a categorical quality score indicating the severity of building maintenance or repair needs: General Maintenance Only (GMO), Minimal Repair Needed (Min), Moderate Repair Needed (Mod), Major Repair Needed (Maj), or Replacement Needed (Rep).

Sixteen building and site systems were selected because they have known associations with school occupant health: 1) Roof, 2) HVAC, 3) Boiler, 4) Electrical Lighting, 5) Interior Ceiling, 6) Interior Floor, 7) Interior Other (e.g. doors, hardware), 8) Exterior Walls, 9) Exterior Windows, 10) Structural Soundness, 11) Water Supply, 12) Plumbing, and 13) Site Parking Lot, 14) Walkways and Drop Areas, 15) Drainage and 16) Site Lighting.

Two building quality measures were evaluated. To test the association between the overall condition of a school building and chronic absenteeism, we created a summary building condition score for each school by dichotomizing the quality of each building or site feature (0: Did not need major repair includes categories GMO, Min, and Mod; 1: Did need a major repair includes categories Maj and Rep) and summed the number of systems per school in need of a major repair. This provided a measure for overall building repair need. To answer our second research question, are specific building systems associated with chronic absenteeism, we grouped the sixteen health-related systems into seven categories reflective of their functionality as well as groupings found in governmental reports (United States General Accounting Office 1995) including 1) Roof, 2) HVAC and Boiler, 3) Electrical Lighting, 4) Interiors (Ceiling;

Floor; Other), 5) Building Envelope (Exterior Walls; Exterior Windows; Structural Soundness), 6) Water (Water Supply; Plumbing), and 7) Site (Parking Lot; Walkways and Drop Areas; Drainage; Lighting). The building quality score was averaged when there was more than one system in a single category, specifically HVAC, Interiors, Building Envelope, Water, and Site.

To refine our independent variable, three building systems underwent further summarization because when present, the oldest and second oldest sections of the roof, windows, and boilers were evaluated at each school. To create a single measure for these building systems, we obtained a weighted average of the two sections. For roof and windows, the weighted average was normalized by the square footage of each roof section and percent of total window coverage, respectively. For boilers, we did not have a way to weight this variable so we assumed both boilers were equally important.

Other building information collected by the School Survey was used as contextual variables, including year the school was built, year of last renovation or addition, number of modular classrooms, total square footage, percentage of schools in which 75% or more classrooms have sufficient power outlets to support technology without extension cords, and percentage of schools that classify as Elementary, Middle, and/or High school.

Chronic Absenteeism

The MA Department of Elementary and Secondary Education (DESE) provided chronic absenteeism rates by school for the 2016-2017 academic year (MA DESE 2019). A student is considered chronically absent if they miss at least 10% of days enrolled for any reason. There were no missing values for the study population.

Covariates

The National Center for Educational Statistics provided most of the covariates used in our analysis via the ElSi Table Generator, which uses the Department of Education's annual, comprehensive data collection database for all public elementary and secondary schools known as the Common Core of Data and includes descriptive, student and teacher data (NCES 2019). Variables used include school Title I eligibility, pupil-teacher ratio, and the percentages of students who were English language learners (ELL), had disabilities, were economically disadvantaged, and were black (NCES 2019). Pediatric asthma prevalence by school was reported by the Massachusetts' Bureau of Environmental Health via the Massachusetts Environmental Public Health Tracking Tool. Pediatric asthma is annually reported by the school nurse for K-8 schools but is not collected for students in 9-12th grade. Asthma prevalence was aggregated at the school level (MDPH-BEH 2019). Information about teachers was provided by MA DESE, including total number of teachers per school, percent of teachers rated as highly qualified, and percent of teacher retention (MA DESE 2019).

Data Analysis

Descriptive statistics were reported statewide as well as stratified by schools with below or above six major repairs to compare demographic differences across buildings with different facility repair needs. For schools with below or above six major repairs, we assumed that the population distributions were identical but not normally distributed and used the non-parametric Mann-Whitney-Wilcoxon test for continuous variables.

Poisson regression models correcting for over-dispersion (i.e. quasi-Poisson models) were used to assess the association between chronic absenteeism and building quality across schools in MA, controlling for relevant sociodemographic covariates (percent of students with disabilities, percent of black students, percent of English Language Learners, Title 1 eligibility, pupil-teacher ratio). To assess the relationship between overall building disrepair and chronic absenteeism, six models were run: 1) All schools, 2) Only Title I eligible schools, 3) Only Title 1 ineligible schools, 4) Elementary schools, 5) Middle schools, and 6) High schools. To assess the relationship between specific building disrepair and chronic absenteeism, a dummy variable for system quality was used and seven separate models were run for each system: 1) Roof, 2) HVAC, 3) Lighting, 4) Interior, 5) Building Envelope, 6) Water, and 7) Site.

Numerical variables used in the models were centered at the mean for all schools. All analyses were performed using the open-source statistical package R version 3.5.1. Robust standard errors were calculated estimating a robust covariance matrix of parameters according to the White method using the R package ‘sandwich’, which accounts for the heteroscedasticity typically found in cross-sectional data (Zeileis 2019).

Results

Table 3-1 shows the demographic and teacher characteristics, and key building features of the 1,379 schools in our analysis. Our sample was predominately elementary schools (63%) and schools that had high proportions of white students (mean 61.7%) compared to other racial groups including black (mean 8.6%), Hispanic (mean 19.5%), and other racial backgrounds (mean 10.2%). On average, one in three students were classified as economically disadvantaged (32.5%) per school. Schools also reported students with chronic conditions such as pediatric asthma (mean 12.8%) and disabilities (mean 17.4%). Teacher characteristics per school included mean number of teachers per school (mean 37.7), percentage of highly qualified teachers (mean 96.2%), pupil-teacher ratio (mean 13.4), and teacher retention (mean 84.5%). In our study, the average age of a school building was 60 years (originally built in 1959), and the average time since last renovation or addition was 24 years (last renovated in 1992) with only two-thirds of schools with the adequate number of electrical outlets (65.6%). School building size by total square footage ranged dramatically from 5,400 to 918,102 square feet.

When we stratified by school buildings with ≥6 major repairs needed vs. <6 major repairs needed across all 21 building systems evaluated in the 2016 School Survey (Table 3-1), we found that buildings that needed more repairs had a higher percentage of students in need of academic or health support, including students for whom English was not their first language (+9.7%, p-value<0.001), English language learners (+8.5%, p-value<0.001), students with disabilities (+2.8%, p-value=0.06), economically disadvantaged (+16.8% p-value<0.001), and pediatric asthma prevalence (+4.1%, p-value=0.001) compared to schools with <6 major repairs. Additionally, in school buildings with ≥6 major repairs needed there was a higher percentage of black (+6.6%, p-value<0.001) and Hispanic (+8.9%, p-value<0.001) students compared to schools with <6 major repairs needed, while the percentage of white students decreased (-14.7%, p-value<0.001). Also, the percentage of highly qualified teachers and teacher retention was lower in school buildings with ≥6 major repairs needed (p-value=0.02). Notably, the average year the school was originally built was 14 years older for schools with ≥6 major repairs needed, and the average time since the last renovation was 8 years longer than the schools with <6 major repairs needed. In schools with <6 major repairs needed, 68% of classrooms had sufficient electrical outlets compared to schools with ≥6 major repairs needed where only 32% of the classrooms had sufficient outlets.

Table 3-1: School Characteristics Statewide and by Number of Major Repairs Needed

	Statewide n= 1379			**<6 Major Repairs** n = 1299			**≥6 Major Repairs** n = 82			**p-value**
	Median	Mean±SD	Range	Median	Mean±SD	Range	Median	Mean±SD	Range	
Students Characteristics										
First Language Not English (%)	10.8	19.3 ± 20.5	0.0 – 100	10.2	18.7 ± 20.3	0.0 – 100	27.3	28.4 ± 21.9	0.0 – 78.6	<0.001
English Language Learner (%)	4.3	10.5 ± 13.8	0.0 – 79.6	4.1	10.0 ± 13.5	0.0 – 79.6	15.8	18.5 ± 16.4	0.0 – 56.3	<0.001
Students with Disabilities (%)	16.0	17.4 ± 9.9	1.1 – 100	15.9	17.2 ± 9.6	1.1 – 100	17.3	20.0 ± 14.0	7.4 – 96.9	0.06
Students Economically Disadvantaged (%)	26.2	32.5 ± 22.9	1.1 – 93.9	25.2	31.5 ± 22.4	1.1 – 93.9	58.4	48.3 ± 25.4	2.7 – 87.5	<0.001
Pediatric Asthma Prevalence (%)	11.9	12.8 ± 6.8	0.0 – 89.8	11.8	12.5 ± 6.5	0.0 – 89.8	14.8	16.6 ± 9.3	2.8 – 60.0	0.001
Chronic Absenteeism (%)	9.6	13.3 ± 12.5	0 – 94.3	9.4	12.8 ± 11.8	0.0 – 94.3	15.9	21.2 ± 18.9	2.2 – 82.9	<0.001
Male (%)	51.4	51.8 ± 4.5	28.7 – 90.6	51.4	51.7 ± 4.2	34.3 – 89.6	52.1	53.4 ± 7.7	28.7 – 90.6	.01
Student Race by School										
Black (%)	3.3	8.6 ± 13.3	0.0 – 77.1	3.1	8.3 ± 12.9	0.0 – 76.5	7.5	14.9 ± 18.1	0.0 – 77.1	<0.001
White (%)	73.1	61.7 ± 30.0	0.5 – 100	74.3	62.5 ± 29.7	0.9 – 100	46.7	47.8 ± 30.1	0.5 – 94.8	<0.001
Hispanic (%)	8.1	19.5 ± 23.2	0 – 97.4	7.8	19.0 ± 23.1	0.0 – 97.4	24.5	27.9 ± 23.2	0.4 – 92.8	<0.001
Other Racial Background (%)	7.1	10.2 ± 9.5	0 – 76.2	7.0	10.2 ± 9.6	0.0 – 76.2	8.1	9.4 ± 6.3	1.0 – 41.3	0.28
Teacher Characteristics										
Total Teachers per School (n)	32.4	37.7 ± 23.7	1 – 253	32.6	37.7 ± 223	5.0 – 208	29.1	37.1 ± 33.8	5.7 – 253	0.12
Highly Qualified Teachers (%)	100	96.2 ± 8.8	0.0 – 100	100	96.3 ± 8.7	0.0 – 100	100	94.0 ± 10.1	47.4 – 100	0.02
Teacher Retention (%)	86.4	84.5 ± 10.1	19.5 - 100	86.6	84.7 ± 9.9	19.5 - 100	83.3	81.0 ± 13.1	32.0 – 100	0.02
Pupil Teacher Ratio	13.4	13.4 ± 2.6	2.6 – 31.2	13.4	13.4 ± 2.6	2.7 – 31.2	13.5	13.5 ± 2.9	2.6 – 20.2	0.48
Building Characteristics										
Year Built	1961	1959 ± 27	1841 - 2016	1961	1960 ± 27	1841 – 2016	1955	1946 ± 24	1894 – 1995	<0.001
Year of Last Renovation/Addition	2000	1995 ± 18	1907 - 2017	2000	1995 ± 17	1907 – 2017	1994	1987 ± 26	1919 – 2016	0.02
Modular Classrooms Present (%)		10%	0.0 – 12.0		9.8%	0.0 – 10.0		16%	0.0 – 12.0	0.06
Total Square Footage	73165.5	95063 ± 74683	5400 - 918102	73685	95104 ± 73562	5400 – 918102	66478	94413 ± 91232	17773 – 563000	0.21
Sufficient Outlets (%)		65.6%			68%			32%		
Elementary		63%			63%			60%		
Middle		26%			26%			23%		
High		22%			22%			23%		

Note: Stratification of major repairs can include any of the 21 building systems evaluated by MSBA, p-value is the difference between the categories of <6 Major Repairs and ≥6 Major Repairs

Relationship Between School Type and Chronic Absenteeism

The relationship between total number of building repairs needed (max = 12) and chronic absenteeism was modeled using quasi-Poisson generalized linear models that controlled for important demographic and socioeconomic variables (Table 3-2). When examining all schools in MA, every additional health-related building system in need of a major repair or replacement was associated with a 3.1% increase in chronic absenteeism (p-value = 0.002), controlling for relevant sociodemographic covariates. Upon stratifying the schools by Title I eligibility, we found that every additional health-related building system in need of a major repair or replacement in a Title 1-eligible school was associated with a 4% increase in chronic absenteeism (p-value <0.001), controlling for relevant sociodemographic variables. However, we did not observe the same effect size (1.8%) and significance in Title 1-ineligible schools (p-value = 0.29). Similarly, when we stratified by school type (i.e. elementary, middle, high school), we found that an increase in the number of major repairs needed in health-related building systems in elementary (2.6%, p = 0.03) and high schools (3.4%, p = 0.05) were positively associated with chronic absenteeism, while there was no association in middle schools (0.9%, p = 0.67). Across all models, the percent of students with disabilities, percent of black students, and the percent of English Language Learners at each school were also significantly associated with chronic absenteeism. Pupil-teacher ratio was negatively associated with chronic absenteeism.

Table 3-2: Exponentiated Quasi-Poisson Regression Model Results: % Change of Chronic Absenteeism (Standard Error)

	Model 1	*Model 2*	*Model 3*	*Model 4*	*Model 5*	*Model 6*
	All Schools	**Title 1-Eligible**	**Title 1 Ineligible**	**Elementary**	**Middle**	**High**
Intercept	10.7**	11.3***	10.4***	8.5 ***	11.2 ***	15.3 ***
Total # of Major Repairs	3.1 (1.2) **	4.0 (1.5) ***	1.8 (2.1)	2.6 (1.6) *	0.9 (1.7)	3.4 (1.7) *
% of English Language Learners	1.1 (0.2) ***	1.1 (0.2) ***	0.3 (0.6)	1.2 (0.2) ***	0.8 (0.2) **	1.9 (0.4) ***
Title I-Eligible	8.0 (4.6)			23.2 (5.7) ***	14.1 (9.7)	0.4 (9.0)
% of Students with Disabilities	1.6 (0.2) ***	1.4 (0.2) ***	2.2 (0.4) ***	1.8 (0.2) ***	1.5 (0.4) ***	1.3 (0.3) ***
% of Black Students	1.4 (0.1) ***	1.5 (0.2) ***	1.4 (0.3) ***	1.4 (0.2) ***	1.3 (0.4) ***	1.1 (0.2) ***
Pupil Teacher Ratio	-3.8 (1.0) ***	-4.0 (1.4) ***	-2.3 (1.8)	-1.9 (1.4) *	-0.5 (1.6)	-4.7 (1.6) ***

Note: Significance denoted p-value <0.05 *, p-value <0.01 **, p-value <0.001 ***

Regarding the relationship between total health-related major repairs needed and chronic absenteeism rate, we observe variability of chronic absenteeism at all amounts of major repairs needed (Figure 3-1). This relationship holds when we look across the 21 building systems (Figure 6-1) found in the Supplemental Materials. We also see that the median chronic absenteeism rate among Title 1-eligible schools exceeds the state median when two or more major repairs is needed, unlike Title I-ineligible schools where the median chronic absenteeism rate never exceeds the state median.

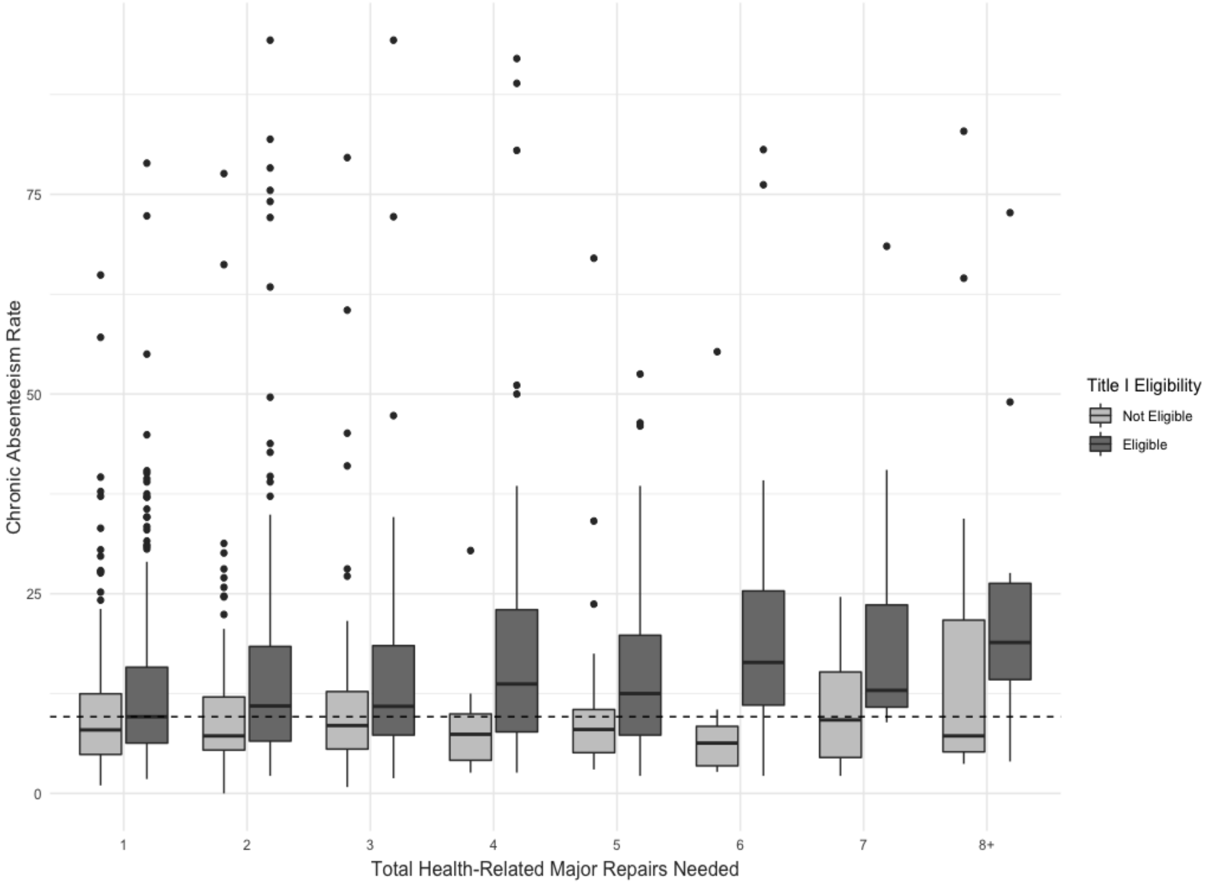

Figure 3-1: Chronic absenteeism rate in 2016-2017 by total major repairs needed for only *health-related* systems per school, stratified by Title I eligibility. Dashed line is the median chronic absenteeism rate for the State in 2016-2017

Relationship Among Building System Disrepair and Chronic Absenteeism

The results of modeling the impact of each of the seven building systems on chronic absenteeism in separate models indicate how chronic absenteeism differs between schools where no repairs of the system are needed (i.e. general maintenance only) and schools in each other quality category (minimal repairs, moderate repairs, or major repairs and replacement) (Table 3-3, Figure 3-2). Schools with major repairs or replacement needed for their *roof*, *building envelope*, or *site* features had significantly higher chronic absenteeism than schools that needed general maintenance only. For example, schools that needed major repair or replacement of their roofs had chronic absenteeism rates 19.4% higher, on average, than schools whose roofs only needed general maintenance, controlling for relevant sociodemographic covariates. There was no significant difference in chronic absenteeism between schools that needed minimal or moderate roof repairs and schools that had roofs that needed general maintenance only. Across all models, the percent of students with disabilities, percent of black students, and the percent of English Language Learners were positively associated with chronic absenteeism ($p<0.05$). Pupil-Teacher Ratio was negatively associated with chronic absenteeism ($p<0.05$) at each school. Title 1 eligibility was not significant for Table 3: Models 1-6, but previous analyses suggest it may be a significant covariate.

Table 3-3: Exponentiated Quasi-Poisson Regression Model Results: % Change of Chronic Absenteeism by Quality of Specific Building Systems (Standard Error)

	Model 1 **Roof**	*Model 2* **HVAC**	*Model 3* **Lighting**	*Model 4* **Interior**	*Model 5* **Building Envelope**	*Model 6* **Water**	*Model 7* **Site**
Intercept	11.0 ***	11.5 ***	11.4***	13.5***	10.0***	11.8***	10.6***
Reference: General Maintenance Only							
Minimal	3.9 (5.2)	-0.9 (7.1)	-2.2 (5.5)	-17.6 (8.4) *	13.2 (6.6)	-3.3 (8.2)	4.2 (8.8)
Moderate	0.4 (5.8)	7.0 (8.9)	8.4 (7.6)	-13.0 (9.0)	19.1 (8.2) *	2.7 (11.4)	17.0 (9.9)
Major & Replacement	19.4 (8.9) *	9.3 (11.0)	16.9 (9.2)	-18.4 (11.2) *	59.6 (18.0) ***	3.3 (13.1)	53.5 (12.3) ***
% English Language Learners	1.1 (0.2) ***	1.1 (0.1) ***	1.1 (0.2) ***	1.1 (0.2) ***	1.1 (0.2) ***	1.1 (0.2) ***	1.1 (0.2) ***
Title I-Eligible	6.8 (4.6)	6.7 (4.5)	7.7 (4.5)	8.3 (4.6)	6.4 (4.5)	7.6 (4.6)	8.4 (4.5) *
% Students with Disabilities	1.6 (0.2) ***	1.6 (0.2) ***	1.6 (0.2) ***	1.6 (0.2) ***	1.5 (0.2) ***	1.6 (0.2) ***	1.5 (0.2) ***
% of Black Students	1.5 (0.1) ***	1.5 (0.1) ***	1.4 (0.1) ***	1.5 (0.1) ***	1.5 (0.1) ***	1.4 (0.1) ***	1.5 (0.1) ***
Pupil Teacher Ratio	-3.6 (1.0) ***	-3.7 (1.0) ***	-3.7 (1.0) ***	-3.8 (1.0) ***	-3.6 (1.0) ***	-3.8 (1.0) ***	-3.8 (1.1) ***

Note: Significance denoted p-value <0.05 *, p-value <0.01 **, p-value <0.001 ***. System quality is a continuous measure from General Maintenance Only to Major Repair and Replacement

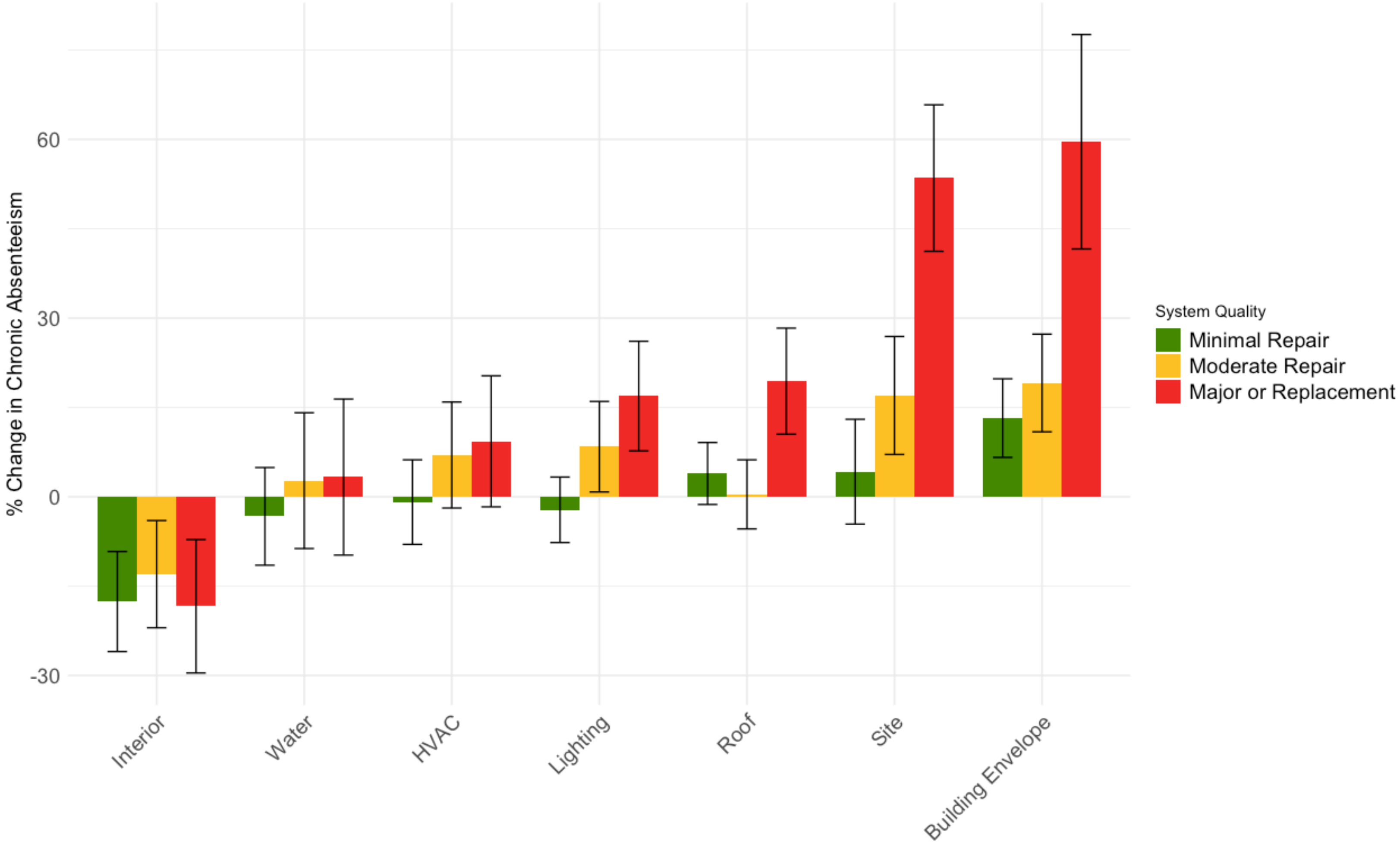

Figure 3-2: Percent Change in Chronic Absenteeism by Building System including standard error bars. Reference ‘General Maintenance Only’.

For HVAC, lighting and water-related systems, there were no significant differences between schools that needed minimal, moderate or major repairs and schools that needed general maintenance only. Although we did not test for trend, decreasing HVAC and lighting quality appears to be associated with increased chronic absenteeism. For interior, schools that needed minor repairs (-17.6% change in chronic absenteeism, p-value<0.05) and schools that needed major repairs or replacement (-18.4% change in chronic absenteeism, p-value<0.05) had significantly lower chronic absenteeism than schools that needed only general maintenance; there was no significant difference between schools that needed moderate repairs and schools that needed general maintenance only. For building envelope, schools that needed moderate repairs (19.1% change in chronic absenteeism, p-value<0.05) and schools that needed major repairs or replacement (59.6% change in chronic absenteeism, p-value<0.001) had significantly higher chronic absenteeism compared to schools that needed only general maintenance; there was no significant difference between schools that needed minimal repairs and schools that needed general maintenance only. For site, schools that needed major repairs or replacement had significantly higher chronic absenteeism (53.5% change in chronic absenteeism, p-value<0.001) compared to schools that needed only general maintenance; there was no significant difference between schools that needed minor repairs or moderate repairs compared to schools that needed general maintenance only.

Discussion

Our findings reveal that overall building disrepair is associated with an increase in chronic absenteeism across MA K-12 public schools, after adjusting for student demographic and school covariates. Schools in need of six or more major repairs had a higher percentage of racial-minority students, and of students in need of academic and health support, including students with disabilities, pediatric asthma diagnosis, and from economically disadvantaged backgrounds compared to schools in need of fewer than six major repairs. This finding suggests that buildings with the greatest need for major repair or replacement are occupied by students with the greatest need for academic and social support. Stratifying schools by Title I-eligibility, we found that each additional health-related building system in need of a major repair or replacement in a Title 1-eligible school was associated with a 4% increase in chronic absenteeism, suggesting that lower-income populations experience disproportionately worse school buildings. When we stratified by school type (i.e. elementary, middle, high school), we found an increase in major repairs in health-related building systems in elementary and high schools were positively associated with chronic absenteeism while there was no significant association between number of major repairs needed and chronic absenteeism in middle schools.

There are two types of major environmental problems associated with most schools: the physical building and the surrounding conditions and siting (Cohen 2010). First, there is substantial evidence documenting how school environmental quality influences student and teacher performance. Many conditions that may be attributed to poor quality school roofs, building envelopes, and siting, including poor indoor air quality (Shendell, Prill et al. 2004); moisture in classrooms (Mendell and Heath 2005); mold and mildew growth (Simons, Lin et al. 2009); structural damage; pest and vermin intrusion; and lack of temperature control, have been shown to acutely and chronically impact school building occupants. Environmental inequities have been documented in school building siting, but few focus on specific infrastructural features of the site (e.g. entrances, lighting, drainage) that may influence security, safety, and morale.

Our findings are suggestive of a positive association between chronic absenteeism and the levels of disrepair of *HVAC*, *lighting*, or *water* systems although they did not reach statistical significance. For these systems, the measures reported by the School Survey may be too broad to characterize students' exposures because HVAC, lighting, and boilers may work differently based on their coverage, age, type, and seasonal use differences. Disrepair of these systems may lead to sub-clinical health effects that do not lead to chronic absenteeism. For example, during the winter, inadequate heating can result in conditions that are too hot or cold, which may be modified by behavioral changes and personal adaptation (e.g. opening a window, adding clothing) which are not captured in our analysis. Similarly, schools lacking air conditioning during hot days may result in acute health symptoms that are not associated with being chronically absent because it only represents a few weeks per year in Massachusetts. Poor lighting conditions, such as flicker, inadequate daylight, and poor and/or uneven illuminance, may not be associated with health conditions that would lead to repeated student absenteeism, but both visual and non-visual (Bellia, Pedace et al. 2013) effects may adversely disrupt academic growth and performance (Eitland 2017). Similarly, plumbing and water supply systems in need of major repair may be influencing health and long-term academic performance through high levels of heavy metals found in water (e.g. lead, copper, arsenic) or food safety concerns due to water system contamination, but may not be associated with acute health events (e.g. asthma, communicable disease transmission) that would cause a student to be chronically absent.

The findings from our *interior* model were unexpected because of their inverse relationship to chronic absenteeism. However, this could be due to the population of schools in the reference group for this model, who appeared to have a higher percentage of disabled students, lower teacher retention, higher percentage of white students than the state average (though none of these differences were significant), and were predominantly located in suburban districts. These schools experience higher levels of chronic absenteeism despite high quality interiors, which could be well-maintained to serve a vulnerable population of students.

Limitations and Strengths

The primary strength of this analysis is that it leverages publicly available data collected by multiple state departments including education, environmental health and the school building authority to create a comprehensive dataset of school quality. The benefits of this approach are 1) a detailed classification of building systems, 2) it creates a school dataset where the exposure and outcome were collected independently at the building-level, and 3) all data collected followed a standardized procedure, which minimized measurement error due to researcher bias and previous studies that relied on self-report measures. This study is novel because it is the first to merge these datasets, which are only available in the few states that systematically evaluate school buildings.

This study has some limitations. First, chronic absenteeism is a complex measure, which has been associated with building condition, morale, community and family engagement, economic instability, familial capacity, and health-related causes (e.g. chronic conditions, siblings provide childcare for younger children). Therefore, we may have remaining confounding not captured by sociodemographic variables, such as home exposures. Second, due to the cross-sectional nature of this study we are unable to determine causation or the direction of school-level trends between chronic absenteeism and building quality. However, we think reverse causation is unlikely and hypothesize that building disrepair acts as a vicious cycle with poor building quality increasing chronic absenteeism rates, resulting in a reduction of school funding due to the reduced number of students counted so there are less resources for building repair. Third, we do not have student-level data so we are unable to examine within-school variability, which may reveal the impact of building quality on the most sensitive students, including students with pre-existing or chronic conditions, learning disabilities or external social challenges. Fourth, the use of the School Survey is a proxy for exposure to poor environmental quality. It does not quantify concentrations of legacy pollutants like lead in drinking water and paint, asbestos, radon, and PCBs, that are commonly documented in school buildings (Herrick, McClean et al. 2004, U. S. Congress Senate 2015, GAO 2018, Gordon, Terry et al. 2018), which are likely present in many MA schools which, on average, were built before 1978. Lastly, in 2016, building assessors did not evaluate buildings that had received funding for new construction since 2007, buildings in the capital pipeline, or buildings that received a facility condition index rating of less than 10% in the last school building assessment in 2010, suggesting the building was in good quality (schools not evaluated = 440). This may have resulted in selection bias because the exclusion of these schools may be associated with both the exposure and outcome. Our generalizability is limited to schools in the Northeast U.S., which have similar building typologies, geographic, facility, and climatic conditions.

Significance

The national budget for school construction and repair of our pre-existing building stock declined after the 2008 recession and has not rebounded to pre-recession spending (American Society of Civil Engineering 2017). Additionally, national spending on school building and alterations, known as capital outlay expenditures, declined by 17% per student from 2000-2001 ($1,383) to 2010-2011 ($1,155), and then remained constant through 2015-2016 (NCES 2019). Yet, more than ten years after the recession, building construction moratoriums remain in place in some states (e.g. PA, AK, VT, NH), preventing repairs and renovations for existing buildings as well as new construction for buildings that need imminent replacement. Other states (e.g. RI) only recently ended their moratorium and have not yet addressed deterioration of school facilities that occurred during the moratorium. Our findings suggest that school building disrepair may impact ESSA indicators. Addressing the environmental health concerns in school buildings may supplement current ESSA-inspired efforts to reduce chronic absenteeism and provide a more holistic, preventative strategy. The benefits of reducing chronic absenteeism are not just for the individual attending school. Studies show that not only do chronically-absent students exhibit lower math and reading performances, other students in the same educational setting also suffer academically from the individuals missing excessive school days (Gottfried 2019).

Environmental inequities experienced by children have been well-documented in studies related to school siting and homes. Our findings also document evidence of disparities in indoor school environments. The positive association between total number of repairs in Title I-eligible schools and chronic absenteeism may be exacerbated by cumulative environmental exposures experienced by minority and low-income students. These students may be exposed to overlapping pollution plumes associated with poor school siting (Mohai, Kweon et al. 2011) and residential exposures (Morello-Frosch, Pastor et al. 2002, Adamkiewicz, Zota et al. 2011). Previous research indicates that low property values near industrial sites, major roadways and other undesirable conditions may cause improper school siting, which disproportionately impacts students of color and low socioeconomic status (Green, Smorodinsky et al. 2002, Chakraborty and Zandbergen 2007, Mohai, Kweon et al. 2011, Sampson 2012, Francis, DePriest et al. 2018). Across the United States (Rachel Morello-Frosch, Jr. et al. 2002, Lucier, Rosofsky et al. 2011, Rosofsky, Lucier et al. 2014), racial/ethnic minorities are disproportionately exposed to air pollution including neurotoxicants (Grineski and Collins 2018), polycyclic aromatic hydrocarbons (Sansom, Kirsch et al. 2018), lead poisoning (Landrigan, Rauh et al. 2010), polybrominated diphenyl ethers (Zota, Rudel et al. 2008), endocrine disruptors (Clark-Reyna, Grineski et al. 2016), and vapor intrusion of volatile organic compounds (Johnston and Macdonald Gibson 2015). Minority students have also been shown to have a higher prevalence of chronic disease including asthma and obesity, compared to non-Hispanic white students (Landrigan, Rauh et al. 2010) and poor children's health and high environmental exposures have been associated with lower grade point averages (Clark-Reyna, Grineski et al. 2016). Also, early childcare exposures may cause deficits and sensitivities prior to entering public schools (Afzal, Witherspoon et al. 2016). Studies have also shown that students in earlier grades are exposed to higher levels of neurotoxicants compared to older students in middle and high school (Grineski and Collins 2018).

Our findings also support current MA efforts, specifically the Accelerated Repair Program (ARP), which is a program that focuses on repairs of roofs, windows, doors and/or boilers to preserve existing school buildings with energy- and cost-saving upgrades (MSBA 2019). However, in the 2016 School Survey Report, MSBA acknowledges that it is unable to meet the needs of all schools in the state due to funding constraints (MSBA 2017). Our findings suggest it would be useful to expand the scope of ARP to include site features (e.g. site lighting, drainage, entrance) as well as allocate additional funding to support more timely school repairs before they become more severe. Additionally, to ensure Massachusetts remains a high performing state academically (U.S. News & World Report 2019), school building quality should not be determined by the mere absence of major repairs but access to high quality, educationally appropriate and adequate spaces for all MA K-12 students. When schools do not have sufficient outlets, especially in the buildings with the greatest number of major repairs, it becomes increasingly difficult to meet state standards that rely on computerized standardized tests and technology in the classroom. Older buildings in need of repair may not only be associated with increases in chronic absenteeism, but a declining ability to deliver 21st century learning curricula.

Future Research Steps

Our findings are illustrative of a common problem of school building disrepair across the United States and prompts new research questions and directions. First, to ensure the most appropriate and effective interventions are being deployed in a finite funding system, there needs to be an evaluation of school building repairs, maintenance, and environmental health policies that attempt to remedy this prevalent problem. Second, to further understand the mechanisms for the association between chronic absenteeism and poor building quality, other pediatric morbidities need to be evaluated including chronic diseases (e.g. asthma incidence, students with neurodevelopmental conditions, obesity) (Landrigan, Rauh et al. 2010). For example, playground quality may be associated with obesity and physical activity due to unsafe play conditions. Third, information about terminal student outcomes including tenth grade standardized test scores and drop-out and graduation rates may provide insights into the economic and academic impact of poor school design. Lastly, this paper is focused on student absenteeism, but further research is needed to understand how multi-year exposures to these building conditions may influence the occupational health and safety of teachers, because teachers have a higher prevalence of asthma compared to other non-industrial occupational groups (Angelon-Gaetz, Richardson et al. 2016). Studies have also shown an association between poor building conditions and teachers' respiratory health (Claudio, Rivera et al. 2016).

Conclusions

Our findings suggest that poor school building quality is associated with elevated chronic absenteeism. Students attending lower socioeconomic status schools appear to be at greater risk of increased chronic absenteeism when greater repairs are needed, unlike higher socioeconomic status schools that do not have a significant association between building disrepair and chronic absenteeism. Disrepair of specific building features may contribute more to chronic absenteeism and therefore targeted repairs and expansion of pre-existing school repair programs may provide a cost-effective and holistic approach to reducing chronic absenteeism in Massachusetts.

CHAPTER 4: Comparison of Academic Performance Between Conventional and Green School Building Designs

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Abstract

To evaluate the factors that influence green school investment and performance in a multi-year study of Massachusetts schools (n=941), we characterized schools at baseline in 2011-2012 and fit a survey-weighted generalized linear model to evaluate school-level associations between green building certification (i.e. Leadership in Energy and Environmental Design and Collaborative for High Performance Schools) and standardized test performance in 2015-2016. In never green buildings, average English MCAS performance was positively associated with baseline building conditions. This effect was not observed for green buildings, predominantly for two reasons: 1) At baseline, future green-certified schools were already higher-performing (3 points higher in English and Mathematics exams than never green schools), and 2) the study population of green-certified buildings did not acquire all indoor environmental quality credits available. Schools that pursued green building certifications were more likely to already have higher test scores, and pursuit of green building credits prioritized energy over health. Allocation of green-certified schools should account for prior academic performance, health, and building quality. Greater prioritization of indoor environmental quality credits during certification may improve student health and performance.

Introduction

Many of the 51 million students in the United States attend public elementary and secondary schools that have building conditions that compromise occupant health and well-being (Mohai, Kweon et al. 2011, Earl, Burns et al. 2016). In these schools, deteriorating indoor air quality, acoustics, lighting, thermal comfort, water quality, moisture, and mold adversely impact student health and learning (Simons, Lin et al. 2009, Simons, Hwang et al. 2010, Muscatiello, McCarthy et al. 2015). To address cases of poor school building conditions, the state of

Massachusetts has developed an application-based process for accessing state-funded resources for renovation or new construction of school buildings (MSBA 2019). Further, the state offers financial incentives for building projects that promote energy efficiency through a green school certification program known as the High Efficiency Green School Program (MSBA 2019). The two leading certifications supported by the program are 1) Leadership in Energy and Environmental Design for Schools (LEED) (USGBC 2007), and 2) The Northeast Collaborative for High Performance Schools (CHPS 2019).

Despite multi-billion dollar investment in green school buildings nationally, there is limited evidence that green-certified school buildings actually improve student performance and health (Issa, Attalla et al. 2013, Thombs and Prindle 2018). It is hypothesized that implementing the design and operating features in green school certifications could reduce the impact of poor indoor environmental quality (IEQ) that many traditional, non-certified buildings endure. IEQ design features include low-emitting materials, daylighting, acoustical performance, pollutant control, improved filtration, ventilation and thermal controls, which have been associated with positive short and long-term impacts on the physiological and psychological health as well as long-term academic performance of K-12 students (Uline and Tschannen-Moran 2008, Bako-Biro, Clements-Croome et al. 2012). However, available green school studies have not shown significant changes in concentrations of indoor pollutant, such as volatile organic compounds (Lexuan, Feng-Chiao et al. 2017), or significant improvements in test performance (Thombs 2015, Thombs and Prindle 2018). For example, in a cross-sectional analysis, Thombs (2015) found that acquiring LEED certification credits in Ohio schools was not strongly associated with improvements in student performance; rather, socioeconomic status, attendance, and school location were greater predictors of student success (Thombs 2015). Later, Thombs used a difference-in-differences estimator and again found no association between Ohio LEED schools and overall student performance between 2006-2016 (Thombs and Prindle 2018). In a cross-sectional study of Toronto schools, teachers working in LEED schools self-reported higher satisfaction with the building quality as well as less student absenteeism and better test performance compared to reports from conventional or energy retrofitted schools (Issa, Rankin et al. 2011). Collectively, these studies suggest the need for a more mechanistic, systems-thinking approach (Leischow, Best et al. 2008) to studying the effect of green certification on student health and performance, which recognizes the potential influence of different student populations, specific credits achieved by green schools, and the criteria by which schools are eligible for capital projects.

To the best of our knowledge our study is the first to address these complexities. We performed a multi-year analysis of 4th grade Mathematics and English standardized test performance between 2010 and 2016 in Massachusetts schools. We focus on elementary school-aged students due to their physiological and developmental sensitivity and susceptibility to their environment (Evans 2006, NRC 2007, Eitland 2017). Furthermore, in Massachusetts, performance on the 4th grade exam determines the students' future academic support and resource allocation, which can influence academic potential and success (MA DESE 2018). Also, students would not have been exposed to previous school environments that influence their current performance unlike middle or high school-aged kids. This paper diversifies the geographic coverage of current green schools' research, expands our understanding of the mechanisms through which green schools may influence student performance and health, and provides a novel discussion of the importance of the context in which certification occurs.

Methods

This study integrated publicly available panel data from various sources for academic years 2010-2011 and 2015-2016 in Massachusetts. We included 922 public elementary schools with 4th grades in 2010-2011and 941 elementary schools in 2015-2016. School building information, including geographic location and green certification details, was provided by the Massachusetts School Building Authority (MSBA), a quasi-independent government agency that approves and allocates resources for building repairs, renovations and/or new construction. MSBA requires that schools pursuing green certification must follow either LEED or Northeast-CHPS standards. We identified 30 green schools in 2015-2016 that had pursued the LEED for Schools (n = 13), CHPS 2006 (n = 10), and CHPS 2009 (n = 7) certifications. The discrepancy in number of credits between CHPS-2006 and CHPS-2009 exists because indoor air strategies that corresponded to multiple credits in CHPS-2006 were collapsed into fewer credits in the updated certification. Schools were excluded from this analysis if they received green certification prior to 2010-2011, did not have 4th grade students complete Massachusetts Comprehensive Assessment System (MCAS) exams in both 2010-2011 and 2015-2016, or if they were charter or private schools because these characteristics are associated with different project funding, pedagogical approaches, and attendance policies, respectively. The dates when schools received final green certifications were not considered in this analysis because the final certification process is completed after students have occupied the building. Instead, the first year of occupancy following any reconstruction required to achieve green certification was confirmed by personal communication with the architecture firms that rebuilt the schools.

Due to the small sample, CHPS- and LEED-certified schools were grouped together in this analysis. To account for the temporal differences in school environmental exposure, we created two distinct categories: 1) Never Green Schools: schools that were not green-certified in 2010-2011 and were not replaced by green-certified schools by 2015-2016, and 2) Green Schools: schools that were not green in 2010-2011 and were replaced by green-certified schools by 2015-2016.

Dependent Variables

Our primary outcome of interest was mean school-wide 4th grade performance on the MCAS exam for the Mathematics and English subject tests. De-identified 4th grade student-level MCAS test score data were accessed through the Massachusetts Department of Elementary and Secondary Education (DESE). The DESE information included student-specific enrollment status for each academic year, test participation, previous MCAS performance, and raw and scaled scores (MA DESE 2019). Test takers were restricted to students who were enrolled in the same school since the beginning of the school year and had both a Mathematics and English scaled score. For our analyses, we summarized MCAS scaled scores, ranging between 200-280, which were standardized to be comparable across the state and across years. A scaled score below 240 suggests students' performance needs improvement and is below the state average.

Independent Variables

Contextual variables were selected based on literature about student performance and indoor environmental quality. Annual pediatric asthma prevalence was provided by the Massachusetts' Bureau of Environmental Health via the Massachusetts Environmental Public Health Tracking Tool from 2009-2017. Pediatric asthma was monitored at the school-level and annually reported by the school nurse for schools that serve K-8 students. Asthma prevalence was not available for individual grades within the school (MDPH-BEH 2019).

Student population characteristics were accessed for each school using the National Center for Education Statistics' ElSi Table Generator Tool, including percentage of racially white students, percentage of male students, and eligibility for a school-wide Title I program (an indicator for low socioeconomic status of student population) (NCES 2019). The ElSi tool uses the Common Core of Data, which is the Department of Education's annual, comprehensive data collection database for all public elementary and secondary schools and includes descriptive, student and teacher, and fiscal data (NCES 2019). The schoolwide Title I program status was not recorded for 298 schools in 2011 and 289 schools in 2016. Schools without a Title I record were assigned as non-eligible because their average academic performance was higher and asthma prevalence was lower than the schools that were designated as not having a school-wide Title I program. Additional school-level information was downloaded from DESE's publicly available Statewide Reports including, pupil/teacher ratio, number of 4th grade students, district spending per pupil, and annual chronic absenteeism rates (MA DESE 2019). For all public elementary and secondary schools that reported absenteeism rates, we obtained the percent of students classified as chronically absent (less than 1% of data was missing).

Physical conditions of school buildings were provided by the 2010 School Survey commissioned by MSBA (MSBA 2019). The School Survey is a third party assessment of building conditions conducted every six years by architectural and engineering experts. They visit Massachusetts public elementary and secondary schools and report their unbiased findings to MSBA. Features in the assessment include: age of building; categorical quality measures of specific building systems (boilers, HVAC, lighting, plumbing, roof, structure, playgrounds, and ceilings), and the school facility condition index (FCI), a building-level metric that is the ratio of repair to replacement cost. An FCI between 10 and 30 percent suggests poor building conditions, and anything exceeding 30 percent is in critical condition (Person-Harm 2014). Systems were evaluated on the following scale: General Maintenance Only (GMO), Minimal Repair Needed (Min), Moderate Repair Needed (Mod), Major Repair Needed (Maj), Replacement Needed (Rep), or Not Recorded in 2010 (N/A). If projects were in the construction pipeline in 2010, they may not have been evaluated in this state-wide assessment; 33 of the 922 schools were not evaluated in 2010, 13 of them being green school recipients. Findings of the MSBA assessment inform the need and urgency of building repairs and contribute to a district's eligibility for school funding. For schools that were not evaluated in the 2010 School Survey, we recoded them as 'Not Recorded' because we had demographic and performance variables for these schools.

Due to new school construction, renovation, consolidation, and/or demolition projects within school districts, state identification numbers for schools may change. To improve our ability to longitudinally track student populations, we expanded the geospatial school database, *Massachusetts' School Metrics and Research Tool* (MA SMART), which contains academic, social, environmental, and demographic information for all public schools in Massachusetts. We created a new numerical identifier (MASMART.ID) that longitudinally grouped schools associated with a repair, renovation, or new construction (MacNaughton, Eitland et al. 2017). For example, if two schools consolidated and students entered a single new green school by 2015-2016, the three schools would share the same MASMART.ID linking the student populations pre- and post-certification. The assignment of this identifier was informed by available documents from school district websites, architectural documents, local news, and school construction proposals. Each identifier includes information about the school openings, closures, and demolition to explain the rationale for school groupings. When consolidation of multiple schools occurred, a weighted average was generated for relevant variables for 2010-2011 (using the number of 4th graders as the weight).

Statistical Analysis

To test differences across the school populations and student average outcomes between never green and future green schools in 2010-2011 and between not green and green schools in 2015-2016, we assumed that the population distributions were identical but not normally distributed (Table 4-1). Therefore, the following non-parametric tests were selected: Mann-Whitney-Wilcoxon test for continuous variables, and Kruskal-Wallis test for categorical variables (i.e., Locale, Title I Eligible). The dichotomous variable generated from the MSBA 2010 School Survey, presence of a major repair, was compared between future green and never green schools using a 2-sample test for equality of proportions with continuity correction. Using ArcGIS 10.6.1 (ESRI; Redlands, CA), we mapped the location of schools to visualize the statewide distribution of our green school sample.

To estimate the effect of green certification on 2016 MCAS performance for Mathematics and English exams, we fit a survey-weighted generalized linear model (GLM) using the 'survey' package in R. We used coarsened exact matching (CEM) (Blackwell, Stefano Iacus et al. 2010) to balance the distribution of covariates between comparison groups by matching future green to never green schools by 2011 baseline sociodemographic and building characteristics. This matching method has been shown to be effective in other public health applications (Obermeyer, Makar et al. 2014, Su, Zhou et al. 2018). We used automated coarsening for the percentage of English Language Learners. We used coarsening by quartiles for the percentage of low-income students (cut-points: 10.9%, 27.9%, 62.8%) and the year the original building was constructed (cut-points: 1949, 1960, 1974). Never green schools were discarded (n=279) if they were not included in a matched stratum; all future green schools were matched. After using CEM, our L_1 statistic, a measure of multivariate imbalance between comparison groups, decreased from 1 to 0.506, suggesting that the matching achieved improved balance between the distribution of future green and never green schools (Iacus, King et al. 2012). The final adjusted model for our matched population, which includes CEM weights, was:

$$\begin{gathered}\text{2016 MCAS Scaled Score} = \beta_0 + \beta_1\ \text{Green Status 2016} + \beta_2\ \text{2011 Mean MCAS Performance} \\ + \beta_3\text{\% White} + \beta_4\ \Delta\ \text{\% White} + \beta_5\ \text{Chronic Absenteeism Rate} + \beta_6\ \Delta\ \text{Chronic Absenteeism} \\ \text{Rate} + \beta_7\ \text{Title I Eligible}\end{gathered}$$

where β_0 is the fixed intercept, β_1 is the effect of green schools compared to not green schools in the 2015-2016 academic year; β_2 is the effect for the average performance of schools on the 2011 MCAS subject test; β_3 is the effect for the percentage of white students centered at the mean; β_4 is the effect for the change in the percentage of white students between 2011 and 2016; β_5 is the effect for the 2016 chronic absenteeism rate centered at the mean; β_6 is the effect for the change in chronic absenteeism rate between 2011 and 2016; and β_7 is the effect for the dummy variable for Title I Eligible schools compared to not eligible schools. This model was run separately for English and Mathematics MCAS scores. Sensitivity analyses were performed to assess whether the inclusion of other covariates improved the fit of the model and the Akaike Information Criterion (AIC) was used to assess the fit of the model.

Using the final project scorecard for each green school certification, we summarized differences in indoor environmental credits obtained by each green school certification. LEED and CHPS certifications included credits for IEQ including acoustics, indoor air quality, thermal comfort, and lighting and views. A two-sample Welch’s t-test was performed to identify statistical differences between LEED and CHPS schools on 2016 MCAS performance and chronic absenteeism rates. Analyses were performed using the open-source statistical package R version 3.5.1.

Results

Baseline School Characteristics

In 2010-2011, prior to investment, future green schools were higher-performing academically and had lower pediatric asthma prevalence than schools that did not receive green certifications by 2016 (Table 4-1). Specifically, future green schools performed on average approximately 3 points higher on both English (p-value: 0.02) and Mathematics (p-value: 0.04) MCAS tests. Future green schools had lower rates of chronic absenteeism compared to never green schools, but this difference did not reach a level of statistical significance (p-value: 0.06). Differences in social and demographic characteristics suggest that future green schools had larger student populations, higher percentages of white students, different geographic distributions, and were less likely to have schoolwide Title I programs compared to never green schools.

Future green schools were more likely to be in rural and suburban communities compared to never green schools despite the greatest density of schools being in urban centers (e.g., Boston, Springfield, and Worcester). These urban districts also have a higher proportion of schools performing below average on MCAS English exams compared to suburban districts (Figure 4-1). The western and central parts of the state have fewer schools and have more diversity in district spending – the highest decile of spending was geographically adjacent to the lowest decile. Figure 4-1 also shows that there were 11 future green schools in the lowest three deciles of in-district expenditure per pupil and 8 in the highest three deciles. Of the 9 future green schools that scored equal to or less than 240 on the MCAS English exam in 2011, the average in-district expenditure per pupil was $12,642 compared to $13,302 for the 22 future green schools that scored above 240.

Table 4-1: Demographics of Schools Serving 4th Graders in Massachusetts by Year & Green Certification Status

	Baseline: AY 2010 - 2011			Post–Intervention: AY 2015 - 2016		
	Never Green	**Future Green**		**Not Green**	**Green School**	
	N = 891	N = 31*		N = 911	N = 30	
School Locale	**N (%)**	**N (%)**	**p-value**	**N (%)**	**N (%)**	**p-value**
City	237 (26.6%)	3 (9.7%)	0.06	199 (21.9%)	3 (10%)	0.31
Rural	91 (10.2%)	6 (19.4%)		88 (9.7%)	4 (13.3%)	
Suburban	532 (59.7%)	22 (71%)		598 (65.8%)	23 (76.7%)	
Town	31 (3.5%)	0		24 (2.6%)	0	
School Wide Title I	323 (36.3%)	7 (22.6%)	0.16	365 (40%)	7 (23.3%)	0.07
School Demographics	**Mean (SD)**	**Mean (SD)**	**p-value**	**Mean (SD)**	**Mean (SD)**	**p-value**
# of 4th grade students	74.4 (44.1)	85.3 (46.8)	0.18	74.3 (42.0)	88.2 (39.5)	0.03
Pupil/Teacher Ratio	14.6 (3.8)	14.0 (2.1)	0.23	14 (2.6)	14 (2.3)	0.92
White Students %	64.9 (30.5)	71.5 (25.8)	0.29	59.7 (30.7)	68.5 (26.9)	0.11
Pediatric Asthma Prevalence %	12.2 (6.6)	10.3 (3.8)	0.06	10.4 (7.7)	9.8 (7.3)	0.57
School Academic Achievement						
MCAS English Score	239.6 (7.8)	242.5 (6.8)	0.02	239.7 (7.6)	243.1 (7.7)	0.02
MCAS Math Score	239.7 (7.3)	242.4 (7.3)	0.04	243.2 (8.3)	247.4 (8.3)	0.01
Chronic Absenteeism %	8.8 (6.8)	6.5 (4.3)	0.06	9.2 (6.9)	6.5 (4.5)	0.02
Baseline Building Condition						
Year Original School Built	1959 (29)	1955 (28)	0.55			
2010 School Facility Condition Index %	23.3 (15.2)	32.0 (12.6)	0.008			
Number of Schools with ≥1 major system repair‡	253 (29.2%)	7 (36.8%)	0.69			

Note: P-value refers to results of a Mann-Whitney-Wilcoxon test for continuous variables and Kruskal-Wallis test for categorical variables (Locale, Schoolwide Title I Program). 2010-2011 Categories: Never Certified = schools that will not be replaced by green-certified schools by 2015-2016; and Future Green School = schools that will be replaced by green-certified schools by 2015-2016. 2015-2016 Categories: Not Green Certified = schools that are not green certified; and Green School = schools that received a green certification between 2011 and 2015.

* In 2010-2011, there were 31 future green schools because two schools consolidated into one green school by 2015-2016.

‡ School building conditions were not recorded if they were in the MSBA project pipeline. Total number of schools evaluated: Never Green = 865; Future Green = 19.

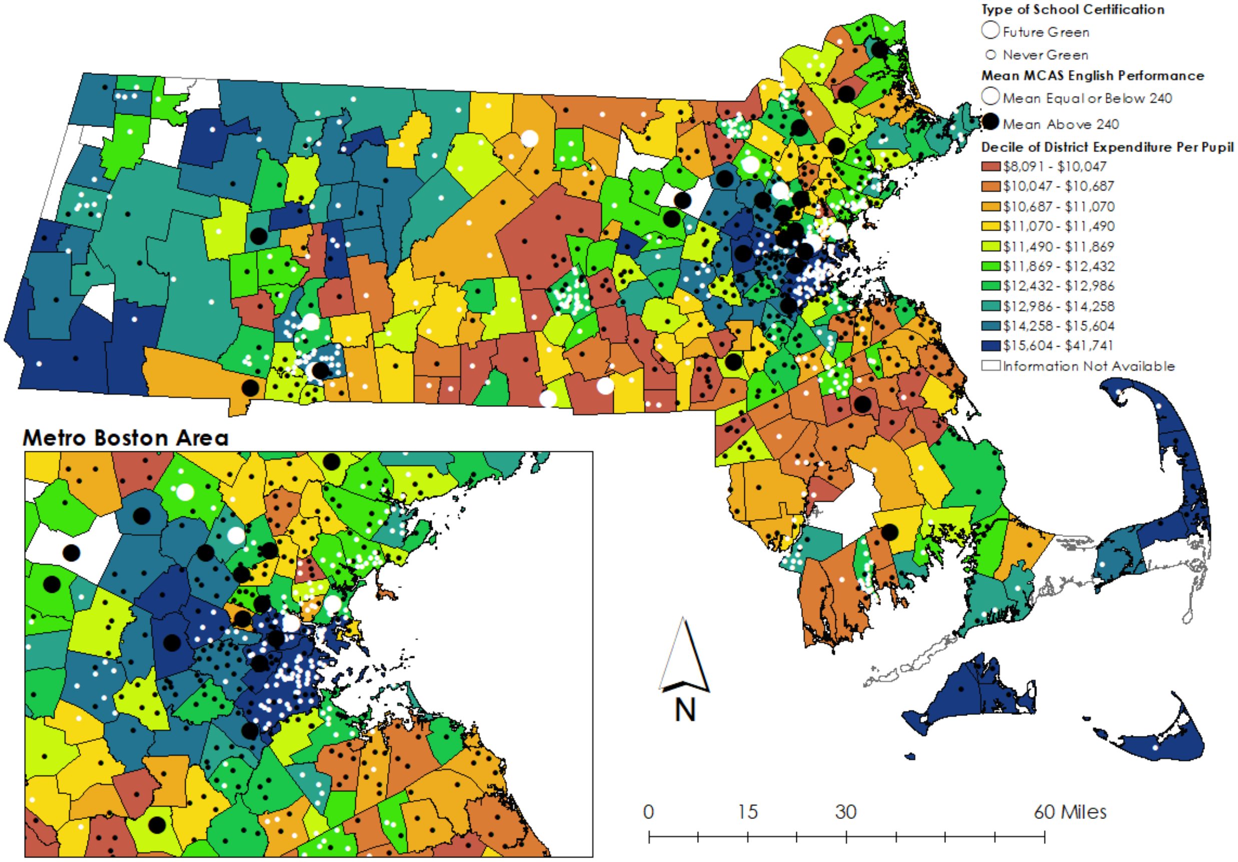

Figure 4-1: Geographic distribution of future green schools and never certified schools in Massachusetts by school district, 2010-2011.

Note: School-level mean English MCAS performance above or below 240 is represented by dot color. Decile of in-district spending per pupil in 2011 is represented by background color.

Baseline Building Quality

Baseline building conditions reported in the 2010 MSBA School Survey suggest future green schools (n= 19, missing = 36%) had significantly worse facility conditions (higher index score) indicating more costly repairs were needed at these schools compared to never green schools (n= 865, missing = 3%) (Table 4-1).

Focusing on building systems (boilers, HVAC, lighting, plumbing, roof, structure, playgrounds, and ceilings), 43% of all schools evaluated required general maintenance only or minimal repairs across the 8 systems. However, 25% (n = 183) of all schools needed major repairs for one or more of these systems. The three building systems in need of the most major repairs in never green schools were HVAC (n = 113, 12.7%), roof (n = 65, 7.3%), and plumbing (n = 62, 7.0%). For the future green schools, two building systems needing the most major repairs were HVAC (n = 3, 15.8%) and lighting (n= 3, 15.8%).

For the schools with MSBA School Survey results, future green schools on average needed 0.32 (standard deviation: 0.65) major repairs compared to 0.44 (standard deviation: 0.84) for never green schools, suggesting that green schools did not require as many major repairs compared to never green schools (Table 4-1, Figure 4-1), despite the FCI being higher in future green schools.

Post Green Certification

In 2015-2016, after 30 schools received either major renovations or new construction that resulted in a green certification, green schools had significantly higher MCAS performance and lower chronic absenteeism compared to the not green schools ($p\text{-value} \leq 0.05$) (Table 4-1). The average number of 4th graders increased for green schools from 85 to 88, and was significantly larger than never green schools (mean: 74.3) in 2015-2016. Compared to baseline, green and never green schools had small non-significant reductions in the percentage of white students attending by 3% and 5.2%, respectively.

2016 MCAS Performance

By comparing the AIC, we found that model fit did not improve when including variables for number of students in 2015-2016, pupil-teacher ratio in 2015-2016, and pediatric asthma prevalence in 2015-2016. Inclusion of change in chronic absenteeism (Δ Chronic Absenteeism

Rate) and change in percentage of white students (Δ % White) during our study period reduced the AIC and increased the adjusted R-squared value.

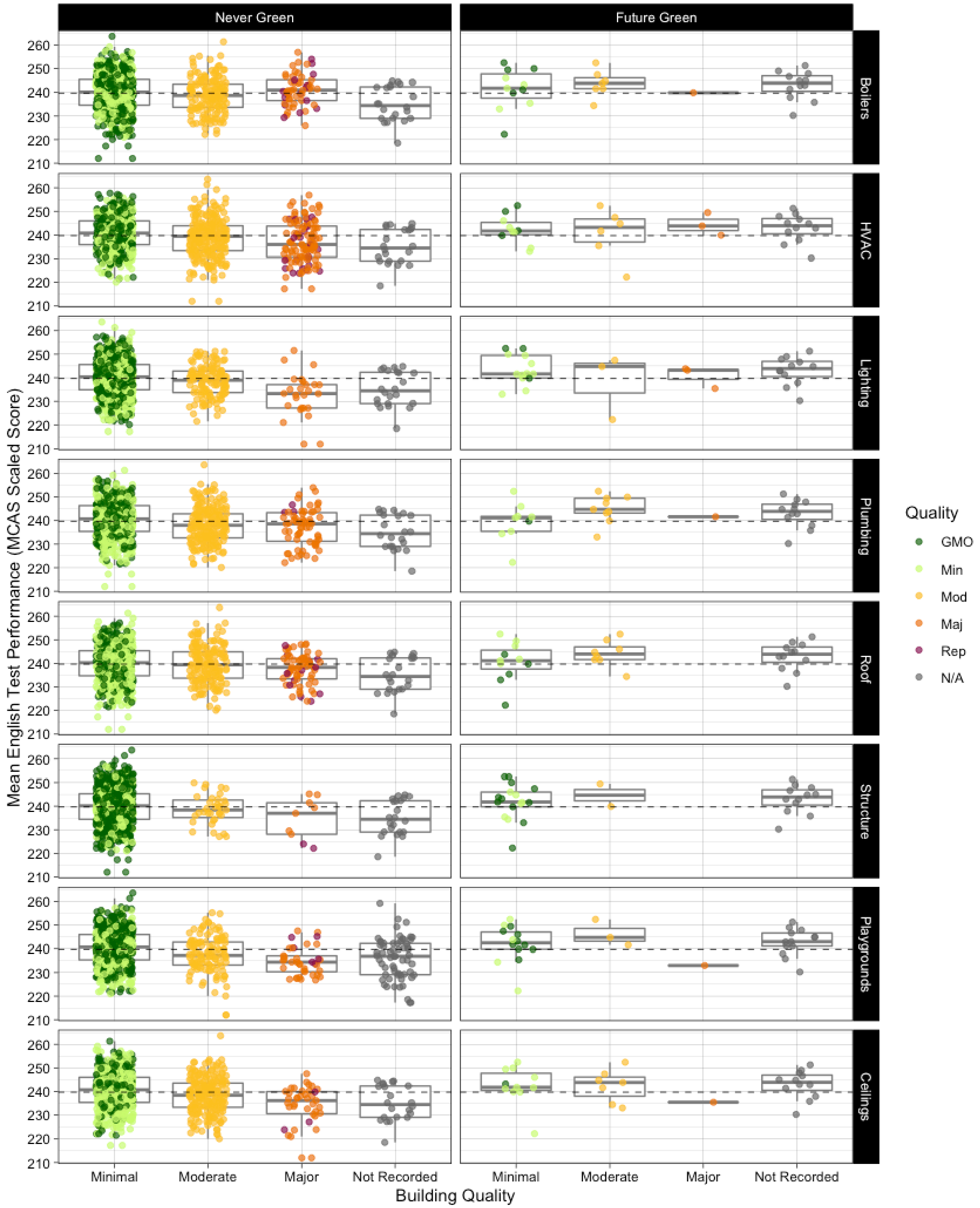

Figure 4-2: Comparison of building quality for future green schools & never certified schools measured by the 2010 MA school buildings' needs assessment stratified by building system

Note: Categories include Minimal: General Maintenance Only (GMO) and Minimum Repair required (Min); Moderate: Moderate repair required (Mod); Major: Major repair required (Maj) and replacement needed (Rep); Not Recorded: Not evaluated in 2010 (N/A). Dashed line is the state mean English MCAS performance of 240.

Table 4-2 contains effect estimates for the matched GLM comparing green schools' 2016 MCAS performance to never green schools. These findings suggest that undergoing renovation and green certification did not improve MCAS performance between 2011 and 2016 compared to schools that have not achieved green certification during the study period. The most significant predictors of school English and Mathematics MCAS performance in 2016 were baseline English/Mathematics performance in 2011, the change in percentage of white students between 2011 and 2016, percentage chronic absenteeism rates in 2015-2016, and having a schoolwide Title I program.

Table 4-2: Survey-Weighted Generalized Linear Model Results

	English		**Mathematics**	
	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value
Intercept	243.6 (242.6, 244.6)	<0.005	247.6 (246.2, 249.0)	<0.005
Green School in 2016	0.03 (-1.7, 1.8)	0.98	0.33 (-1.9, 2.6)	0.78
MCAS Performance in 2011	0.4 (0.3, 0.6)	<0.005	0.4 (0.3, 0.6)	<0.005
% White Students in 2016	-0.01 (-0.07, 0.02)	0.38	-0.05(-0.1, -0.01)	0.02
Change in % White Students since 2011	13.1 (4.9, 21.3)	<0.005	15.1 (4.6, 25.6)	<0.005
% Chronic Absenteeism in 2016	-0.3 (-0.5, -0.1)	<0.005	-0.5 (-0.7, -0.3)	<0.005
Change in % Chronic Absenteeism since 2011	0.04 (-0.2, 0.3)	0.73	0.1 (-0.1, 0.4)	0.31
Schoolwide Title 1 in 2016	-5.6 (-8.8, -2.3)	<0.005	-6.7 (-10.4, -3.0)	<0.005
R^2	0.66		0.64	
Adjusted R^2	0.39		0.36	

Note: Outcome is mean 4th grade English (left) and Mathematics (right) MCAS performance in 2016. Estimates are the change in MCAS score.

Indoor Environmental Quality Credits Achieved by Green Schools

The total number of required IEQ credits across all categories (*acoustics, indoor air quality, thermal comfort, light, and views*) made up 16.9%, 7.8%, and 2.8% of available credits for CHPS-2006, CHPS-2009, and LEED, respectively. IEQ credits (required plus optional) made up 31.5%, 15.6%, and 14.7% of available credits for CHPS-2006, CHPS-2009, and LEED, respectively (Table 4-3). Additional information about specific credits obtained by each green certification type can be found in Table 6-4.

Notably, CHPS schools achieved a higher percentage of required and optional IEQ credits and were associated with higher 2015-2016 MCAS performance compared to LEED-certified schools. Across all certification types, schools achieved the required acoustics credits, but few schools achieved optional credits focused on enhanced acoustical performance. CHPS certifications required more indoor air quality credits than LEED, but optional CHPS credits were also widely adopted including *enhanced filtration* and *advanced low-emitting materials*. Also, *Light* and *Views*-related credits, on average, were more widely adopted in CHPS schools (CHPS-2006: 78%; CHPS-2009: 82.9%) than LEED schools (46.2%). Due to the small number of green schools in this analysis, we could not perform an evaluation of the impact of pursuing specific credits.

Table 4-3: Overview of Credits Achieved by Certification Type for 2015/2016 Green Schools

	CHPS 2006 (n=10)	**CHPS 2009** (n=7)	**LEED** (n=13)	
Total Credits Per Standard	89	128	110	
Required IEQ Credits	15	10	3	
Additional IEQ Credits	28	20	16	
Total Available Credits (Mean Percentage of Credits Earned)				
Acoustics	4 (42.5%)	2 (78.6%)	2 (53.8%)	
Indoor Air Quality	18 (90.5%)	12 (94%)	9 (59%)	
Thermal Comfort	1 (90%)	1 (100%)	3 (61.5%)	
Light & Views	5 (78%)	5(82.9%)	2 (46.2%)	
Academic Performance Differences	**CHPS (2006 & 2009)**		**LEED**	**p-value**
Mean English 2015-2016 MCAS Score	244.1		241.9	0.46
Mean Math 2015-2016 MCAS Score	249.4		244.6	0.11
Mean Chronic Absenteeism	6.2		6.8	0.73

Note: Indoor Environmental Quality (IEQ) credits: Acoustics, Indoor Air Quality, Thermal Comfort, Light & Views are a collection of credits provided by each building standard. For a more detailed list of credits see Supplemental Information. A Welch Two Sample t-test was performed for academic performance differences for English and Mathematics Scaled MCAS Scores and Chronic Absenteeism in 2015-2016.

Discussion

We found that in never green buildings, average English MCAS performance was positively associated with baseline building conditions, supporting the hypothesis that the quality of the building impacts student performance (Figure 4-2). This finding is corroborated by previous schools' literature, which has shown poor indoor and outdoor school facilities conditions to be associated with lower standardized test scores and worse health outcomes (Wakefield 2002, Haverinen-Shaughnessy, Moschandreas et al. 2011, Mohai, Kweon et al. 2011, Eitland 2017). Interestingly, we did not observe the same effect in green schools, despite the benefits characterized in other green building typologies (Colton, MacNaughton et al. 2014, Allen, MacNaughton et al. 2015, Colton, Laurent et al. 2015, Macnaughton, Satish et al. 2017). This can be explained by two factors: 1) at baseline, schools that would receive certification already had building conditions, social demographics, health, and indoor environmental quality factors consistent with higher MCAS scores, suggesting that the effect of green schools on performance may be limited due to a "ceiling effect" phenomenon (Koedel and Betts 2008), and 2) green school buildings, especially those pursuing LEED certification, did not acquire the full set of IEQ credits available.

Green certification may be a poor proxy for the actual conditions experienced at the school post-occupancy. First, the academic and health benefits of green certification might depend on specific building credits pursued, specifically credits that improve air quality, acoustics and lighting. School buildings might achieve LEED and CHPS certification through non-IEQ credits. In fact, 80% of the credits related to site, energy, water, waste management, and sustainable material credits have not been shown to influence learning or test scores. Consequently, architects can preferentially pursue improved energy performance, which has an easy to calculate return on investment (ROI) compared to health and performance-based metrics, notwithstanding more than 30 years of research documenting the role of indoor environmental quality on student health and performance (Sarpong, Wood et al. 1997, Shendell, Prill et al. 2004, NRC 2007, Bako-Biro, Clements-Croome et al. 2012). Yet, schools can obtain green status if the architects preferentially focus on energy and other non-indoor environmental quality features. As more green schools are built, future analysis may parse the specific impacts of IEQ features.

Second, green certifications are based on design and not post-occupancy operations, maintenance and/or responses of teachers, students and staff. If the building is not operated in a manner consistent with design intent, learning maybe compromised. MSBA recognizes that this could happen so it covers 100% of the cost of post-occupancy evaluations with the goal of improving system functioning, energy performance, and indoor environmental quality (MSBA 2019). Although we did not have access to these commissioning reports, this information could be used to improve indoor exposure classification and determine if the school was performing as intended.

These findings provide potential mechanistic reasons for the lack of significant impact on MCAS test performance, which is consistent with other research findings (Thombs 2015, Thombs and Prindle 2018). Specifically, the high baseline academic performance, low acquisition of IEQ-promoting credits, and small sample sizes may prevent researchers from quantifying changes in academic performance. Additionally, we do not know why some schools with high academic or environmental need did not apply for or receive funding for green certification, and the reasons for this are worth further investigation.

Strengths & Limitations

Unlike previous studies, strengths of this analysis include: the use of two green school certifications (LEED and CHPS), access to building repair information prior to renovation, and the longitudinal nature of this analysis, allowing control for pre-certification performance, an important predictor of future performance regardless of certification (Magzamen, Mayer et al. 2017). The creation of the MASMART.ID allows tracking of populations over time which supports more accurate comparisons between student groups. This method relies on data commonly collected by states, thus can be adopted in other contexts. Finally, by focusing solely on 4th graders, it is more likely that the students were attending a neighborhood school for the previous grades. Analyzing the standardized test scores for middle and high school students would introduce uncertainty about how conditions in previously attended school building might influence results.

Our analysis has some limitations. First, small sample sizes limit the power to detect small changes in test performance associated with green school certification, especially in under-performing schools (e.g. Title 1, high pediatric asthma) which may have the most to gain by improvements in environmental quality. Second, standardized test scores are a coarse metric of success and an imperfect proxy for child aptitude and learning. Test scores represent one of the multiple potentially-relevant outcomes, which may not capture specific social and behavioral health improvements in schools. Third, there may be measurement error in the group of never green schools because these buildings may have been extensively renovated or repaired without receiving green certification. We also were unable to test if there was a lag between green school conversion and benefits; this analysis assumes occupancy for one or more years is sufficient and that benefits remain year after year. Due to the lack of documentation, we are not aware of prior disruption that may have displaced students prior to moving into their new school.

These findings may be generalizable to other states with progressive K-12 school policies for improving energy efficiency in existing school buildings (Chayacani and Toy 2017) and pursuing green certification including California (CA DOE 2013), Ohio (OFCA 2019), Tennessee (TN DOE 2019), and/or across the 12 states that have adopted state or regional CHPS criteria (CHPS 2019). With increasing focus on net zero energy schools and energy-efficient schools, these findings may offer opportunities to extend this analysis to other states with different policies, performance metrics, and population demographics.

Policy, Procedure and Practice Opportunities

The observed differences in the pre- and post-certification demographics of Massachusetts green schools compared to not green schools provide further evidence for a multidisciplinary, systems-based approach to determine where and how sustainable school infrastructure may be the most beneficial for student health and well-being (Magzamen, Mayer et al. 2017). We suggest four procedural and policy opportunities to target students with significant needs, where certification may have a greater potential for improvements.

First, it is likely that school size is positively associated with student performance because larger schools have greater administrative efficiency, reduce the cost spent per pupil, and may recruit and afford teachers with greater experience and specialization (Gershenson and Langbein 2015). These factors may influence the administrative capacity required to acquire community buy-in and complete applications for renovations and new construction. This may explain why the number of 4th graders per school attending green schools was significantly larger compared to not green schools in 2016. Therefore, providing additional tailored support (e.g.

human resources, public support, and initial financial investments) to disadvantaged communities may help to overcome barriers faced by schools in these communities when they set out to submit a green school application.

Second, when a new green school building is not viable, states should prioritize effective operations and maintenance in existing buildings. Efforts may include integrated pest management, green cleaning, remediation of persistent pollutants, systematic inspections of HVAC systems, and utilization of best indoor air quality practices (Shendell, Barnett et al. 2004, Sampson 2012). The Environmental Protection Agency’s Tools for Schools program provides tools and information for managing environmental exposures in schools (U.S. EPA 2019).

Third, energy code requirements are increasingly promoting energy efficiency (Becker, Goldberger et al. 2007, Allouhi, El Fouih et al. 2015, Ruparathna, Hewage et al. 2016), which may reduce the need for incentivizing energy efficiency through green building certifications. States where energy codes are more energy-efficient than the American Society of Heating, Refrigerating and Air-Conditioning Engineers’ ASHRAE 90.1, including Washington, California, Nevada, Florida, and Massachusetts, could restructure their reimbursement incentives to reward schools for pursuing health-promoting indoor environmental quality credits (U.S. DOE 2018). As Table 4-3 shows, there is ample room to increase the uptake of acoustics, indoor air quality, thermal comfort, and lighting & views credits, particularly in the group of schools pursuing LEED certification.

Fourth, longitudinal collection of standardized metrics across state departments (e.g., school building authority, education, public health) pre- and post-occupancy would support the identification of intermediate benefits and/or concerns for student and staff performance associated with green certification without violating the 2008 Family Educational Rights and

Privacy Act (FERPA). The collection and analysis of diverse outcomes of interest such as daily pediatric asthma incidence, teacher absenteeism, student engagement, classroom engagement, communicable and non-communicable disease incidence as well as environmental factors including energy consumption and indoor air quality could provide a more holistic evaluation of the impact of green certification on school occupants' health and well-being (Paulson and Barnett 2016, Magzamen, Mayer et al. 2017).

Conclusions

To date, the Massachusetts program funding improvement or replacement of public schools has preferentially approved schools with high baseline academic achievement and better building conditions. Hence improvements in academic performance may have been difficult to detect with this small sample. Our findings suggest that changes to the application process and design incentives such as promoting indoor environmental quality over energy efficiency may promote a more equitable distribution of green schools across Massachusetts and may result in an observable impact of green schools on student performance. Certification processes of school buildings ought to require all the design features that relate to providing good indoor environmental quality.

CHAPTER 5: CONCLUSIONS

The goal of this dissertation was to evaluate a set of building-related strategies that could mitigate adverse indoor exposures and better characterize the implications of changing schools' indoor environmental quality for student performance. The findings of these analyses highlight the complexity of effective implementation of current indoor air technologies and school policy efforts. They also show how transparent, multidisciplinary data collection in schools can be a useful tool for supporting future public health and equitable investment.

Starting in student residences in an individual room, the findings of Chapter 2 were consistent with previous literature, indicating that air purifiers are associated with an overall reduction in daily $PM_{2.5}$ and VOC concentrations. During periods of high $PM_{2.5}$ or acute peak events (e.g. cleaning events and occupancy), dynamic-response purifiers can reduce the duration of peak events and maximum $PM_{2.5}$ concentrations as well as lower VOC concentrations compared to traditional, continuous air purification.

Then examining the second longest indoor environmental exposure for students, Chapter 3 evaluates the association between school building conditions and chronic absenteeism. The findings suggest that students with increased susceptibility to poor environments (e.g. economically disadvantaged, chronic health conditions, English language learners) are in schools with the greatest number of needed repairs. Buildings in need of more repairs are detrimental to students in low socioeconomic schools but not in high socioeconomic schools, which suggests an opportunity to close educational achievement gaps through improvements to physical learning environments. This chapter also found that specific building systems may contribute differentially to school chronic absenteeism rates, which could inform future building investments. Fortunately, some of the systems that this study identified as being most detrimental to chronic absenteeism when in need of a major repair (roof and building envelope), are already targeted by statewide building repair programs.

Lastly, evaluating a subset of schools in Massachusetts that received green certification for renovations, repairs or new construction of energy efficient school buildings, Chapter 4 provided mechanistic reasons for the minimal association between green certifications and test performance. The demographics, prior performance, location, and IEQ features adopted in the new green-certified building collectively contribute to changes in performance. In Massachusetts, the administration of green school incentives has disproportionately gone to schools with high baseline academic achievement and better building conditions. While the study's sample size was small, it provides another example of environmental inequity where high-quality school environments are not attended by students with the greatest social and academic needs. The disproportionate exposure to hazardous materials is a clear form of environmental injustice, but so too is the lack of access to financial, administrative, or political resources that may improve physical environments.

Implications on Practice and Research

The results documented in this dissertation bridge the fields of health, education, and building science and make contributions to both practice and research. First, in terms of practice, the efforts evaluated may serve to reduce harmful exposures. In Chapter 2, observing $PM_{2.5}$ and VOC reductions in low-pollutant environments suggest promising implications for dynamic-response, "smart" purifiers in residential, school, and other types of buildings. Chapter 3 highlights the need for a systematic building assessments across the United States because in Massachusetts, a high-performing state, there was evidence of unidentified indoor environmental injustices that may have significant implications on reaching school performance targets under the Every Student Succeeds Act. By integrating MSBA's building-specific findings with other data collection efforts performed by state departments, the Department of Education can adopt a holistic approach to promoting student well-being. More equitable and targeted decision making can be made when we properly diagnose environmental health needs of the student population. Lastly, in an effort to be environmentally responsible, states across the country have incentivized green building certifications in response to climate change concerns. However, these considerations do not need to be made at the expense of daily, indoor exposures that influence the health of students, teachers and staff. When states have the opportunity to financially support green school building certification, the process should be accessible for all districts in need and should incentivize the achievement of design features related to providing good indoor environmental quality (acoustics, indoor air quality, lighting, thermal comfort), in addition to energy efficiency.

As for research implications, the increasing prevalence of sensor-activated technology requires health-oriented refinements to current purifiers on the market through field studies (Chapter 2). For instance, portable room air cleaners continuously running at a set fan speed supplemented by a low trigger threshold dynamic response may provide a promising public health intervention to reduce individuals' exposure to $PM_{2.5}$ and VOCs. For Chapters 3 and 4, the use of interdisciplinary datasets and input from school stakeholders allowed for the identification of underlying mechanisms that may influence the relationship between building quality and academic performance. Further use of this integrated methodology may be helpful for determining the effectiveness of other practical building-related solutions and guidance.

Future Research and Next Steps

Future research opportunities identified by each of the studies include the evaluation of these interventions in settings with higher levels of environmental exposures, greater follow-up time or temporal variation, and/or use by vulnerable populations. Specifically, for Chapter 2, evaluating sensor-activated portable room air cleaners in environments with higher ambient concentrations of $PM_{2.5}$ and VOCs may provide evidence for additional public health benefits with this technology. With other sensor-activated purifiers on the market and in single-family homes, we expect to see different results across geographies, building types, and occupant behaviors. In areas with higher pollution, we expect greater purification effectiveness, especially in lower socioeconomic status communities, which have been shown to be at increased risk of indoor and outdoor air pollution.

Chapter 3 suggests the need for a follow-up national study on the relationship between building disrepair and chronic absenteeism that integrates building quality, student performance, and student demographics. The results in Massachusetts highlight how different building systems can be associated with chronic absenteeism, yet other health and academic performance outcomes need to be evaluated due to the complex way they can influence health. Also, further research is needed on the occupational health impacts of long-term exposure to poor indoor environmental quality for teachers and staff, especially due to the increasing number of reports of cancer documented in long-term teachers.

For Chapter 4, expanding the MA SMART database using community-based participatory exposure research methods may efficiently diagnose specific environmental concerns and bolster political will needed to allocate resources for school buildings. For example, developing trusting partnerships with schools may provide the ability for collection of health performance indicators with greater temporal granularity per individual including teachers, staff, and students. Also, once green schools are certified and occupied, future field studies using exposure assessment methodology similar to Chapter 2 as well as rigorous qualitative research methods may provide a more complete environmental profile instead of the proxy measures (e.g., green school credits achieved) used in Chapter 4.

In conclusion, indoor environmental quality matters and there are building interventions available that can protect student health and well-being if deployed equitably. With refinement and further evaluation, these strategies can be used to promote indoor environmental quality and community health and resilience for decades to come.

CHAPTER 6: Supplementary Materials

Table 6-1: Average Peak Event Characteristics by Peak Type

Peak Type	**Purifier Setting (# of peaks)**	**Decay Rate (μg/m^3/min)**	**Peak Concentration (μg/m^3)**	**End Concentration (μg/m^3)**	**Duration (mins)**
Minor Peaks	Baseline (194)	0.05	7.38	2.96	71.5
	Smart Home (201)	0.06	7.01	2.93	57.5
	Continuous (225)	0.06	6.77	2.53	62.5
	p-value	0.12	0.04	<0.005	<0.005
Moderate Peaks	Baseline (90)	0.13	18.44	6.76	61.8
	Smart Home (118)	0.18	18.21	5.52	51.7
	Continuous (146)	0.15	17.93	6.47	46.4
	p-value	0.011	0.82	0.03	0.013
Major Peaks	Baseline (42)	0.65	90.46	4.44	122.9
	Smart Home (49)	0.85	71.11	4.48	70.7
	Continuous (42)	0.59	76.93	4.14	104.8
	ANOVA	0.44	0.277	0.86	<0.005

Table 6-2: VOC Concentrations (μg/m^3) Measured with TD Tubes

	Baseline		**Continuous**		**Smart Home**	
	Mean	SD	**Mean**	SD	**Mean**	SD
Chloroform	0.53	0.45	0.54	0.49	0.49	0.39
Tetrahydrofuran	1.09	0.66	0.96	0.46	7.51	26.41
Benzene	0.40	0.06	0.32	0.05	0.36	0.13
Carbontetrachloride	0.53	0.08	0.52	0.11	0.50	0.07
2,5-Dimethylfuran	0.04	0.16	0.00	0.00	0.00	0.00
Toluene	1.75	0.72	0.97	0.26	1.35	0.44
n-Octane	1.56	0.53	0.75	0.22	1.13	0.57
Tetrachloroethylene	0.24	0.67	0.11	0.10	0.13	0.12
Chlorobenzene	0.01	0.02	0.00	0.00	0.00	0.00
Ethylbenzene	0.28	0.15	0.14	0.04	0.20	0.10
m,p-Xylene	0.80	0.25	0.43	0.10	0.61	0.31
Styrene	0.23	0.17	0.13	0.06	0.20	0.12
o-Xylene	0.30	0.12	0.16	0.04	0.24	0.18
n-Nonane	0.66	0.18	0.39	0.14	0.44	0.16
Isopropylbenzene	0.03	0.01	0.02	0.01	0.02	0.01
alpha-Pinene	0.96	0.69	0.55	0.35	0.66	0.34
2-Chlorotoluene	0.00	0.00	0.00	0.00	0.00	0.00
Propylbenzene	0.04	0.02	0.03	0.01	0.03	0.02
1,3,5-Trimethylbenzene	0.07	0.03	0.04	0.02	0.07	0.05
1,2,4-Trimethylbenzene	0.22	0.10	0.11	0.06	0.16	0.08
n-Decane	1.27	1.56	0.70	0.55	0.79	0.47
1,4-Dichlorobenzene	0.70	2.56	0.29	0.83	0.22	0.48
p-Isopropyltoluene	0.38	0.30	0.22	0.26	0.24	0.20
d-Limonene	20.87	42.72	15.39	31.61	11.55	27.78
n-Undecane	0.62	0.68	0.34	0.24	0.45	0.34
Naphthalene	0.30	0.23	0.15	0.09	0.19	0.09
n-Dodecane	0.61	0.44	0.36	0.17	0.41	0.18
n-Tridecane	0.94	0.78	0.65	0.57	0.69	0.47
n-Tetradecane	0.98	0.77	0.82	0.61	0.95	0.83
n-Pentradecane	0.74	0.45	0.60	0.33	0.74	0.45
TVOC	37.15	44.83	25.68	32.48	30.33	37.01

Table 6-3: Demographics of Study Population

Characteristics	**Cohort 1 (n = 16)**	**Cohort 2 (n=16)**
Female (%)	12 (75.0)	8 (50.0)
Mean Age (SD)	30.38 (5.2)	32.81 (5.8)
Residency > 3 months (%)	8 (50.0)	9 (56.2)
Number of Occupants		
1	11 (68.8)	12 (75.0)
2	4 (25.0)	3 (18.8)
3	1 (6.2)	1 (6.2)
Open Window Less than Everyday	2 (12.5)	4 (25.0)
Frequency of Air Conditioner Use		
No AC Used	8 (50.0)	10 (62.5)
Less than Everyday	2 (12.5)	1 (6.2)
Everyday	6 (37.5)	5 (31.2)

	CHPS 2006 (n = 10)		CHPS 2009 (n=7)		LEED (n=13)	
Acoustics	IEQC3.1: Minimum Acoustical Performance	6 (60%)	**EQ.P9: Minimum Acoustical Performance**	**7 (100%)**	**EQp3: Minimum Acoustical Performance**	**13 (100%)**
	IEQC3.2: Improved Acoustical Performance, Maximum 35 NC	6 (60%)	EQ.C7: Enhanced Acoustical Performance	4 (57.1%)	EQc9: Enhanced acoustical performance	1 (7.7%)
	IEQC3.3: Improved Acoustical Performance, Maximum 30 NC	3 (30%)				
	IEQC3.4: Improved Acoustical Performance, Noise Pollution Reduction	2 (20%)				
Indoor Air Quality	**IEQP 1: ASHRAE Standard 62.1-2004 Compliance**	**10 (100%)**	**EQ.P1: HVAC Design - ASHRAE 62.1**	**6 (85.7%)**	**EQp1: Minimum IAQ Performance**	**13 (100%)**
	IEQ P2: SMACNA IAQ Guidelines	**10 (100%)**	**EQ.P5: Minimum Filtration**	**7 (100%)**	**EQp2: Environmental Tobacco Smoke Control**	**13 (100%)**
	IEQC 2.2: Pollutant Source Control, Ducted HVAC Returns	6 (60%)	**EQ.P3: Pollutant and Chemical Source Control**	**7 (100%)**	EQc5: Indoor chemical and pollutant source control	7 (53.8%)
	IEQC 2.3: Pollutant Source Control, High Efficiency Filters	7 (70%)	EQ.C4: Ducted Returns	7 (100%)	EQc1: Outdoor air delivery monitoring	2 (15.4%)
	IEQP 9: Electric Ignitions for Gas-Fired Equipment	**10 (100%)**	EQ.C5: Enhanced Filtration	7 (100%)	EQc2: Increased ventilation	1 (7.7%)
	IEQP 10: Air Intake Location	**9 (90%)**	**EQ.P10 Minimum Low Emitting Materials**	**7 (100%)**	EQc4: Low-emitting materials	12 (92.3%)
	IEQP 11: Duct Liners	**9 (90%)**	EQ.C3: Advanced Low-Emitting Materials	7 (100%)	EQc3.1: Construction IAQ Management Plan - During Construction	13 (100%)
	IEQP 12: Prohibit Fossil-Fuel-Burning Equipment Indoors	**9 (90%)**	**EQ.P2: Construction IAQ Management**	**7 (100%)**	EQc3.2: Construction IAQ Management Plan - Before Occupancy	7 (53.8%)
	IEQP 13: Minimum Filter Requirements for HVAC Equipment	**9 (90%)**	EQ.C6: Post-Construction IAQ	7 (100%)	EQc10: Mold prevention	1 (7.7%)
	IEQ P4: Pollutant Source Control, Off-Gassing	**10 (100%)**	**EQ.P4: Moisture Management**	**7 (100%)**		
	IEQC 2.1: Low Emitting Materials	9 (90%)	EQ.C8: Controllability of Systems	7 (100%)		
	IEQ P3: Construction IAQ Duct Protection	**10 (100%)**	EQ.C9: Duct Access & Cleaning	3 (42.9%)		
	IEQC 2.4: Construction Control, HEPA Vacuuming	9 (90%)				
	IEQC 2.5: Construction IAQ, Building Flushout	7 (70%)				
	IEQ P6: Drainage	**10 (100%)**				
	IEQ P7: Irrigation Design	**10 (100%)**				
	IEQ P8: Mold Protection	**10 (100%)**				
	IEQP 5: Walk-Off Mats	**9 (90%)**				
Thermal Comfort	**IEP 14: ASHRAE Standard 55-2004 Code Compliance**	**9 (90%)**	**EQ.P6: Thermal Comfort - ASHRAE 55**	**7 (100%)**	EQc6.2: Controllability of Systems - Thermal Comfort	10 (77%)
					EQc7.1: Thermal Comfort - Design	7 (53.8%)
					EQc7.2: Thermal Comfort - Verification	7 (53.8%)
Light & Views	**IEQP 15: Access to Views, 70%**	**9 (90%)**	**EQ.P7: View Windows, 70%**	**7 (100%)**	EQc8.1: Daylight and views - daylight	5 (38.5%)
	IEQC 1.1: Access to Views, 90%	8 (80%)	**EQ.P8: Eliminate Glare**	**7 (100%)**	EQc8.2: Daylight and Views - Views	7 (53.8%)
	IEQC 1.2: Daylighting in Classrooms	5 (50%)	EQ.C1: View Window, 80-90%	5 (71.4%)		
	IEQC 4.1: Controllability of Systems, Windows	8 (80%)	EQ.C2: Daylighting in Classrooms	5 (71.4%)		
	IEQC 4.2: Controllability of Systems, Temperature/ Lighting	9 (90%)	EQ.C10: Electric Lighting	5 (71.4%)		

Table 6-4: High performance schools credits and achievement (n (%)). Bold credits are required.

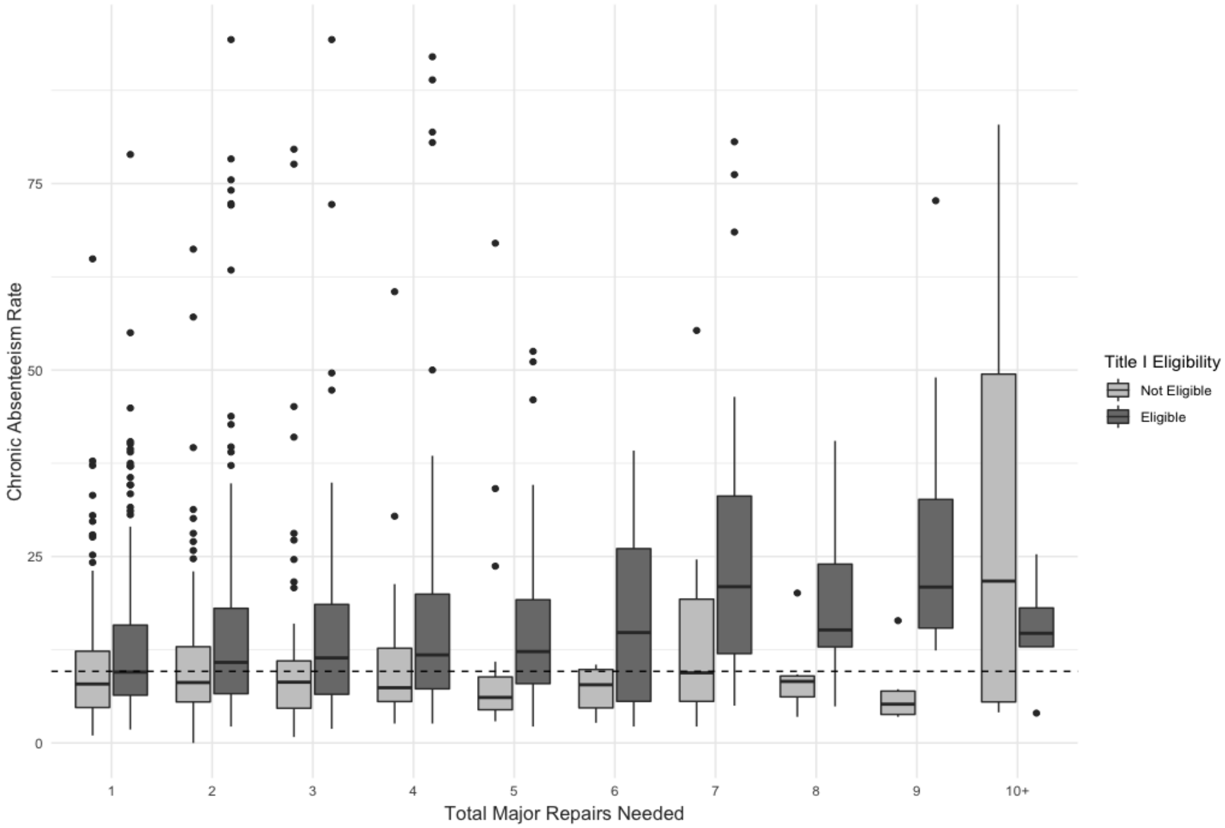

Figure 6-1: Chronic absenteeism rate in 2016-2017 and total major repairs needed per school, stratified by Title I eligibility. Dashed line is the median chronic absenteeism rate for the state in 2016-2017.

BIBLIOGRAPHY

Adamkiewicz, G., A. Zota, M. P. Fabian, T. Chahine, R. Julien, J. D. Spengler and J. Levy (2011). "Moving Environmental Justice Indoors: Understanding Structural Influences on Residential Exposure Patterns in Low-Income Communities." American Journal Of Public Health **101**(s1): S238-S245.

Afzal, B., N. O. Witherspoon and K. Trousdale (2016). "Children’s Environmental Health: Homes of Influence." Environmental Health Perspectives **124**(12): A209-A213.

Alexander, D. and L. Lewis (2014). Condition of America's Public School Facilities: 2012-13. First Look. NCES 2014-022, National Center for Education Statistics. Available from: ED Pubs. P.O. Box 1398, Jessup, MD 20794-1398. Tel: 877-433-7827

Web site: http://nces.ed.gov/.

Allen, J. G., S. Gale, R. T. Zoeller, J. D. Spengler, L. Birnbaum and E. McNeely (2016). "PBDE flame retardants, thyroid disease, and menopausal status in U.S. women." Environmental Health **15**(1).

Allen, J. G., P. MacNaughton, J. G. Laurent, S. S. Flanigan, E. S. Eitland and J. D. Spengler (2015). "Green Buildings and Health." Curr Environ Health Rep **2**(3): 250-258.

Allen, J. G., P. MacNaughton, U. Satish, S. Santanam, J. Vallarino and J. D. Spengler (2015). "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." Environmental Health Perspectives **124**(6).

Allen, R. W., C. Carlsten, B. Karlen, S. Leckie, S. van Eeden, S. Vedal, I. Wong and M. Brauer (2011). "An air filter intervention study of endothelial function among healthy adults in a woodsmoke-impacted community." American Journal of Respiratory and Critical Care Medicine **183**(9): 1222.

Allouhi, A., Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraouli and Y. Mourad (2015). "Energy consumption and efficiency in buildings: current status and future trends." Journal of Cleaner Production **109**: 118-130.

Alphasense Air. (2017). "Particulates." from http://www.alphasense.com/index.php/products/optical-particle-counter/

Amegah, A. K. and J. J. K. Jaakkola (2016). "Household air pollution and the sustainable development goals." Bulletin of the World Health Organization **94**(3): 215.

American Society of Civil Engineering (2017). 2017 Infrastructure Report Card: Schools.

Angelon-Gaetz, K., D. Richardson, S. Marshall and M. Hernandez (2016). "Exploration of the effects of classroom humidity levels on teachers’ respiratory symptoms." International Archives of Occupational and Environmental Health **89**(5): 729-737.

Ara Begum, B., E. Kim, C.-H. Jeong, D.-W. Lee and P. K. Hopke (2005). "Evaluation of the potential source contribution function using the 2002 Quebec forest fire episode." Atmospheric Environment **39**(20): 3719-3724.

Bako-Biro, Z., D. Clements-Croome, N. Kochhar, H. Awbi and M. Williams (2012). "Ventilation rates in schools and pupils' performance." Building and Environment **48**(1): 215-223.

Barn, P. K., C. T. Elliott, R. W. Allen, T. Kosatsky, K. Rideout and S. B. Henderson (2016). "Portable air cleaners should be at the forefront of the public health response to landscape fire smoke.(Report)." Environmental Health: A Global Access Science Source **15**(1).

Barnes, C., N. Alexis, J. Bernstein, J. Cohn, J. Demain, E. Horner, E. Levetin, A. Nel and W. Phipatanakul (2013). "Climate Change and Our Environment: The Effect on Respiratory and Allergic Disease." Journal of Allergy and Clinical Immunology. In Practice **1**(2): 137-141.

Becker, R., I. Goldberger and M. Paciuk (2007). "Improving energy performance of school buildings while ensuring indoor air quality ventilation." Building and Environment **42**(9): 3261-3276.

Bellia, L., A. Pedace and G. Barbato (2013). "Lighting in educational environments: An example of a complete analysis of the effects of daylight and electric light on occupants." Building and Environment **68**: 50-65.

Berman, J. D., M. C. McCormack, K. A. Koehler, F. Connolly, D. Clemons-Erby, M. F. Davis, C. Gummerson, P. J. Leaf, T. D. Jones and F. C. Curriero (2018). "School environmental conditions and links to academic performance and absenteeism in urban, mid-Atlantic public schools." International Journal of Hygiene and Environmental Health **221**(5): 800-808.

Blackwell, M., Stefano Iacus, Gary King and G. Porro (2010). "cem: Coarsened Exact Matching in Stata." Stata Journal **9**(4): 524-546.

Bolden, A. L., C. Kwiatkowski and T. Colborn (2015). "New Look at BTEX: Are Ambient Levels a Problem?" Environmental Science & Technology **49**(9): 5261-5276.

Bräuner, E. V., L. Forchhammer, P. Møller, L. Barregard, L. Gunnarsen, A. Afshari, P. Wåhlin, M. Glasius, L. O. Dragsted, S. Basu, O. Raaschou-Nielsen and S. Loft (2008). "Indoor particles affect vascular function in the aged: an air filtration-based intervention study." American Journal of Respiratory and Critical Care Medicine **177**(4): 419-425.

Breysse, P. N., T. J. Buckley, D. a. Williams, C. M. Beck, S.-J. Jo, B. Merriman, S. Kanchanaraksa, L. J. Swartz, K. A. Callahan, A. M. Butz, C. S. Rand, G. B. Diette, J. A. Krishnan, A. M. Moseley, J. Curtin-Brosnan, N. B. Durkin and P. A. Eggleston (2005). "Indoor exposures to air pollutants and allergens in the homes of asthmatic children in inner-city Baltimore." Environmental Research **98**(2): 167-176.

Bruno, P., M. Caselli, G. De Gennaro, S. Iacobellis and M. Tutino (2008). "Monitoring of volatile organic compounds in non-residential indoor environments." Indoor Air **18**(3): 250-256.

Cal Fire. (2018). "Incident Information." from http://cdfdata.fire.ca.gov/incidents/incidents_stats?year=2018.

California Department of Education (2013). Senate Bill No. 73: CHAPTER 29:

California Clean Energy Jobs Act (Proposition 39).

Carslaw, N. and D. Shaw (2019). "Secondary product creation potential (SPCP): a metric for assessing the potential impact of indoor air pollution on human health." Journal of Environmental Monitoring **21**(8): 1313-1322.

Chakraborty, J. and P. A. Zandbergen (2007). "Children at risk: measuring racial/ethnic disparities in potential exposure to air pollution at school and home." Journal of Epidemiology and Community Health **61**(12): 1074.

Chang, I. T., J. Sarnat, J. Wolfson, L. Rojas-Bracho, H. Suh and P. Koutrakis (1999). "Development of a personal multi-pollutant exposure sampler for particulate matter and criteria gases." Pollution Atmospherique: 31-39.

Chayacani, Y. and B. M. Toy (2017). State-level Legislation to Support Energy Efficiency: Dedicated Funding for Existing K-12 Schools, Center for Green Schools at the U.S. Green Building Council.

Chin, J. Y., C. Godwin, E. Parker, T. Robins, T. Lewis, P. Harbin and S. Batterman (2014). "Levels and sources of volatile organic compounds in homes of children with asthma." Indoor Air **24**(4): 403-415.

Clark-Reyna, E. S., E. S. Grineski and W. T. Collins (2016). "Health Status and Residential Exposure to Air Toxics: What Are the Effects on Children's Academic Achievement?" Family & Community Health **39**(3): 160-168.

Clark-Reyna, S. E., S. E. Grineski and T. W. Collins (2016). "Ambient Concentrations of Metabolic Disrupting Chemicals and Children's Academic Achievement in El Paso, Texas." International Journal of Environmental Research and Public Health **13**(9): 874.

Claudio, L., G. A. Rivera and O. F. Ramirez (2016). "Association Between Markers of Classroom Environmental Conditions and Teachers' Respiratory Health." J Sch Health **86**(6): 444-451.

Cohen, A. (2010). "Achieving healthy school siting and planning policies: understanding shared concerns of environmental planners, public health professionals, and educators." New Solutions: A Journal of Environmental and Occupational Health Policy **20**(1): 49-72.

Collaborative for High Performance Schools. (2019). "CHPS Criteria: Setting a National Standard." from https://chps.net/chps-criteria.

Colton, M. D., J. G. Laurent, P. MacNaughton, J. Kane, M. Bennett-Fripp, J. Spengler and G. Adamkiewicz (2015). "Health Benefits of Green Public Housing: Associations With Asthma Morbidity and Building-Related Symptoms." American Journal of Public Health **105**(12): 2482-2489.

Colton, M. D., P. MacNaughton, J. Vallarino, J. Kane, M. Bennett-Fripp, J. D. Spengler and G. Adamkiewicz (2014). "Indoor air quality in green vs conventional multifamily low-income housing." Environmental Science & Technology **48**(14): 7833.

Corlan, A. D. (2019). "Medline trend: automated yearly statistics of PubMed results for any query, 2004." Retrieved 2019-02-14, from http://dan.corlan.net/medline-trend.html

Cox, J., K. Isiugo, P. Ryan, S. A. Grinshpun, M. Yermakov, C. Desmond, R. Jandarov, S. Vesper, J. Ross, S. Chillrud, K. Dannemiller and T. Reponen (2018). "Effectiveness of a portable air cleaner in removing aerosol particles in homes close to highways." Indoor Air **28**(6): 818-827.

Dallongeville, A., N. Costet, D. Zmirou-Navier, B. Le Bot, C. Chevrier, S. Deguen, I. Annesi-Maesano and O. Blanchard (2016). "Volatile and semi-volatile organic compounds of respiratory health relevance in French dwellings." Indoor Air **26**(3): 426-438.

Deng, G., Z. Li, Z. Wang, J. Gao, Z. Xu, J. Li and Z. Wang (2017). "Indoor/outdoor relationship of PM2.5 concentration in typical buildings with and without air cleaning in Beijing." Indoor and Built Environment **26**(1): 60-68.

Dionisio, K. L., V. Isakov, L. K. Baxter, J. A. Sarnat, S. E. Sarnat, J. Burke, A. Rosenbaum, S. E. Graham, R. Cook, J. Mulholland and H. Özkaynak (2013). "Development and evaluation of alternative approaches for exposure assessment of multiple air pollutants in Atlanta, Georgia." Journal of Exposure Science and Environmental Epidemiology **23**(6): 581.

Earl, R., N. Burns, T. Nettelbeck and P. Baghurst (2016). "Low-level environmental lead exposure still negatively associated with children's cognitive abilities." Australian Journal of Psychology **68**(2): 98-106.

Eitland, E., Klingensmith, L., MacNaughton, P., Cedeno Laurent, J., Spengler, J. Bernstein, A., Allen, J. (2017). Schools for Health: Foundations for Student Success, Harvard T.H. Chan School of Public Health.

EPA, U. S. (2019). "Volatile Organic Compounds' Impact on Indoor Air Quality." from https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality#Levels.

Evans, G. W. (2006). "Child development and the physical environment." Annual Review of Psychology **57**: 423.

Fisk, W. J. (2013). Health benefits of particle filtration, Indoor Air. **23:** 357-368.

Fisk, W. J. and W. R. Chan (2017). "Health benefits and costs of filtration interventions that reduce indoor exposure to PM2.5 during wildfires." Indoor Air **27**(1): 191-204.

Fisk, W. J., J. A. Paulson, L. J. Kolbe and C. L. Barnett (2016). "Significance of the School Physical Environment – A Commentary." Journal of School Health **86**(7): 483-487.

Fleisch, A. F., D. R. Gold, S. L. Rifas-Shiman, P. Koutrakis, J. D. Schwartz, I. Kloog, S. Melly, B. A. Coull, A. Zanobetti, M. W. Gillman and E. Oken (2014). "Air Pollution Exposure and Abnormal Glucose Tolerance during Pregnancy: The Project Viva Cohort." Environmental Health Perspectives **122**(4).

Francis, L., K. DePriest, M. Wilson and D. Gross (2018). "Child Poverty, Toxic Stress, and Social Determinants of Health: Screening and Care Coordination." Online Journal of Issues in Nursing **23**(3): 2.

Frey, S. E., H. Destaillats, S. Cohn, S. Ahrentzen and M. P. Fraser (2014). "Characterization of indoor air quality and resident health in an Arizona senior housing apartment building." Journal of the Air & Waste Management Association **64**(11): 1251-1259.

GAO (2018). GAO-18-382: Lead Testing of School Drinking Water Would Benefit from Improved Federal Guidance, United States Government Accountability Office.

Gershenson, S. and L. Langbein (2015). "The Effect of Primary School Size on Academic Achievement." Educational Evaluation and Policy Analysis **37**(1_suppl): 135S-155S.

Gillooly, S. E., Y. Zhou, J. Vallarino, M. T. Chu, D. R. Michanowicz, J. I. Levy and G. Adamkiewicz (2019). "Development of an in-home, real-time air pollutant sensor platform and implications for community use." Environmental Pollution **244**: 440-450.

Gordon, K., P. D. Terry, X. Liu, T. Harris, D. Vowell, B. Yard and J. Chen (2018). "Radon in Schools: A Brief Review of State Laws and Regulations in the United States." International Journal of Environmental Research and Public Health **15**(10): 2149.

Gottfried, M. A. (2019). "Chronic Absenteeism in the Classroom Context: Effects on Achievement." Urban Education **54**(1): 3-34.

Green, R., S. Smorodinsky, B. McLaughlin and J. Kim (2002). "Proximity of California public schools to busy roads." Epidemiology **13**(4): S210-S210.

Grineski, S. E. and T. W. Collins (2018). "Geographic and social disparities in exposure to air neurotoxicants at U.S. public schools." Environmental Research **161**: 580-587.

Guo, H., S. C. Lee, L. Y. Chan and W. M. Li (2004). "Risk assessment of exposure to volatile organic compounds in different indoor environments." Environmental Research **94**(1): 57-66.

Haverinen-Shaughnessy, U., D. Moschandreas and R. Shaughnessy (2011). "Association between substandard classroom ventilation rates and students' academic achievement." Indoor Air **21**(2): 121-131.

Héroux, M.-E., N. Clark, K. V. Ryswyk, R. Mallick, N. L. Gilbert, I. Harrison, K. Rispler, D. Wang, A. Anastassopoulos, M. Guay, M. MacNeill and A. J. Wheeler (2010). "Predictors of Indoor Air Concentrations in Smoking and Non-Smoking Residences." International Journal of Environmental Research and Public Health **7**(8): 3080-3099.

Herrick, R. F., M. D. McClean, J. D. Meeker, L. K. Baxter and G. A. Weymouth (2004). "An unrecognized source of PCB contamination in schools and other buildings.(Research: Commentary)." Environmental Health Perspectives **112**(10): 1051.

Hien, P. D., V. T. Bac, H. C. Tham, D. D. Nhan and L. D. Vinh (2002). "Influence of meteorological conditions on PM 2.5 and PM 2.5–10 concentrations during the monsoon season in Hanoi, Vietnam." Atmospheric Environment **36**(21): 3473-3484.

Hoffmann, B., S. Moebus, N. Dragano, A. Stang, S. Mohlenkamp, A. Schmermund, M. Memmesheimer, M. Brocker-Preuss, K. Mann, R. Erbel and K.-H. Jockel (2009). "Chronic residential exposure to particulate matter air pollution and systemic inflammatory markers.(Research)(Report)." Environmental Health Perspectives **117**(8): 1302.

Hsu, J., X. Qin, S. F. Beavers and M. C. Mirabelli (2016). "Asthma-Related School Absenteeism, Morbidity, and Modifiable Factors." American Journal of Preventive Medicine **51**(1): 23-32.

Hu, K., Q. Chen and J.-H. Hao (2013). "Influence of suspended particles on indoor semi-volatile organic compounds emission." Atmospheric Environment **79**: 695-704.

Iacus, S. M., G. King and G. Porro (2012). "Causal Inference without Balance Checking: Coarsened Exact Matching." Political Analysis **20**(1): 1-24.

Issa, M. H., M. Attalla, J. H. Rankin and A. J. Christian (2013). "Detailed Analysis of the Construction, Operating, Maintenance, and Rehabilitation Costs of Green Toronto Schools." Journal of Architectural Engineering **19**(1): 1-11.

Issa, M. H., J. H. Rankin, M. Attalla and A. J. Christian (2011). "Absenteeism, Performance and Occupant Satisfaction with the Indoor Environment of Green Toronto Schools." Indoor and Built Environment **20**(5): 511-523.

Jia, C. and X. Fu (2017). "Diffusive Uptake Rates of Volatile Organic Compounds on Standard ATD Tubes for Environmental and Workplace Applications." Environments **4**(4): 87.

Johnston, J. and J. Macdonald Gibson (2015). "Indoor Air Contamination from Hazardous Waste Sites: Improving the Evidence Base for Decision-Making." International Journal of Environmental Research and Public Health **12**(12): 15040-15057.

Jones (1999). "Indoor air quality and health." Atmospheric Environment, Oxford, England **33**(28): 4535-4564.

Kilburn, K. H. (2000). "Indoor Air Effects after Building Renovation and in Manufactured Homes." The American Journal of the Medical Sciences **320**(4): 249-254.

Kinney, P. L. (2008). "Climate Change, Air Quality, and Human Health." American Journal of Preventive Medicine **35**(5): 459-467.

Koedel, C. and J. Betts (2008). "Test-Score Ceiling Effects and Value-Added Measures of School Quality." Social Statistics Section - JSM Proceedings.

Koep, T. H., F. T. Enders, C. Pierret, S. C. Ekker, D. Krageschmidt, K. L. Neff, M. Lipsitch, J. Shaman and W. C. Huskins (2013). "Predictors of indoor absolute humidity and estimated effects on influenza virus survival in grade schools." BMC Infectious Diseases **13**(1): 71.

Kponee, K., J. Nwanaji-Enwerem, X. Fu, I. Kakulu, M. Weisskopf and C. Jia (2018). "Elevated Indoor Volatile Organic Compound Exposure in the Niger Delta Region of Nigeria." International Journal of Environmental Research and Public Health **15**(9).

Landrigan, P. J., V. A. Rauh and M. P. Galvez (2010). "Environmental Justice and the Health of Children." Mount Sinai Journal of Medicine: A Journal of Translational and Personalized Medicine **77**(2): 178-187.

Lary, M. A., L. Allsopp, D. J. Lary and D. A. Sterling (2019). "Using machine learning to examine the relationship between asthma and absenteeism." Environ Monit Assess **191**(Suppl 2): 332.

Leischow, S. J., A. Best, W. M. Trochim, P. I. Clark, R. S. Gallagher, S. E. Marcus and E. Matthews (2008). "Systems thinking to improve the public's health." American Journal of Preventive Medicine **35**(2 Suppl): S196-S203.

Lexuan, Z., S. Feng-Chiao and B. Stuart (2017). "Volatile Organic Compounds (VOCs) in Conventional and High Performance School Buildings in the U.S." International Journal of Environmental Research and Public Health **14**(1): 100.

Lucier, C., A. Rosofsky, B. London, H. Scharber and J. M. Shandra (2011). "Toxic Pollution and School Performance Scores: Environmental Ascription in East Baton Rouge Parish, Louisiana." Organization & Environment **24**(4): 423-443.

MacNaughton, P., E. Eitland, I. Kloog, J. Schwartz and J. Allen (2017). "Impact of Particulate Matter Exposure and Surrounding “Greenness” on Chronic Absenteeism in Massachusetts Public Schools." International Journal of Environmental Research and Public Health **14**(2).

Macnaughton, P., U. Satish, J. G. C. Laurent, S. Flanigan, J. Vallarino, B. Coull, J. D. Spengler and J. G. Allen (2017). "The impact of working in a green certified building on cognitive function and health." Building and Environment **114**: 178-186.

Magzamen, S., A. P. Mayer, S. Barr, L. Bohren, B. Dunbar, D. Manning, S. J. Reynolds, J. W. Schaeffer, J. Suter and J. E. Cross (2017). "A Multidisciplinary Research Framework on Green Schools: Infrastructure, Social Environment, Occupant Health, and Performance." Journal of School Health **87**(5): 376-387.

Mahalingaiah, S. (2018). "Is there a common mechanism underlying air pollution exposures and reproductive outcomes noted in epidemiologic and in vitro fertilization lab-based studies?" Fertility and Sterility **109**(1): 68-68.

Massachusetts Department of Elementary and Secondary Education (2017). Massachusetts Consolidated State Plan Under the Every Student Succeeds Act (ESSA).

Massachusetts Department of Elementary and Secondary Education (2018). 2017 Next-Generation MCAS and MCAS-Alt Technical Report

Massachusetts Department of Elementary and Secondary Education (2018). Supporting Social-Emotional Learning, Health & Safety. Key Initiatives. http://www.doe.mass.edu/sfs/attendance/, Massachusetts Department of Elementary and Secondary Education.

Massachusetts Department of Elementary and Secondary Education. (2019). "Statewide Reports." from http://profiles.doe.mass.edu/state_report/.

Massachusetts Department of Public Health - Bureau of Environmental Health. (2019). "Massachusetts Environmental Public Health Tracking - Asthma Overview." from https://matracking.ehs.state.ma.us/Health-Data/Asthma/index.html.

Massachusetts School Building Authority (2017). 2016 School Survey Report.

Massachusetts School Building Authority. (2019). "Accelerated Repair Program." from https://www.massschoolbuildings.org/programs/Accelerated_Repair.

Massachusetts School Building Authority. (2019). "Commissioning." from http://www.massschoolbuildings.org/building/design/commissioning.

Massachusetts School Building Authority. (2019). "Green Schools." from https://www.massschoolbuildings.org/programs/green_schools.

Massachusetts School Building Authority. (2019). "School Survey." from http://www.massschoolbuildings.org/programs/school_survey.

Massachusetts School Building Authority. (2019). "Statements of Interest." from https://www.massschoolbuildings.org/building/SOIs.

McNamara, M. L., J. Thornburg, E. O. Semmens, T. J. Ward and C. W. Noonan (2017). "Reducing indoor air pollutants with air filtration units in wood stove homes." Science of the Total Environment **592**: 488-494.

Mendell, M. J. and G. A. Heath (2005). "Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature." Indoor Air **15**(1): 27-52.

Meng, Y.-Y., S. H. Babey and J. Wolstein (2012). "Asthma-related school absenteeism and school concentration of low-income students in California." Preventing Chronic Disease **9**: E98-E98.

Miller, K., D. Siscovick, L. Sheppard, K. Shepherd, J. Sullivan, G. Anderson and J. D. Kaufman (2007). "Long-term exposure to air pollution and incidence of cardiovascular events in women." New England Journal of Medicine **356**(5): 447-458.

Mirabelli, M. C., A. Vaidyanathan, W. D. Flanders, X. Qin and P. Garbe (2016). "Outdoor [PM.sub.2.5], ambient air temperature, and asthma symptoms in the past 14 days among adults with active asthma.(Research)." Environmental Health Perspectives **124**(12): 1882.

Mohai, P., B.-S. Kweon, S. Lee and K. Ard (2011). "Air pollution around schools is linked to poorer student health and academic performance." Health affairs (Project Hope) **30**(5): 852.

Moonie, S. A., D. A. Sterling, L. Figgs and M. Castro (2006). "Asthma Status and Severity Affects Missed School Days." Journal of School Health **76**(1): 18-24.

Morawska, L., G. A. Ayoko, G. N. Bae, G. Buonanno, C. Y. H. Chao, S. Clifford, S. C. Fu, O. Hänninen, C. He, C. Isaxon, M. Mazaheri, T. Salthammer, M. S. Waring and A. Wierzbicka (2017). "Airborne particles in indoor environment of homes, schools, offices and aged care facilities: The main routes of exposure." Environment International **108**: 75-83.

Morello-Frosch, R., M. Pastor, C. Porras and J. Sadd (2002). "Environmental justice and regional inequality in southern California: Implications for future research." Environmental Health Perspectives **110**: 149-154.

Mott, M., D. Robinson, T. Williams-Black and S. McClelland (2014). "The supporting effects of high luminous conditions on grade 3 oral reading fluency scores." SpringerPlus **3**(1): 1-5.

Mott, M. S., D. H. Robinson, A. Walden, J. Burnette and A. S. Rutherford (2012). "Illuminating the Effects of Dynamic Lighting on Student Learning." SAGE Open **2**(2).

Muscatiello, N., A. McCarthy, C. Kielb, W. H. Hsu, S. A. Hwang and S. Lin (2015). "Classroom conditions and CO2 concentrations and teacher health symptom reporting in 10 New York State Schools." Indoor Air **25**(2): 157-167.

National Center for Education Statistics. (2019). "Common Core of Data." from https://nces.ed.gov/ccd/.

National Center for Education Statistics. (2019). "Public School Expenditures." from https://nces.ed.gov/programs/coe/indicator_cmb.asp.

National Research Council (2007). Green Schools: Attributes for health and learning. Washington, DC, National Academies Press.

Nazaroff, W. W. and C. J. Weschler (2004). "Cleaning products and air fresheners: exposure to primary and secondary air pollutants." Atmospheric Environment **38**(18): 2841-2865.

NCES. (2019). "Elsi tableGenerator." from https://nces.ed.gov/ccd/elsi/tableGenerator.aspx.

NCES. (2019). "How Old are America’s Public Schools?", 2019, from https://nces.ed.gov/surveys/frss/publications/1999048/.

Netatmo. (2017). "Smart Home Weather Station." from https://www.netatmo.com/en-US/product/weather/weatherstation.

Nosek, Š., V. Fuka, L. Kukačka, Z. Kluková and Z. Jaňour (2018). "Street-canyon pollution with respect to urban-array complexity: The role of lateral and mean pollution fluxes." Building and Environment **138**: 221-234.

Obermeyer, Z., M. Makar, S. Abujaber, F. Dominici, S. Block and D. M. Cutler (2014). "Association Between the Medicare Hospice Benefit and Health Care Utilization and Costs for Patients With Poor-Prognosis Cancer." JAMA **312**(18): 1888.

Ohio Facilities Construction Authority. (2019). "Green Schools." from https://ofcc.ohio.gov/Services-Programs/Energy-Services/Green-Schools.

Paciência, I., J. Madureira, J. Rufo, A. Moreira and E. d. O. Fernandes (2016). "A systematic review of evidence and implications of spatial and seasonal variations of volatile organic compounds (VOC) in indoor human environments." Journal of Toxicology and Environmental Health - Part B **19**: 47-64.

Paulson, J. and C. Barnett (2016). "Public Health Stops at the School House Door." Environmental Health Perspectives (Online) **124**(10): A171.

Person-Harm, A. (2014). The care and keeping of cultural facilities : a best practice guidebook for museum facility management. Lanham [Maryland], Rowman & Littlefield.

Polidori, A., J. Kwon, B. J. Turpin and C. Weisel (2009). "Source proximity and residential outdoor concentrations of PM2.5, OC, EC, and PAHs." Journal of Exposure Science and Environmental Epidemiology **20**(5): 457.

Population Reference Bureau. (2016). "Fact Sheet: Aging in the United States." from http://www.prb.org/Publications/Media-Guides/2016/aging-unitedstates-fact-sheet.aspx.

Rachel Morello-Frosch, M. P. Jr. and J. Sadd (2002). "SECTION 1: EPIDEMIOLOGY AND SCIENCE: Integrating Environmental Justice and the Precautionary Principle in Research and Policy Making: The Case of Ambient Air Toxics Exposures and Health Risks among Schoolchildren in Los Angeles." Annals of the American Academy of Political and Social Science **584**: 47-203.

Rice, J., E. Brigham, R. Dineen, S. Muqueeth, G. O'Keefe, S. Regenold, K. Koehler, A. Rule, M. McCormack, N. N. Hansel and G. B. Diette (2018). "The feasibility of an air purifier and secondhand smoke education intervention in homes of inner city pregnant women and infants living with a smoker." Environmental Research **160**: 524-530.

Rogalsky, D., P. Mendola, T. Metts and W. Martin (2014). "Estimating the Number of Low-Income Americans Exposed to Household Air Pollution from Burning Solid Fuels." Environmental Health Perspectives (Online) **122**(8): 806.

Rosofsky, A., C. A. Lucier, B. London, H. Scharber, R. Borges-Mendez and J. Shandra (2014). "Environmental ascription in Worcester County, MA: toxic pollution and education outcomes." Local Environment **19**(3): 283-299.

Rousseau-Salvador, C., R. Amouroux, D. Annequin, A. Salvador, B. Tourniaire and S. Rusinek (2014). "Anxiety, depression and school absenteeism in youth with chronic or episodic headache." Pain Research & Management **19**(5): 235-240.

Rumchev, K., J. Spickett, M. Bulsara, M. Phillips and S. Stick (2004). "Association of domestic exposure to volatile organic compounds with asthma in young children." Thorax **59**(9): 746.

Ruparathna, R., K. Hewage and R. Sadiq (2016). "Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings." Renewable and Sustainable Energy Reviews **53**: 1032-1045.

Samet, J. M., M. C. Marbury and J. D. Spengler (1987). "Health effects and sources of indoor air pollution. Part I." The American Review of Respiratory Disease **136**(6): 1486.

Samet, J. M. and R. H. White (2004). "Urban air pollution, health, and equity." Journal of Epidemiology and Community Health **58**(1): 3.

Sampson, N. (2012). "Environmental Justice at School: Understanding Research, Policy, and Practice to Improve Our Children's Health." Journal of School Health **82**(5): 246-252.

Sansom, G. T., K. R. Kirsch, K. W. Stone, T. J. McDonald and J. A. Horney (2018). "Domestic Exposure to Polycyclic Aromatic Hydrocarbons in a Houston, Texas, Environmental Justice Neighborhood." Environmental Justice **11**(5): 183-191.

Sarpong, S. B., R. A. Wood, T. Karrison and P. A. Eggleston (1997). "Cockroach allergen (Bla g 1) in school dust." The Journal of Allergy and Clinical Immunology **99**(4): 486-492.

Schwartz, J. (2004). "Air pollution and children's health." Pediatrics **113**(4 Suppl): 1037-1043.

Semple, S., A. Apsley, T. Azmina Ibrahim, S. W. Turner and J. W. Cherrie (2015). "Fine particulate matter concentrations in smoking households: just how much secondhand smoke do you breathe in if you live with a smoker who smokes indoors?" Tobacco Control **24**(e3): e205.

Shah, J. and H. Singh (1988). "Distribution of volatile organic chemicals in outdoor and indoor air." Environmental Science and Technology **22**: 1381-1388.

Shaughnessy, R. J. and R. G. Sextro (2006). "What Is an Effective Portable Air Cleaning Device? A Review." Journal of Occupational and Environmental Hygiene **3**(4): 169-181.

Shendell, D. G., C. Barnett and S. Boese (2004). "Science-Based Recommendations to Prevent or Reduce Potential Exposure to Biological, Chemical, and Physical Agents in Schools." Journal of School Health **74**(10): 390-396.

Shendell, D. G., R. Prill, W. J. Fisk, M. G. Apte, D. Blake and D. Faulkner (2004). "Associations between classroom CO2 concentrations and student attendance in Washington and Idaho." Indoor air **14**(5): 333.

Sherbinin, A. d., D. Carr, S. Cassels and L. Jiang (2007). "Population and Environment." **32**(1): 345-373.

Simons, E., S.-A. Hwang, E. F. Fitzgerald, C. Kielb and S. Lin (2010). "The impact of school building conditions on student absenteeism in Upstate New York." American Journal of Public Health **100**(9): 1679-1686.

Simons, E., S. Lin and S. Hwang (2009). "The Impact of School Building Conditions on Student Absenteeism and Performance in Upstate New York." The Journal of Allergy and Clinical Immunology **123**(2): S21-S21.

Sofowote, U. and F. Dempsey (2015). "Impacts of forest fires on ambient near–real–time PM2.5 in Ontario, Canada: Meteorological analyses and source apportionment of the July 2011–2013 episodes." Atmospheric Pollution Research **6**(1): 1-10.

Spengler, J. D. (2012). "Climate change, indoor environments, and health." Indoor Air **22**(2): 89-95.

Su, M., Z. Zhou, Y. Si, X. Wei, Y. Xu, X. Fan and G. Chen (2018). "Comparing the effects of China's three basic health insurance schemes on the equity of health-related quality of life: using the method of coarsened exact matching." Health and Quality of Life Outcomes **16**(1).

Sublett, J. (2011). "Effectiveness of Air Filters and Air Cleaners in Allergic Respiratory Diseases: A Review of the Recent Literature." Current Allergy and Asthma Reports **11**(5): 395-402.

Sunderland, E. M., X. C. Hu, C. Dassuncao, A. K. Tokranov, C. C. Wagner and J. G. Allen (2019). "A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects." Journal of Exposure Science & Environmental Epidemiology **29**(2): 131-147.

Tennessee Department of Education. (2019). "Energy Efficient Schools Initiative (EESI)." from https://www.tn.gov/eesi/.

Thombs, R. (2015). Factors that Affect Student Performance Among Ohio LEED Schools: An Examination of LEED Credit Categories, IEQ Credits and School Typology, Otterbein University.

Thombs, R. and A. Prindle (2018). "Ohio LEED Schools and Academic Performance: A Panel Study, 2006-2016." Sustainability **10**(10).

Thurston, G. D., J. Ahn, K. R. Cromar, Y. Shao, H. R. Reynolds, M. Jerrett, C. C. Lim, R. Shanley, Y. Park and R. B. Hayes (2016). "Ambient particulate matter air pollution exposure and mortality in the NIH-AARP diet and health cohort." Environmental Health Perspectives **124**(4): 484.

Tong, Z., Y. Chen, A. Malkawi, G. Adamkiewicz and J. D. Spengler (2016). "Quantifying the impact of traffic-related air pollution on the indoor air quality of a naturally ventilated building." Environment International **89-90**: 138-146.

Turunen, M., O. Toyinbo, T. Putus, A. Nevalainen, R. Shaughnessy and U. Haverinen-Shaughnessy (2014). "Indoor environmental quality in school buildings, and the health and wellbeing of students." Int J Hyg Environ Health **217**(7): 733-739.

U. S. Congress Senate (2015). Failing the Grade: Asbestos in America's Schools. Congressional Publications.

U.S. Department of Education. (2019). "Chronic Absenteeism in The Nation's Schools." from https://www2.ed.gov/datastory/chronicabsenteeism.html#four.

U.S. Department of Energy. (2018). "Status of State Energy Code Adoption." Building Energy Codes Program, 2019, from https://www.energycodes.gov/adoption/states.

U.S. Environmental Protection Agency. (2019). "Creating Healthy Indoor Air Quality in Schools." from https://www.epa.gov/iaq-schools.

U.S. Green Building Council (2007). LEED for Schools for New Construction and Major Renovations.

U.S. Green Building Council, 21st Century School Fund and National Council on School Facilities (2016). 2016 State of our Schools: America's K-12 Facilities.

U.S. News & World Report. (2019). "Education Rankings." Retrieved November 13, 2019, from https://www.usnews.com/news/best-states/rankings/education.

Uline, C. and M. Tschannen-Moran (2008). "The Walls Speak: The Interplay of Quality Facilities, School Climate, and Student Achievement." Journal of Educational Administration **46**(1): 55-73.

United States General Accounting Office (1995). School Facilities: Condition of America's schools - Report to Congressional requesters.

Vette, A., J. Burke, G. Norris, M. Landis, S. Batterman, M. Breen, V. Isakov, T. Lewis, M. I. Gilmour, A. Kamal, D. Hammond, R. Vedantham, S. Bereznicki, N. Tian and C. Croghan (2013). "The Near-Road Exposures and Effects of Urban Air Pollutants Study (NEXUS): Study design and methods." Science of the Total Environment **448**: 38-47.

Wakefield, J. (2002). "Learning the Hard Way: The Poor Environment of America's Schools." Environmental Health Perspectives **110**(6).

Wallace, J. and P. Kanaroglou (2009). "The effect of temperature inversions on ground-level nitrogen dioxide (NO 2) and fine particulate matter (PM2.5) using temperature profiles from the Atmospheric Infrared Sounder (AIRS)." Science of the Total Environment **407**(18): 5085-5095.

Weichenthal, S. (2012). "Selected physiological effects of ultrafine particles in acute cardiovascular morbidity." Environmental Research **115**(C): 26-36.

Weschler, C. J. and W. W. Nazaroff (2014). "Dermal uptake of organic vapors commonly found in indoor air." Environmental science & technology **48**(2): 1230-1237.

Wheeler, A. J., S. L. Wong, C. Khouri and J. Zhu (2013). "Predictors of indoor BTEX concentrations in Canadian residences." Health reports **24**(5): 11.

World Health Organization. (2017). "Urban Population Growth." from http://www.who.int/gho/urban_health/situation_trends/urban_population_growth/en/.

World Health Organization. (2018). "Household Air Pollution." from https://www.who.int/en/news-room/fact-sheets/detail/household-air-pollution-and-health.

Xu, Y., S. Raja, A. R. Ferro, P. A. Jaques, P. K. Hopke, C. Gressani and L. E. Wetzel (2010). "Effectiveness of heating, ventilation and air conditioning system with HEPA filter unit on indoor air quality and asthmatic children's health." Building and Environment **45**(2): 330-337.

Yuan, C., E. Ng and L. K. Norford (2014). "Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies." Building and Environment **71**: 245-258.

Zeileis, A. (2019). Econometric Computing with HC and HAC Covariance Matrix Estimators. Universit¨at Innsbruck.

Zhan, Y., K. Johnson, C. Norris, M. M. Shafer, M. H. Bergin, Y. Zhang, J. Zhang and J. J. Schauer (2018). "The influence of air cleaners on indoor particulate matter components and oxidative potential in residential households in Beijing." Science of the Total Environment **626**: 507-518.

Zhu, J., S. L. Wong and S. Cakmak (2013). "Nationally representative levels of selected volatile organic compounds in Canadian residential indoor air: population-based survey." Environmental Science & Technology **47**(23): 13276.

Zota, A. R., R. A. Rudel, R. A. Morello-Frosch and J. G. Brody (2008). "Elevated house dust and serum concentrations of PBDEs in California: unintended consequences of furniture flammability standards?" Environmental Science & Technology **42**(21): 8158-8164.