Development of a Multidimensional Housing and Environmental Quality Index (HEQI): Application to the American Housing Survey

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Abstract

Background: Substandard housing conditions and hazardous environmental exposures indoors contribute to significant morbidity and mortality worldwide. Housing indices that capture the multiple dimensions of healthy housing are important for tracking conditions over time and identifying vulnerable households. However, most indices focus on physical deficiencies and repair costs and omit indoor environmental exposures, as few data sources routinely collect this data at the national level.

Methods: We developed a national, multidimensional Housing and Environmental Quality Index (HEQI) based on the World Health Organization's Housing and Health Guidelines and applied it to the national American Housing Survey (AHS) 2019 data. The HEQI consisted of ten domains associated with poor health: indoor combustion sources, dampness and mold, pests and allergens, lead paint risk, high indoor temperatures, low indoor temperatures, household crowding, injury hazards, inadequate water and sanitation, and ventilation. We evaluated the validity and performance of the HEQI against three housing characteristics (i.e., year built, monthly rent costs, unit satisfaction rating) and two established indices (i.e., Adequacy index, Poor Quality Index).

Results: Approximately 79% (92 million) of U.S. households reported at least one HEQI risk factor (mean per household: 1.5; range: 0,19). Common risk factors included indoor combustion sources (e.g. gas stoves, fireplaces) (62.0%), dampness and mold (15.4%), inadequate water and sanitation (11.7%), and injury hazards (11.6%). Prevalence of pest and allergens, low indoor temperature, and injury hazards were associated with older housing, lower rent costs, and worse unit satisfaction. Compared to established housing indices, the HEQI captured four new environmental domains and at least 62% (57.7 million) more households with environmental risk factors like mold, cockroaches, crowding, indoor combustion sources, and higher building leakage.

Conclusions: Indoor environmental exposures are prevalent in U.S. households and not well-captured by established housing indices. The HEQI is a national, multidimensional tool that can be used to monitor indoor environmental exposures and housing quality trends in the U.S. The mounting evidence linking residential environmental exposures with adverse health outcomes underscore the need for this data in the AHS and other national surveys.

I. Background

The World Health Organization (WHO) defines healthy housing as one that “supports a state of complete physical, mental and social well-being” [1]. Poor housing conditions and exposure to environmental hazards in the home are risk factors for adverse health, including respiratory, cardiometabolic, and reproductive health effects; physical injuries; poor mental health; and shorter life expectancy [1–4]. These housing-related health risk factors fall within the multiple dimensions of healthy housing, such as structural deficiencies (e.g. cracks in walls or ceilings, no insulation), chemical/material hazards (e.g. lead paint, asbestos, volatile organic compounds, pesticides, flame retardants, phthalates), poor indoor air quality (e.g. particulate matter, carbon monoxide, radon, environmental tobacco smoke), indoor allergens (e.g. mold, dust, pet dander), pests (e.g. rodents, cockroaches), and noise [1, 5, 6]. Exposure to these hazards are driven by the joint influence of both indoor and outdoor sources, the building design and conditions, the presence and performance of ventilation systems, and residential activity patterns, including the use of consumer products and appliances that emit environmental pollutants [7, 8]. In addition, the characteristics of the living space (e.g., thermal comfort, natural lighting, occupancy) and access to basic resources (e.g., heating, plumbing, cookstove) also contribute to residents' health, well-being, and quality of life [1].

Environmental health indices that can capture the multiple dimensions of healthy housing are important tools for characterizing the risk of exposure as well as evaluating the effectiveness of interventions. For example, a study among low-income housing developments used a summed environmental health index to identify risk factors associated with poor self-reported health [8]. The Massachusetts health department developed an Environmental Scoring System to evaluate changes in environmental triggers (e.g. mold, pest, smoke, dust, and chemical hazards) following implementation of home-based asthma education programs [9]. In Arizona, the Phoenix Children's Hospital conducted a visual assessment of 29 potential injury hazards and seven potential respiratory health hazards to evaluate the effectiveness of a multidisciplinary home-intervention program for low-income families [10]. Collectively, these studies underscore the need for comprehensive, evidence-based environmental health indices for housing portfolios. However, at the national level, there is a paucity of indices that capture multiple domains of housing quality and indoor environmental risk factors. In addition, data are often not routinely collected, inhibiting the ability to track housing and environmental conditions over time.

The American Housing Survey (AHS), a nationally-representative and longitudinal household survey, may provide a platform to address existing data gaps. It is the most comprehensive survey of housing conditions in the U.S. and has been widely used to track and report on housing quality, housing stability, and occupant characteristics over time. AHS variables can be mapped onto key indoor environmental exposures that influence residents' health [7]. To date, a housing and environmental health index based on AHS data has not been developed. Established AHS indices focus solely on housing adequacy and quality, such as the Adequacy index and the Poor Quality Index (PQI) [11, 12], and are framed around a particular way of *seeing* quality, such as the need or cost of repairs, presence of (typically major) physical deficiencies, or resident's satisfaction with their unit [13]. These indices do not account for environmental conditions that have been associated with adverse health, such as poor indoor air quality, mold, chemical hazards, thermal discomfort, and ventilation.

The objective of our study was to develop a national Housing and Environmental Quality Index (HEQI) that can capture the multiple dimensions of healthy housing, particularly indoor environmental exposures. The selection of our HEQI domains was informed by the WHO Housing and Health Guidelines [1] and applied to the AHS data. We evaluated the performance of the HEQI against housing characteristics and established indices in the AHS.

2. Methods

2.1 Data

The AHS is a biennial U.S. survey of housing units since 1973 led by the U.S. Office of Housing and Urban Development (HUD). Participation in the AHS is voluntary and consists of a computer-assisted, in-person or phone interview with the main householder in primarily English and Spanish languages. Each sampled housing unit is weighted to represent approximately 50 to 15,410 housing units [25].

For our HEQI development, we used the 2019 AHS national public flat file downloaded from U.S. Census Bureau website on December 11, 2020 with a sample size of 63,185 households. At the time of the analysis, the 2019 survey was the most recent data available. In Supplemental Data, we provide the variable and response coding for the HEQI using AHS data from the 2011 to 2019 survey cycles to allow for longitudinal assessment (Table S1). However, researchers should note differences in the sample design and housing units between the 2011-2013 and the 2015-2019 AHS data [26].

We excluded housing units that were vacant or if the owner had usual residence elsewhere because they were ineligible for AHS questions pertinent to our HEQI. We also excluded mobile housing types (e.g., trailers, boat, van, RV) given their low prevalence in the data (5.7% of occupied units) and to reduce heterogeneity of our sample. Our final sample consisted of 51,933 occupied housing units.

2.2 Housing and health domain identification

We identified domains that captured indoor environmental risk factors and housing conditions associated with adverse health effects. The WHO Housing and Health Guidelines and related guidance documents recommended 15 priority areas based on systematic reviews of environmental health hazards and substandard housing conditions associated with poor health and the availability of recommendations to correct such hazards or conditions [1, 5, 6, 14–24]. The WHO guidelines provided an evidence-based health framework for our HEQI development (Table 1).

2.3 Data selection

We reviewed the availability of AHS questions (referred to as ‘AHS items’) for each of the 15 HEQI domains (Table S2). To ensure longevity of the HEQI, we prioritized AHS items that were asked across multiple survey years, particularly in the most recent survey cycles (i.e., 2015-2019). AHS data was considered ‘available’ if it contained items relevant to the HEQI domain for multiple survey years; ‘limited’ if items did not directly relate to the domain but proxy measures could be applied; and ‘unavailable’ if neither of these conditions were met (Table 1). From the 15 WHO domains, ten had available or limited information in the AHS (Table 2). Thus, we integrated the following ten domains into the HEQI:

1. Indoor air quality, specifically indoor combustion sources
2. Dampness and mold
3. Pests and allergens, specifically rodents and cockroaches
4. Lead, specifically lead paint risk
5. High indoor temperatures
6. Low indoor temperatures
7. Household crowding, specifically severe crowding
8. Injury hazards, specifically electrical and structural integrity
9. Inadequate water and sanitation
10. Ventilation, specifically building normalized leakage

The final HEQI consisted of 43 AHS items across these ten domains. The four HEQI domains of dampness and mold, low indoor temperatures, household crowding, and inadequate water and sanitation were well-captured by the AHS based on the relevance and robustness of items included (Table 2). For the remaining six HEQI domains, indoor combustion sources, pest and allergens, lead paint risk, high indoor temperatures, injury hazards, and ventilation, the relevance and precision of AHS items to approximate the underlying health risk factor varied. In addition, the AHS does not ask about household crowding, lead exposure, periods of high indoor temperatures, nor ventilation factors such as insulation or building leakage. Therefore, we had to approximate these domains using available AHS data or external data sources. We created a severe crowding indicator that identified households with 1.5 or more persons per room, consistent with the U.S. Census and HUD’s definition of severe crowding [27, 28]. We also created an indicator for lead paint risk to identify housing units built before 1980 that also had peeling paint larger than 8x11 inches. We selected the year threshold of 1980 to temporally align with the ban of lead from residential paint starting in 1978 [29]. High indoor temperatures was flagged if the household reported not having central air or window air conditioning unit(s), which are mechanical controls known to reduce the risk of health-related illnesses [30, 31]. Ownership of these controls could vary across geographic regions and climate types [32] and thus, we controlled for U.S. Census regions in regression analyses.

Lastly, the ventilation domain was based on an approximation of building leakage (i.e., normalized leakage), which is a measure of building envelope airtightness relative to its size and height [33]. To create the building leakage indicator, we adapted methods by Chan et al. (2013) and accounted for year built, unit size and height, basement and foundation types, and the International Energy Conservation Code (IECC) Climate Zones [33]. Data on weatherization assistance program, basement foundation type, and IECC Climate Zones were not available in the AHS and had to be approximated based

on income-to-poverty thresholds, county-level IECC estimates, and the 2009 Residential Energy Consumption Survey, respectively. See Supplemental Data Appendix 1 for more details about the building leakage indicator.

We excluded several AHS items from the HEQI. Mold in the basement and outside infrastructural problems were only asked of single-family households and thus excluded. For domains with multiple AHS items, items that were moderately or strongly correlated (Spearman $r > |0.60|$) were removed to reduce collinearity. Specifically, we selected wood heating fuel over wood heating type ($r = 0.69$) [6] and water from a non-public source over septic tank or cesspool sewer system ($r = 0.63$) [34, 35] because they were more inclusive and better approximated the underlying hazard. The HEQI AHS item codebook can be found in Supplemental Table S1. Inter-item correlations within each HEQI domain can be found in Supplemental Table S2.

2.4 Data reduction

All AHS item responses were binary coded (yes/no) to indicate prevalence of the risk factor. Within each HEQI domain, AHS responses were summed to create a domain-specific count. We then calculated a cumulative count based on the sum of responses across AHS items.

2.5 Validity testing

We assessed the validity of the HEQI using several approaches. We computed Spearman rank correlation matrices to evaluate the inter-domain correlations and the extent to which each domain captured a unique latent feature of healthy housing (i.e. *discriminant validity*) [36]. Secondly, we evaluated criterion validity, specifically predictive validity, of the HEQI domain and its association with housing characteristics like unit rating, year built, and monthly rent costs, consistent with previous studies [13, 37, 38]. The AHS item on unit rating asked: “On a scale of 1 to 10, how would you rate your unit as a place to live?”, with 10 ranked as the best place to live. Year built was categorized as intervals (<1960 (ref), 1960-1969; 1970-1979; 1980-1989; 1990-1999; 2000+). We ran ordinal logistic regressions to examine the association of HEQI domains (independent variables) with unit rating and year built (dependent variables) separately. For the analysis with year built, we excluded the criteria of housing built before 1980 from the lead paint risk domain to avoid endogeneity with the outcome. Monthly rent costs (dollar units) was continuous, had a right-tailed distribution, and log-transformed prior to modeling. We used linear regression to assess the association of HEQI domains and monthly rent costs among renter households (N=20,205).

Third, we evaluated *convergent validity*, i.e. the extent to which our index aligned with the two established AHS housing indices: Adequacy index and Poor-Quality Index (PQI). The Adequacy index (named ZADEQ prior to AHS 2015) is comprised of eight criterion capturing severe physical deficiencies like no running water, plumbing facilities, heating, or electricity, and signs of structural weaknesses like water leaks and presence of rats [11]. Units are categorized as “adequate,” “moderately inadequate,” or “severely inadequate” based on the prevalence and various combinations of these risk factors. The PQI is comprised of 35 AHS items that fall into eight housing quality domains, such as electricity, heating, inside and outside structural hazards, bathroom, kitchen, water and sewer, and elevator problems [12]. The PQI items of ‘No working elevator in building of 4+ stories’ and outside infrastructural problems were excluded from our comparisons because they were not available in recent AHS survey cycles and not asked of multifamily households, respectively. Although the PQI assigned weights to each AHS item based on severity of the risk factor, we used unweighted PQI counts to be comparable to the HEQI and Adequacy index, which are unweighted. Across the three indices, we compared the frequency of overlap in AHS items and estimated the number of U.S. households with at least one risk factor (i.e., HEQI count ≥ 1 , PQI count ≥ 1 , and Adequacy categories of ‘moderately’ or ‘severely’ inadequate). To obtain estimates of the U.S. households and associated standard errors, we applied the WEIGHT variable and 160 replicate weights using the balanced repeated replications (BRR) method [39] in the R *survey* package [40].

2.6 Statistical analyses

We ran descriptive statistics summarizing the frequency and means of the cumulative and domain-specific HEQI counts overall and by homeownership and building type (single-family vs. multifamily). All regression models were adjusted for building type (single-family [ref] vs. multifamily); housing tenure (homeowner [ref] vs. renter/live without pay); race/ethnicity of the main householder (white non-Hispanic [ref], Asian non-Hispanic, Black non-Hispanic, and Latina/o/Hispanic); educational attainment of the main householder (Bachelor/Graduate degree [ref], high school graduate/some college experience, and less than high school), and U.S. Census regions (Pacific [ref], East North Central, Middle Atlantic, New England, Middle Atlantic, South Atlantic and East South Central; and West Central). Statistical significance was set at a two-sided alpha-level of 0.05. All analyses were conducted in R (R Core Team, Vienna, Austria).

3. Results

In the 2019 national AHS sample of U.S. households, approximately 78.9% (n=41,012) reported at least one HEQI risk factor (Table 3), which represented approximately 92 million U.S. households at risk. On average, each household reported 1.5 HEQI risk factors (range: 0, 19). Prevalent HEQI domains were indoor combustion sources (62%), dampness and mold (15.4%), inadequate water/sanitation (11.7%), and injury hazards (11.6%) (Table 3). Major individual risk factors reported were use of gas cooking fuel (42.6%), prevalence of a working fireplace (36.8%), access to water from non-public sources (e.g. wells) (7.5%), and unit being uncomfortably cold for 24 or more hours (5.7%). HEQI domains with lowest prevalence were lead paint risk (1.5%) and severe household crowding (0.5%) (Table 2). By homeownership and building type, homeowners (74%) and single-family (72%) households reported higher prevalence of indoor combustion sources compared to non-homeowners (44%) and multifamily (40%) households, respectively. In contrast, non-homeowners and multifamily households reported a higher prevalence of high indoor temperatures (14-15% vs. 8%), pest and allergens (8% vs. 2-3%), and high building leakage (6-9% vs. 1.0%) (Table 3).

We found that HEQI had good discriminant validity to capture unique dimensions of healthy housing as indicated by the low correlation coefficients across the ten HEQI domains (range: -0.05 to 0.17) (Table S2). Indoor combustion sources were slightly negatively correlated with high building leakage (-0.10), while dampness and mold was slightly positively correlated with several domains: pest and allergens (0.13), low indoor temperature (0.16), lead paint risk (0.16), and injury hazard (0.17) (Table S2).

We also found good criterion validity of HEQI domains with AHS characteristics of unit rating, year built, and monthly rent costs. Most HEQI domains were negatively associated with unit rating and year built (Table 4), specifically, pests and allergens, lead paint risk, and injury hazards with unit rating (adjusted odds ratios [aORs] ≤ 0.66), and high indoor temperatures, high building leakage, and pest and allergens with building age (aORs ≤ 0.70). The associations with monthly rent costs were more modest for most HEQI domains. However, high building leakage was strongly negatively associated with monthly rent costs (adjusted relative ratio [aRR]: 0.77 (95% CI: 0.73, 0.80), while severe crowding was strongly positively associated (aRR: 1.26, 95% CI: 1.13, 1.42). Also, the direction of associations for HEQI domains were generally consistent across the three housing characteristics. Indoor combustion sources were positively associated with higher unit rating, newer housing, and higher monthly costs (aORs and aRR: 1.03-1.09), while pests and allergens (0.46-0.96), low indoor temperatures (0.80-0.94), and injury hazards (0.66-0.97) were negatively associated with these characteristics (Table 4).

Compared to the PQI and Adequacy index, the HEQI captured approximately 270,000 more sample households, or an estimated 61.4 million more U.S. households, with one or more healthy housing risk factor(s). Specifically, out of the 43 AHS items in the HEQI, the PQI overlapped with 25 items (58%) and the Adequacy Index overlapped with 21 items (49%) (Table 2). The PQI and Adequacy index did not contain three HEQI domains of severe crowding, high building leakage, and high indoor temperatures, which impacted approximately 13 million U.S. households. Additionally, the Adequacy index did not capture any indoor combustion sources, while the PQI only captured the AHS item on 'kerosene heating', which resulted in an underestimation of approximately 57.7 million households (Table 5). For the remaining domains, the Adequacy index and PQI varied in their capture. For example, they did not include items about mold, which underestimated approximately 1.7 million households compared to the HEQI. For the pest and allergens domain, they did not ask about cockroaches, which underestimated approximately 3 million households. For the domains of low indoor temperatures, injury hazards, and water and sanitation, the PQI adequately overlapped with the HEQI items (86-100%) (Table 2).

4. Discussion

Substandard housing conditions and hazardous environmental exposures indoors contribute to significant morbidity and mortality worldwide [1]. Despite known adverse health effects associated with these conditions, most national surveys and housing indices do not include this information. Our study developed a national, multidimensional housing and environmental quality index (HEQI) informed by the WHO's Health and Housing Guidelines and composed of ten healthy housing domains addressing structural deficiencies, indoor environmental exposures, and building conditions associated with adverse health. Using the 2019 AHS data, the HEQI identified approximately 92 million (79%) U.S. households with one or more HEQI risk factor(s). Compared to established housing quality and adequacy indices, the HEQI captured four new environmental health domains and at least 57.7 million (62%) more households at risk.

The multidimensional HEQI performed better than established housing indices at capturing both housing quality and environment health risk factors. Established indices focus primarily on physical deficiencies, costs of repair, or deflation in home values as a result of these deficiencies [11–13, 37, 38]. In particular, the PQI and Adequacy index underestimated approximately 61.4 million U.S. households with environmental risk factors like mold, cockroaches, household crowding, indoor combustion sources, and higher building leakage. Moreover, although prior studies have used the AHS to characterize environmental risk factors, most have focused on single AHS items like thermal comfort [41], air exchange [42], wood combustion [43], mold [44], and pests [45]. To our knowledge, the HEQI is the first multidimensional index that captures a range of housing quality and environmental health risk factors.

Prevalent environmental risk factors identified by the HEQI and not well-captured by established housing indices were indoor combustion sources and dampness and mold. Indoor combustion sources include gas cookstoves, wood and kerosene heating fuel, and unvented fireplaces. These sources emit carbon monoxide, particulate matter, nitrogen dioxide, and other hazardous air pollutants that are associated with adverse cardio-respiratory health effects [46–48]. Approximately 72 million (62%) U.S. households reported the presence of at least one combustion source indicator, particularly the use of gas cookstoves and fireplaces. Mold and damp environments were reported by approximately 18.7 million (15.4%) households, particularly water leaks from the roof, basement, and pipes, and mold in bathrooms. Mold spores can enter the indoor environment through building openings (e.g., doorways, windows, cracks, HVAC systems) and thrive in damp areas with excessive moisture, leaks, and flooding events [15, 44]. Mold triggers allergic symptoms, eczema, respiratory infections, asthma, dyspnea, and other pulmonary diseases [15, 49, 50]. Given that U.S. households spend approximately 87% of their time indoors [51], the risk of chronic exposure to these indoor hazards are high, and particularly in the wintertime and in cold climates when the building envelope is more sealed [52].

Our study found that the HEQI had good discriminant and criterion validity to capture unique dimensions of housing and environmental quality. The inverse correlation of indoor combustion sources with the building leakage domain reflects known trade-offs in indoor air quality and energy efficiency. In homes with frequent combustion-source activities (e.g., smoking, cooking, or candle/incense) and without proper ventilation controls, building airtightness can trap air pollutants and increase concentrations indoors. At the same time, high building leakage increases the risk of dampness, mold, pest problems, and energy loss [53–56]. Structural deficiencies can also lead to moisture and mold problems, physical injuries, openings for pests to enter the home, as well as energy loss resulting in lower indoor temperatures. As such, we observed positive correlations between the domains of dampness and mold with low indoor temperatures, lead paint risk, and injury hazards that are all associated with building structural integrity. Surprisingly,

dampness and mold were not correlated with building leakage, which may be due to spatial imprecision of this indicator due to regional U.S. estimates and/or its coarseness as a binary indicator.

Furthermore, the HEQI was associated with measures such as unit rating, year built, and rent costs. Unit rating is a consumer rating index capturing residents' perception of well-being and quality of life [57]. In our study, risk factors strongly associated with lower unit satisfaction generally included those that residents were able to directly observe or experience, such as pests and allergens, lead paint risk, and injury hazards, consistent with previous study [13]. Older housing has been associated with greater physical deficiencies and chemical hazards [58]. While we could not evaluate chemical hazards, we found that older housing was strongly associated with deficiencies like inadequate water and sanitation, higher building leakage, and high indoor temperatures attributed to no central air or window air conditioning units. Rent costs is a market value index that assigns a monetary value to the quality of housing and neighborhood amenities, with higher rents suggestive of better quality [38]. In our study, the modest associations between HEQI domains and monthly rent costs could be due to the omission of neighborhood amenities from our analyses [38]. However we still found significant negative associations for four HEQI domains of pests and allergens, low indoor temperatures, injury hazards, and high building leakage. Additionally, severe crowding was significantly associated with higher rent costs, consistent with previous findings that cost-burdened residents report doubling-up to save on rent [2, 59, 60].

Our analysis also yielded findings that inform areas for future research. Indoor combustion sources and high building leakage were positively associated with higher unit satisfaction. Since we did not have direct measures of indoor air quality or building leakage, we used proxy measures such as appliance type (e.g., cooking, heating) and building features (e.g., unit size and height, basement and foundation type, year built). In effect, the positive associations may reflect residents' preferences for these attributes instead of their understanding of potential health risks. Indoor air pollution levels and building ventilation are generally difficult to observe without the assistance of sensor technology [61]. In addition, both of these domains have not traditionally been included in housing quality indices. Our findings underscore the need for further education among residents and housing practitioners about the sources of and strategies for reducing indoor air pollution and improving building ventilation.

We also found positive associations of inadequate water and sanitation with unit satisfaction and year built, which was primarily driven by the high proportion of households with non-public water sources (7.5%) (exclusion of this item switched the direction of the coefficient for this domain to be negative, data not shown). Non-public water sources have been attributed with a higher risk of waterborne illnesses [34, 35]. The positive association between non-public water sources and higher unit satisfaction may be attributed to suburban housing status, since suburbs that have a higher percentage of newer construction [62]. Unfortunately, we were not able to investigate this given the lack of information about urban/suburban status in the public AHS data in recent survey cycles.

Next, we evaluate the application of the HEQI to AHS data and make recommendations for areas of improvement. Five healthy housing domains recommended by the WHO were not captured by the AHS due to the lack of data across survey years or in the full sample of households: radon, pesticides, asbestos, noise, and housing accessibility. These housing and environmental risk factors have been widely associated with adverse health effects (Table 1) [1] and should be ascertained in future national surveys. The four HEQI domains of dampness and mold, low indoor temperatures, household crowding, and inadequate water and sanitation were well-captured by the AHS and should be continued in future surveys to allow for longitudinal assessments. The remaining six HEQI domains, indoor combustion sources, pest and allergens, lead paint risk, high indoor temperatures, injury hazards, and ventilation, roughly approximated the underlying risks and were likely imprecise. In particular, the indoor combustion sources domain could be improved with more direct questions about the frequency and intensity of source activities such as cooking, smoking, candle use, incense use, and cleaning that can contribute to higher indoor air pollution concentrations [14]. Questions about appliance efficiency, furniture and flooring types, and the types of ventilation controls like kitchen and bathroom exhaust fans are also important determinants of indoor air quality. For the pests and allergens domain, the AHS only asked about the presence and frequency of rodents and cockroaches. Future surveys should consider other types such as bed bugs and pet dander [16]. For the injury hazards domain, only about electrical hazards and building integrity were collected in the AHS across multiple survey years. Information about smoke and carbon monoxide detectors, stairs and window railings, pool safety, and chemical storage have been asked in previous AHS cycles and discontinued in recent years or are only asked among a sub-sample of households. Going forward, these questions should be asked on a routine basis and among all households.

Our HEQI development has several limitations that could be addressed with improved data collection. The domain for high indoor temperatures was inferred from AHS items on central air and window air conditioning. High indoor temperatures could be influenced by ambient temperatures and humidity, which could not be ascertained in the AHS [32, 63]. Future surveys should include direct questions about heat stress (e.g., unit was uncomfortably hot for 24+ hours) and usual temperature in the home. The ventilation domain should include more questions about the types and performance of natural and mechanical ventilation controls (e.g., bathroom and kitchen exhausts, number of doors and windows, frequency of window opening). In addition, information about climate conditions, basement foundation type, and weatherization are needed to more accurately estimate building leakage. Lastly, routine data collection about energy efficiency (e.g., insulation, solar panels, Energy Star ratings) is important to track cost-savings and understand adaptation strategies for climate change.

The AHS data is also subject to limitations common to national surveys. AHS items were self-reported and may be susceptible to recall error or social desirability bias. The AHS survey design is based on a federally-sponsored in-person and telephone survey, which may underestimate households in precarious or temporary housing arrangements. These issues could impact the precision of our findings and/or underestimate the prevalence of the hazards identified. Lastly, the AHS is conducted predominantly in English and Spanish languages, which applied to 95% of households in the 2019 AHS data. Therefore, findings may not be generalizable to the small proportion of non-English speaking U.S. households.

In spite of these limitations, a major strength of the HEQI is its accessibility for widespread adoption. The HEQI is based on AHS data that is nationally-representative, publicly-available, and collected biennially by the U.S. Census Bureau. In addition, AHS items in the HEQI are available across survey cycles since 2011 and asked of all occupied households. Therefore, the HEQI can be used in longitudinal analyses to evaluate HEQI trends across U.S. households.

5. Conclusions

Our study demonstrated the utility of the HEQI for tracking and evaluating multiple healthy housing domains and identifying vulnerable households at the national level. HEQI findings can contribute to national annual housing reports, such as the Worst Case Housing Needs report to Congress [64] and the Joint Center for Housing Studies' State of the Nation's Housing report [62]. In addition, the HEQI expands the portfolio of housing and health disparities research to include environmental health risk factors in the home. Previous studies documenting socioeconomic, racial/ethnic, and nativity-related disparities in housing quality relied on single AHS items or indices that have limited environmental risk factors [7, 65–67]. In addition, national surveys such as the AHS, American Community Survey (ACS), U.S. Rental Housing Finance Survey (RHFS), and Residential Energy Consumption Survey (RECS) as well as physical inspections databases like U.S. HUD's Real Estate Assessment Center (REAC) lack key data on environmental risk factors, which then severely limits our ability to identify vulnerable households and inform areas for intervention. Often these existing data systems were created with specific design and research goals in mind that may be distinct from a health-based approach. The HEQI can be used to inform gaps in these federal data collection programs for capturing health-relevant attributes. For example, HEQI findings can inform how REAC and other systems could be modified or improved to best capture development- or unit-level data that could be used for hazard identification or program evaluation. Similarly, the inclusion of HEQI risk factors in the ACS data would enable better understanding of how population and neighborhood-level attributes shape residential environmental exposures.

In conclusion, while we recognize that the addition of residential environmental health data to national surveys may pose financial and administrative challenges, mounting evidence linking residential environmental exposures with adverse health outcomes underscore the need for this data. Furthermore, the most disadvantaged households continue to bear the disproportionate burden of substandard housing conditions, hazardous exposures, and related adverse health outcomes. National environmental health indices that can capture the multiple dimensions of healthy housing enable opportunities to identify vulnerable households and appropriately tailor interventions. Additionally, these indices can be used to benchmark progress over time. Improving housing and indoor environmental quality is a key facet of environmental and climate justice and on the path to advancing health equity.

Abbreviations

AHS American Housing Survey

HEQI Housing and Environmental Quality Index

HUD U.S Office of Housing and Urban Development

PQI Poor Quality Index

REAC Real Estate Assessment Center

WHO World Health Organization

Declarations

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CRediT authorship contribution statement

MyDzung T. Chu: Conceptualization; Methodology; Data curation; Formal analysis; Software; Validation; Roles/Writing - original draft; Writing - review & editing. **Andrew Fenelon:** Conceptualization; Methodology; Writing - review & editing. **Judith Rodriguez:** Methodology; Writing - review & editing. **Ami R. Zota:** Conceptualization; Methodology; Writing - review & editing; Supervision, Resources. **Gary Adamkiewicz:** Conceptualization; Methodology; Roles/Writing - original draft; Writing - review & editing; Supervision.

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Availability of data and materials

National Public Use Flat (PUF) files for the American Housing Survey can be found at: <https://www.census.gov/programs-surveys/ahs/data.html>. DOIs and hyperlinks are included throughout the literature cited.

The American Housing Survey 2019 National Public Use Flat (PUF) dataset supporting the conclusions of this article is available in the U.S. Census survey data repository, [<https://www.census.gov/programs-surveys/ahs/data.html>].

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

None. The authors declare that they have no actual or potential competing financial interests and that their freedom to design, conduct, interpret, and publish research is not compromised by any controlling sponsor.

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Tables

Table 1
World Health Organization (WHO) Recommended Housing and Housing Domains

No.	WHO Housing and Health Domains	WHO References	Examples of hazards	Health effects	Data availability in the AHS ^a
1	Indoor air quality	1,5,6,14	Particulate matter, carbon monoxide, volatile organic compounds, methane, black carbon, nitrous oxides	Cardiovascular, stroke, respiratory (e.g., chronic obstructive pulmonary disease, asthma, lung cancer), neurological, shortened life expectancy, poisonings, mortality.	Available
2	Dampness and mold	1,15	Bacteria and fungi	Respiratory (e.g., allergies, asthma, hypersensitivity), immunological reactions	Available
3	Pests and allergens	16	Transport of endoparasites vector and/or pathogenic organisms	Respiratory (e.g., asthma), allergies, conjunctivitis, rodent-related diseases (e.g., plague, leptospirosis, rickettsia pox, rat-bite fever, dysentery, typhus).	Available
4	Lead	1,5	Lead poisoning	Neurotoxicant, impairments to children's cognitive and social development.	Available
5	High indoor temperatures	1	Extreme heat stress	All-cause mortality, heat stroke, dehydration, heart and kidney co-morbidities. Older adults (65+) vulnerable.	Limited
6	Low indoor temperatures	1,5,17	Extreme cold stress Increased risk of dampness and mold	Respiratory (e.g., chronic obstructive pulmonary disease, asthma, lung inflammation), cardiovascular (e.g., vasoconstriction, chest pain, high blood pressure), strokes, all cause-mortality, depression, subarachnoid hemorrhage.	Available
7	Household crowding	1,5	Resuspension of air pollutants, infectious disease transmission, poor sanitation, noise, second-hand tobacco smoke.	Poor mental health, sleep disturbance, gastroenteritis and diarrheal diseases, infectious disease, behavioral issues (e.g., hostility), domestic violence, impaired children's cognitive development.	Available
8	Injury hazards	1,5,18	Fires, falls, drowning, poor storage or labelling of hazardous chemicals	Electrocutions, burns, fractures, lacerations, chemical poisonings, hospitalization, mortality.	Available
9	Inadequate water and sanitation	1,19,20	Endoparasites vectors, pathogenic organisms, toxic chemicals, metals, particles (e.g. lead, arsenic).	Cholera, diarrhea illnesses, hepatitis A, typhoid, polio, lead poisoning, dehydration.	Available
10	Ventilation	1	Low leakage traps air pollutants indoors. Higher leakage increase risk for dampness, mold, pest problems, and infiltration of air pollution.	<i>See health effects related to WHO domains on indoor air quality, dampness and mold, pest and allergens, high and low indoor temperatures.</i>	Limited
11	Radon ^b	1,5,21	Radon	Lung cancer, mortality.	Unavailable
12	Pesticides	1,16,22	Fungicides, herbicides, biocides	Headaches, vertigo, nausea, muscular weakness, endocrine disruption, carcinogenesis, neurological and reproductive effects.	Unavailable
13	Asbestos	1,23	Asbestos	Respiratory, cancer (e.g. asbestosis, mesothelioma).	Unavailable
14	Noise	1,5,24	Unwanted noise, frequency and loudness, beyond 40 dB (or 55 dB for short-term)	Cardiovascular, cognitive impairments, sleep disturbance. Long-term effects: Hearing damage, psychological and physiological distress, increased allostatic load.	Unavailable
15	Housing accessibility for people with functional impairments ^c	1	Safety: fires, slips/trips. Drowning	Electrocutions, burns, falls, chemical poisonings, burns, drowning, fractures, hospitalization, mortality.	Unavailable

^a Data availability was based on questions asked in the national AHS from 2011-2019 surveys of occupied units. Available = The AHS asked question(s) directly relevant to this domain and asked in multiple years; Limited = The AHS did not ask direct question(s) for this domain but the data could be combined with external sources to approximate this domain; Unavailable = No AHS questions were asked relevant to this domain.

^b AHS asked questions about radon in AHS subsamples.

^c AHS asked questions on housing accessibility in specific AHS years and subsamples, and not for all five survey years, 2011-2019.

Table 2

Housing and Environmental Quality Index (HEQI): Frequency distribution of AHS items by domain and availability in established housing indices, American Housing Survey 2019 national public file (N=51,993)

No.	WHO Domains and available AHS items	Sample prevalence N (%)	AHS items in Poor Quality Index (PQI)? ^a	AHS items in the Adequacy Index? ^b
1	Indoor air quality	32,226 (62.0%)		
	Indoor combustion sources			
	Cooking fuel: Has piped gas or LP gas	22,137 (42.6%)	No	No
	Heating fuel: Kerosene or other liquid fuel	107 (0.2%)	Yes ¹	No
	Heating fuel: Coal or coke	17 (0.0%)	No	No
	Heating fuel: Wood	518 (1.0%)	No	No
	Heating type: Cooking stove to heat home	31 (0.1%)	No	No
	Heating type: Fireplace without inserts	23 (0.0%)	No	No
	Heating type: Has unvented room heaters	213 (0.4%)	No ¹	No
	Unit has a useable fireplace	19,137 (36.8%)	No	No
2	Dampness and mold	8,012 (15.4%)		
	Mold (in last 12 months)			
	Mold in bathroom	721 (1.4%)	No	No
	Mold in bedroom	358 (0.7%)	No	No
	Mold in kitchen	248 (0.5%)	No	No
	Mold in living room	191 (0.4%)	No	No
	Mold in other room	224 (0.4%)	No	No
	Dampness (in last 12 months)			
	Water leak from roof	2,069 (4.0%)	Yes	Yes
	Water leak from wall or closed window or door	841 (1.6%)	Yes	Yes
	Water leak from basement	1,223 (2.4%)	Yes	Yes
	Water leak with unknown inside source	155 (0.3%)	Yes	Yes
	Water leak from broken water heater	344 (0.7%)	No	Yes? ²
	Water leak from somewhere else outside	592 (1.1%)	Yes	Yes
	Water leak from pipes leaking	1,579 (3.0%)	Yes	Yes
	Water leak from own plumbing fixtures	934 (1.8%)	Yes	Yes
	Water leak from somewhere else inside	1,038 (2.0%)	Yes	Yes
3	Pests and allergens	2,313 (4.4%)		

^a Eggers, F. J., & Moumen, F. (2013b). American Housing Survey: A Measure of (Poor) Housing Quality. US Department of Housing and Urban Development. Access at: www.census.gov/programs-surveys/ahs/research/publications/PoorHousingQuality.html.

^b Eggers, F. and Moumen, F. (2013a). American Housing Survey: Housing adequacy and quality as measured by the AHS. Available at SSRN 2284174. 2013 Mar 1. Access at: <https://www.census.gov/content/dam/Census/programs-surveys/ahs/publications/HousingAdequacy.pdf>.

^c Development adapted from Chan, W. R., Joh, J., & Sherman, M. H. (2013). Analysis of air leakage measurements of US houses. Energy and Buildings, 66, 616-625.

¹ PQI and ZADEQ only asked about 'Main heating equipment as unvented kerosene heater(s)'

² In ZADEQ, unclear which inside and outside water leak questions were used. For comparison, we assumed all questions related to water leaks were included.

No.	WHO Domains and available AHS items	Sample prevalence N (%)	AHS items in Poor Quality Index (PQI)? ^a	AHS items in the Adequacy Index? ^b
	Evidence of rodents (daily or weekly)	836 (1.6%)	Yes ³	Yes
	Evidence of cockroaches (daily or weekly)	1,713 (3.3%)	No	No
4	Lead	805 (1.5%)		
	Lead paint risk: Peeling paint larger than 8x11 inches AND year built before 1980	805 (1.5%)	Yes ⁴	Yes ⁴
5	High indoor temperatures	5,482 (10.5%)		
	No central or window air conditioning unit	5,482 (10.5%)	No	No
6	Low indoor temperatures	2,938 (5.7%)		
	Unit was uncomfortable cold for 24+ hours	2,938 (5.7%)	Yes	Yes
	Main heating equipment broke down 1+ times for 6 hours or more	1,108 (2.1%)	Yes	Yes
7	Household crowding	252 (0.5%)		
	Severe crowding: Occupancy-to-room Ratio > 1.5	252 (0.5%)	No	No
8	Injury hazards	6,014 (11.6%)		
	Electrical			
	No electrical wiring	19 (0.0%)	Yes	Yes
	Electrical wiring exposed	1,396 (2.7%)	Yes	No
	Not every room has working electrical plug	1,048 (2.0%)	Yes	No
	Fuse(s) blown or circuit breakers tripped 2+ times in the last 3 months	1,711 (3.3%)	Yes	Yes
	Structural Integrity			
	Floor has holes	547 (1.1%)	Yes	Yes
	Walls or ceilings have open holes or cracks wider than dime	2,568 (4.9%)	Yes	Yes
9	Inadequate water and sanitation	6,077 (11.7%)		
	Water quality and quantity			
	Unit has no hot/cold running water	120 (0.2%)	Yes	Yes
	Unit without running water in last 90 days	1,361 (2.6%)	Yes ⁵	Yes ⁵
	Non-public water source (e.g. wells)	3,874 (7.5%)	No	No
	Poor sanitation			
	1+ toilet breakdowns within last 3 months that lasted 6+ hours	659 (1.3%)	Yes	Yes
	1+ sewer breakdowns within last 3 months that last 6 hours or more	497 (1.0%)	Yes	No
	Unit has NO bathtub OR shower OR no flush toilet	48 (0.1%)	Yes	Yes

^a Eggers, F. J., & Moumen, F. (2013b). American Housing Survey: A Measure of (Poor) Housing Quality. US Department of Housing and Urban Development. Access at: www.census.gov/programs-surveys/ahs/research/publications/PoorHousingQuality.html.

^b Eggers, F. and Moumen, F. (2013a). American Housing Survey: Housing adequacy and quality as measured by the AHS. Available at SSRN 2284174. 2013 Mar 1. Access at: <https://www.census.gov/content/dam/Census/programs-surveys/ahs/publications/HousingAdequacy.pdf>.

^c Development adapted from Chan, W. R., Joh, J., & Sherman, M. H. (2013). Analysis of air leakage measurements of US houses. Energy and Buildings, 66, 616-625.

¹ PQI and ZADEQ only asked about 'Main heating equipment as unvented kerosene heater(s)'

² In ZADEQ, unclear which inside and outside water leak questions were used. For comparison, we assumed all questions related to water leaks were included.

No.	WHO Domains and available AHS items	Sample prevalence N (%)	AHS items in Poor Quality Index (PQI)? ^a	AHS items in the Adequacy Index? ^b
	Unit does NOT have working kitchen sink	92 (0.2%)	Yes ⁶	No
10	Ventilation	1,624 (3.1%)		
	High building leakage ^c : Normalized leakage > 2.5	1,624 (3.1%)	No	No
^a Eggers, F. J., & Moumen, F. (2013b). American Housing Survey: A Measure of (Poor) Housing Quality. US Department of Housing and Urban Development. Access at: www.census.gov/programs-surveys/ahs/research/publications/PoorHousingQuality.html .				
^b Eggers, F. and Moumen, F. (2013a). American Housing Survey: Housing adequacy and quality as measured by the AHS. Available at SSRN 2284174. 2013 Mar 1. Access at: https://www.census.gov/content/dam/Census/programs-surveys/ahs/publications/HousingAdequacy.pdf .				
^c Development adapted from Chan, W. R., Joh, J., & Sherman, M. H. (2013). Analysis of air leakage measurements of US houses. Energy and Buildings, 66, 616-625.				
¹ PQI and ZADEQ only asked about 'Main heating equipment as unvented kerosene heater(s)'				
² In ZADEQ, unclear which inside and outside water leak questions were used. For comparison, we assumed all questions related to water leaks were included.				

³ In the PQI, question was grouped with the component 'Inside structural or other problems'

⁴ In the PQI, the only AHS item used was if unit has an area of peeling paint larger than 8 by 11 inches, irrespective of year built.

⁵ This question not asked of units with no hot/cold running water. The PQI counts each time the unit "is completely without water".

⁶ In the PQI, question was grouped with the component 'Kitchen Problems'

Table 3
Summary of cumulative and domain-specific HEQI counts, overall and by homeownership and building type, American Housing
Survey 2019 national public file (N=51,993)

	All Households	Homeowner	Non-homeowners ^a	Single-family	Multifamily
	(N=51,993)	(N=31,131)	(N=20,862)	(N=35,977)	(N=16,016)
Cumulative					
Count ≥ 1, n (%)	41,012 (78.9%)	26,349 (84.6%)	14,663 (70.3%)	30,164 (83.8%)	10,848 (67.7%)
Mean (Min, Max)	1.6 (0, 19)	1.7 (0, 16)	1.4 (0, 19)	1.7 (0, 16)	1.3 (0, 19)
Indoor combustion sources					
Count ≥ 1, n (%)	32,226 (62.0%)	22,970 (73.8%)	9,256 (44.4%)	25,900 (72.0%)	6,326 (39.5%)
Mean (Min, Max)	0.81 (0, 4.0)	1.0 (0, 4.0)	0.51 (0, 4.0)	0.98 (0, 4.0)	0.43 (0, 3.0)
Dampness and mold ^b					
Count ≥ 1, n (%)	8,012 (15.4%)	4,531 (14.6%)	3,481 (16.7%)	5,541 (15.4%)	2,471 (15.4%)
Mean (Min, Max)	0.20 (0, 9.0)	0.18 (0, 8.0)	0.24 (0, 9.0)	0.20 (0, 8.0)	0.22 (0, 9.0)
Pests and allergens					
Count ≥ 1, n (%)	2,313 (4.4%)	698 (2.2%)	1,615 (7.7%)	1,108 (3.1%)	1,205 (7.5%)
Mean (Min, Max)	0.049 (0, 2.0)	0.024 (0, 2.0)	0.087 (0, 2.0)	0.034 (0, 2.0)	0.084 (0, 2.0)
Lead Paint Risk					
Count ≥ 1, n (%)	805 (1.5%)	360 (1.2%)	445 (2.1%)	501 (1.4%)	304 (1.9%)
Mean (Min, Max)	0.015 (0, 1.0)	0.012 (0, 1.0)	0.021 (0, 1.0)	0.014 (0, 1.0)	0.019 (0, 1.0)
High indoor temperatures					
Count ≥ 1, n (%)	5,482 (10.5%)	2,566 (8.2%)	2,916 (14.0%)	3,043 (8.5%)	2,439 (15.2%)
Mean (Min, Max)	0.11 (0, 1.0)	0.082 (0, 1.0)	0.14 (0, 1.0)	0.085 (0, 1.0)	0.15 (0, 1.0)
Low indoor temperatures					
Count ≥ 1, n (%)	2,938 (5.7%)	1,497 (4.8%)	1,441 (6.9%)	1,941 (5.4%)	997 (6.2%)
Mean (Min, Max)	0.078 (0, 2.0)	0.065 (0, 2.0)	0.097 (0, 2.0)	0.073 (0, 2.0)	0.088 (0, 2.0)
Severe crowding					
Count ≥ 1, n (%)	252 (0.5%)	57 (0.2%)	195 (0.9%)	98 (0.3%)	154 (1.0%)
Mean (Min, Max)	0.0048 (0, 1.0)	0.0018 (0, 1.0)	0.0093 (0, 1.0)	0.0027 (0, 1.0)	0.0096 (0, 1.0)
Injury hazards					
Count ≥ 1, n (%)	6,014 (11.6%)	3,184 (10.2%)	2,830 (13.6%)	4,021 (11.2%)	1,993 (12.4%)
Mean (Min, Max)	0.14 (0, 5.0)	0.12 (0, 5.0)	0.17 (0, 5.0)	0.13 (0, 5.0)	0.16 (0, 5.0)
Inadequate Water and sanitation					
Count ≥ 1, n (%)	6,077 (11.7%)	4,220 (13.6%)	1,857 (8.9%)	4,812 (13.4%)	1,265 (7.9%)
Mean (Min, Max)	0.13 (0, 4.0)	0.14 (0, 4.0)	0.10 (0, 4.0)	0.14 (0, 4.0)	0.090 (0, 4.0)
High building leakage					
Count ≥ 1, n (%)	1,624 (3.1%)	316 (1.0%)	1,308 (6.3%)	220 (0.6%)	1,404 (8.8%)
Mean (Min, Max)	0.031 (0, 1.0)	0.010 (0, 1.0)	0.063 (0, 1.0)	0.0061 (0, 1.0)	0.088 (0, 1.0)
^a The non-homeowner group includes renters (n=20,205) and those occupied without payment of rent (n=657).					
^b Missing nine respondents.					

Table 4

Associations between HEQI domain counts and AHS housing characteristics, American Housing Survey 2019 PUF (N=51,993)

	Rating of unit as a place to live	Year built	Monthly rent costs
	Ordinal scale: 1: Worse place to live, 10: Best place to live	Ordinal categories: <1960 (ref), 1960-1969 1970-1979, 1980-1989 1990-1999, 2000+	Dollars: Range \$4-\$11,700
	Odds Ratio (95% CI)	Odds Ratio (95% CI)	Relative ratio ^a (95% CI)
Indoor combustion sources	1.09 (1.06, 1.12)	1.03 (1.01, 1.06)	1.09 (1.06, 1.11)
Dampness and mold	0.68 (0.66, 0.70)	0.81 (0.79, 0.84)	1.01 (0.99, 1.02)
Pests and allergens	0.46 (0.42, 0.49)	0.70 (0.65, 0.75)	0.96 (0.92, 0.99)
Lead paint risk	0.50 (0.43, 0.57)	^b NA	0.93 (0.86, 1.01)
High indoor temperature	0.74 (0.70, 0.78)	0.45 (0.42, 0.47)	1.00 (0.97, 1.03)
Low indoor temperature	0.80 (0.76, 0.84)	0.80 (0.77, 0.84)	0.94 (0.91, 0.97)
Severe crowding	0.70 (0.55, 0.89)	0.89 (0.70, 1.11)	1.26 (1.13, 1.42)
Injury hazards	0.66 (0.64, 0.69)	0.89 (0.85, 0.92)	0.97 (0.95, 0.99)
Inadequate water and sanitation	1.06 (1.01, 1.11)	1.16 (1.11, 1.21)	1.00 (0.96, 1.03)
High building leakage	1.27 (1.15, 1.41)	0.26 (0.23, 0.28)	0.77 (0.73, 0.80)
^a Estimates represent the mean change in monthly rent costs per 1-count increase in a HEQI risk factor.			
^b Data not shown since the lead paint risk domain includes year of construction.			

Bolded are statistically significant associations (p<0.05).

Models adjusted for all HEQI domains simultaneously to account for their potential correlations, as well as householder race/ethnicity, education, number of rooms in unit, multifamily status, US Census divisions, and survey year.

Table 5

Distribution of U.S. households with at least one risk factor identified by the Housing and Environmental Quality Index (HEQI), Poor Quality Index (PQI), and Adequacy Index across domains, American Housing Survey 2019 PUF (N=51,993)

	HEQI		PQI	Difference		Adequacy Index	Difference	
				PQI - HEQI			Adequacy Index - HEQI	
	Sample N	Weighted N (SE) ^a	Weighted N (SE) ^a	Count	Percent	Weighted N ^a	Count	Percent
Cumulative	41,012	92,043 (184,371)	34,314 (142)	-57,730	-63%	30,646 (143)	-61,397	-67%
Indoor combustion sources	32,226	71,962 (195,257)	311 (17)	-71,651	-100%	0	-71,962	-100%
Dampness and mold	8,012	18,699 (128,923)	16,955 (123)	-1,745	-9%	16,954 (123)	-1,745	-9%
Pests and allergens	2,313	4,949 (69,738)	1,946 (45)	-3,001	-61%	1,946 (45)	-3,003	-61%
Lead paint risk	805	1,952 (48,166)	2,423 (54)	471	+19%	2,423 (54)	471	+19%
High indoor temperature	5,482	10,344 (139,743)	NA	-10,344	0%	NA	-10,344	0%
Low indoor temperature	2,938	6,841 (75,754)	6,841 (76)	0	100%	6,841 (76)	0	100%
Severe overcrowding	252	507 (18,516)	NA	-507	-100%	NA	-507	-100%
Injury hazards	6,014	13,959 (127,360)	13,959 (127)	0	0%	10,073 (98)	-3,887	-28%
Inadequate water and sanitation	6,077	16,802 (159,690)	5,455 (54)	-11,346	-68%	4,525 (55)	-12,277	-73%
High building leakage	1,624	2,813 (43,086)	NA	-2,813	-100%	NA	-2,813	-100%
^a Weighted estimates are per 1,000 households, rounded to nearest thousandth.								
^b The PQI and Adequacy index did not have a lead paint risk domain. They did include the AHS item of 'Peeling paint larger than 8x11 inches', which we used to calculate weighted estimates and estimate differences with the HEQI.								

Supplementary Files

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- [ChuSupplementalData.docx](#)