Long-term Association between Urban Air Ventilation and Mortality in Hong Kong

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Highlights

- First study of the association of area-level urban air ventilation with mortality.
- Poorer ventilation was significantly associated with higher all-cause mortality.
- Asthma mortality had the strongest association with poorer ventilation.
- Poor ventilation can lessen pollutant dispersal and worsen urban heat islands.
- Smarter urban design can improve urban air ventilation.

Abstract

While associations between population health outcomes and some urban design characteristics, such as green space, urban heat islands (UHI), and walkability, have been well studied, no prior studies have examined the association of urban air ventilation and health outcomes. This study used data from Hong Kong, a densely populated city, to explore the association between urban air ventilation and mortality during 2008-2014. Frontal area density (FAD), was used to measure urban ventilation, with higher FAD indicating poorer ventilation, due to structures blocking wind penetration. Negative binomial regression models were constructed to regress mortality counts for each 5-year age group, gender, and small area group, on small area level variables including green space density, population density and socioeconomic indicators. An interquartile range increase in FAD was significantly associated with a 10% (95% confidence interval (CI) 2% to 19%, p=0.019) increase in all-cause mortality and a 21% (95% CI: 2% to 45%, p=0.030) increase in asthma mortality, and non-significantly associated with a 9% (95% CI:-1% to 19%, p=0.073) in cardio-respiratory mortality. Better urban ventilation can help disperse vehicle-related pollutants and allow moderation of UHIs, and for a coastal city may allow moderation of cold temperatures. Urban planning should take ventilation into account. Further studies on urban ventilation and health outcomes from different settings are needed.

Keywords

Wind; air ventilation; mortality; health; urban design

Ethics approval

Ethics approval was obtained from the Survey and Behavioural Research Ethics Committee of the Chinese University of Hong Kong (reference: 14121916).

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Main finding

Geographic areas of Hong Kong with poorer urban air ventilation, as measured by frontal area density, had higher all-cause, asthma, and breast cancer mortality rates.

Abbreviations

COPD **Chronic Obstructive Pulmonary Disease**

FAD **Frontal Area Density**

GEE **Generalized Estimating Equations**

HKCD **Hong Kong Census & Statistics Department**

IQR **Interquartile Range**

NDVI **Normalized Difference Vegetation Indicator**

SES **Socioeconomic Status**

TPU **Tertiary Planning Unit(s)**

UHI **Urban Heat Island(s)**

1. Introduction

The world's urban population continues to increase rapidly, both in absolute numbers and in percentage terms. In 2018 an estimated 55% of the world's population lived in urban areas compared to 30% in 1950, and this is expected to grow to 68% by 2050 [1]. By 2050 the world's total urban population is expected to increase by 2.5 billion, with 90% of the population growth occurring in Asia and Africa [1]. The rapid increases in urban populations are a challenge for urban development planning, which needs to balance the need for housing, while protecting the environment, preserving and enhancing positive features such as green and blue spaces, and mitigating negative attributes including urban heat islands (UHIs), environmental pollution, and noise.

Prior studies on small area characteristics and mortality have focused mainly on socioeconomic status (SES) indicators. Among urban design characteristics, green space has been the most frequently studied with studies examining associations between residential area green space and mortality giving inconsistent results[2]. In Hong Kong our previous study found that higher coverage of green space was associated with reduced risk of mortality at the small area level[3]. Proposed mechanisms by which green space provision might positively affect health include increased opportunities for physical activity, facilitation of social contacts, recovery from stress [4], and mitigation of urban heat island (UHI) effects [5].

UHIs, are becoming more of an issue due to climate change and increasing urbanization and have been found to increase heat-related health risk in cities[6-8], including Hong Kong[6]. Wind speed has been found to be the most influential meteorological variable affecting UHI intensity, and in addition to decreasing urban temperatures, higher wind speeds can improve air circulation, and dissipate pollutants[9].

Frontal area density (FAD) is a wind direction-dependent measure of building permeability which is used to measure urban air ventilation, with higher FAD meaning poorer ventilation [10]. The FAD used in this paper was especially developed for high density cities and was shown to be very highly correlated with wind velocity ratio at the pedestrian level relative to a reference level of 500 meters[10]. Higher building density and compact building morphology have also been found to be correlated with higher ambient temperatures[11-12], while higher FAD has been associated with stronger urban heat island effects [13], and poorer urban air quality [14-15 -] in Hong Kong. Our prior study reported a positive association of FAD and suicide in Hong Kong [16]. The potential association of urban air ventilation with natural mortality has not been previously examined. However, there are reasons to expect that it could impact health as better urban air ventilation has the potential to disperse locally produced pollutants[15], break up urban heat islands during periods of high temperature[13], and in the case of coastal cities, possibly moderate cold weather if the wind is coming off the ocean. Although Hong Kong is among the most densely populated areas in the world, its urban geography is highly variable, with some areas dominated by compact high-rise buildings, and other consisting of high-rises with more space in between, village houses, farmland, or country parks. The objective of this study was to estimate the area level associations between all-cause and cause-specific mortality and urban air ventilation as measured by FAD, while controlling for age, gender, green space coverage, population density, and small area socioeconomic characteristics.

The methods section of this manuscript presents the nature and sources of the data used in the analyses, including the individual level mortality data, and the small area level data on socioeconomic status and urban characteristics. The results section presents descriptive statistics for important variables and the results of regression analyses showing the association between FAD and mortality, including subgroup analyses, while controlling for important confounders. Finally, in the discussion section we provide potential explanations for the findings, discuss some limitations and suggest some policy implications.

2. Methods

2.1 Mortality and SES data

Datasets containing information on all deaths occurring in Hong Kong from 2008-2014 were obtained from the Hong Kong Census and Statistics Department (HKCSD). Variables available in the dataset included the age, gender, cause of deaths (ICD-10 coded), and tertiary planning unit (TPU) of residence of the decedent. From this data we created mortality counts for the 7-year period for each TPU by 5-year age group (20-24, 25-29, ..., 85+) and gender. Similarly, population counts by TPU, 5-year age group, and gender, and TPU level SES status variables, including median monthly household income, percentage of population over 15 years old with a tertiary education, and percentage of the population over 15 who were unmarried, were also obtained from the HKCSD.

2.2 Urban morphological data

Urban morphological data were extracted from the digital topographic map produced by the Hong Kong Lands Department iB1000 dataset, including land use information, shapefiles with building footprint and height, and road networks. These data were rasterized at 1m resolution into various urban morphological parameters and aggregated for each TPU in order to characterize the built environment of each TPU. FAD is calculated as the total projected area along a particular wind direction of all buildings in a parcel of land divided by the lot area of the land. In this study, 16-wind direction probability weighted FAD was calculated to represent the prevailing wind condition over seasons:

$$FAD = \sum_{\theta=1}^{16} [\frac{A_{F(\theta)}}{A_T}] \cdot P_{(\theta)}$$

where A_T is the lot area of the land parcel, $A_{F(\theta)}$ is the total projected area along a particular wind direction (θ) of all buildings in the land parcel, and $P_{(\theta)}$ is the wind direction probability of the 16 corresponding wind direction (θ). In addition, Normalized Difference Vegetation Index (NDVI) data for the year 2011 were calculated from Landsat-5 satellite images in order to indicate the greenery density for each TPU.

2.3 Statistical analysis

Analyses were restricted to adults > 15 years old. Negative binomial regression models were used to regress mortality counts for each age (5-year groups), gender, and TPU group, on the area level characteristics, with generalized estimating equations (GEE) employed to account for the correlations among mortality counts from the same TPUs. The model equation is:

$$Log(E(D_{ijk})) = \beta_0 + \beta_1 I(age = 20\text{-}24) + \ldots + \beta_{14} I(age = 85+) + \beta_{15} I(female) + log(Pop_{ijk}) + \beta_{16} x_{1k} + \ldots + \beta_{m+15} x_{mk}$$

where D_{ijk} and POP_{ijk} are the number of deaths and person-years, respectively, from 2008-2014 in the i^{th} gender, j^{th} age group, and k^{th} TPU, $x_{1k}, \ldots, x_{mk}$ are TPU level covariates, I(female) is an indicator variable that the counts are for females (reference = males), and I(age = ..) is an indicator that the counts are for a particular age group (reference = 15-19). The TPU level SES variables included the percentage of the population in the TPU that had a tertiary education, the median monthly household income, and the percentage of the population of the TPU that was unmarried. As the main purpose of including these variables was to control for potential confounding of the FAD-mortality association, no model selection procedure was applied and all variables were included in the final model. Negative binomial models were chosen as they are a more flexible way to model count data than Poisson regression models due to the fact that the negative binomial distribution does not require the mean and variance to be equal. Relative risks (RR) associated with a given change in a TPU level covariate Δx were calculated as RR = $Exp[\beta*(\Delta x)]$, and 95% confidence intervals and p-values testing the statistical significance of covariates were calculated using the GEE approach. The following outcomes were separately analyzed: all non-external deaths, deaths due to all cardiorespiratory deaths (ICD-10: I00-I99 and J00-J99), all cardiovascular diseases (ICD-10: I00-I99) with subgroup analyses including ischemic heart disease (ICD-10: I20-I25), acute myocardial infarction (ICD-10: I21), heart failure (ICD-10: I50), and cerebrovascular disease (ICD-10: I60-I69)), all respiratory diseases (J00-J99) with subgroup analyses including pneumonia and influenza (ICD-10: J09-J18), chronic respiratory diseases (including chronic obstructive pulmonary disease (COPD)

(ICD-10: J40-J44, J47) and asthma (ICD-10: J45-J46)), breast cancer (ICD-10: C50), colorectal cancer (ICD-10: C18-C20), lung cancer (ICD-10: C34), lymphoma and hematologic malignancies (ICD-10: C81-C96), diabetes mellitus (ICD-10: E10-E14), renal failure (ICD-10: N17-N19), and dementia (ICD-10:F01-F03). These specific causes of death were chosen a priori. Extensive evidence has shown that cardiorespiratory mortality rises with both hot and cold temperatures [17-21]∴. Extreme temperatures have also been found to be associated with asthma[20], diabetes[18,21], renal failure[18,22], and dementia[23]. Cardiorespiratory[24] and lung cancer[25] mortality have been found to be associated with ambient air pollution. Therefore, urban design characteristics associated with urban climate and pollution was expected to impact on the risk of all these conditions. The other three types of cancer were selected as positive controls and were not expected to be associated with FAD. Separate models by age group (< 75 vs. ≥ 75), gender, and median monthly household income of the area of residence were also fit in order to test whether there was effect modification of the associations between FAD and mortality by these variables. All analyses were performed using the Statistical Analysis System (SAS) statistical software package, version 9.3.

3. Results

3.1 Descriptive statistics

We included 135 TPUs covering the entire Hong Kong territory in the current study. A total of 294,374 deaths were recorded in Hong Kong during 2008-2014, among which 163,572 (55.6%) were male and 188,532 (64.0%) were among those aged 75 years or above. Table 1 shows the descriptive statistics for all-cause and cause-specific mortality as well as for the two built environment variables in this study. Of the selected causes of death, circulatory diseases (24.6%), four types of cancer (16.4%), and pneumonia and influenza (14.9%) accounted for the largest number of deaths. Figure 1 shows scatterplots of the associations between FAD, SES factors, population density, and green space.

Figure 1 Scatterplots, histograms, and Pearson's correlation between frontal area density, socioeconomic factors, population density, and greenery. FAD: frontal area density; NDVI: normalized difference vegetation index; corr: Pearson's correlation coefficient.

3.2 Regression analysis

Table 1 summarizes the relative risks (RRs) corresponding to an interquartile range (IQR) increase in FAD and their 95% confidence intervals (CI) for different groups. After adjusting for SES variables, population density and green space as well as age and gender in the model, FAD was found to be positively associated with all-cause mortality and most types of cause-specific mortality, with significant associations observed for overall mortality, and asthma, and breast cancer-caused deaths. An IQR increase in FAD was associated with 10% (95% CI 1.02-1.19, p = .019) increase in the risk of all-cause mortality and a 9% (95% CI 0.99, 1.19) for cardiorespiratory deaths. Further breakdown of cardiorespiratory deaths showed that an IQR increase in FAD was associated with a 7% (95% CI: -3%, 18%) increase in cardiovascular mortality, with roughly similar increased risks for subgroups, and a 9% (95% CI: -1%, 21%) increase in respiratory mortality with subgroup increases ranging from 21% (95% CI 1.02-1.45) for asthma deaths to 7% (-5%, 20%) and 2% (-10%, 14%) for mortality due to pneumonia and influenza and COPD death, respectively. Regarding cancer mortality, a 3% (95% CI 0.94-1.12) increase in the risk of death due to lung cancer was found, while among those chosen as positive controls, the risk of colorectal cancer deaths was slightly decreased, -3% (95% CI: -10%, 5%), while a modest increase was found for deaths due to lymphoma and hematologic malignancies, 2% (-6%, 11%), and a strong and significant increase was found for the risk of breast cancer-caused deaths, 10% (95% CI: 1%, 22%). In the main model, unmarried status and higher household income were found to be significantly associated with higher mortality rate whereas higher education was significantly associated with decreased risk for mortality. A positive but non-significant association was found for population density and no apparent association was observed for NDVI.

We also stratified the analyses by gender, age, and monthly household income to explore the possible effect modification (Figure 3). Significant associations were observed among males, those aged younger than 75 years, and those living in wealthier districts with an increased RR of 1.10 (95% CI 1.01-1.20), 1.11 (95% CI 1.03-1.20), and 1.18 (95% CI 1.06-1.31), respectively (Table 1).

Table 1 Number of deaths and relative risks of an interquartile range increase in frontal area density for different population groups and causes of death

	N. of deaths	***Relative Risk***	***P-value***
All-cause			
Overall	294,374	**1.10 (1.02,1.19)**	**0.019**
Male	163,572	**1.10 (1.01,1.20)**	**0.021**
Female	130,802	1.08 (0.99,1.18)	0.063
Age<75	105,842	**1.11 (1.03,1.20)**	**0.007**
Age≥75	188,532	1.04 (0.95,1.15)	0.389
Monthly household income<$2500	149,881	1.06 (0.92,1.22)	0.450
Monthly household income≥$2500	144,493	**1.18 (1.06,1.31)**	**0.003**
Cause-specific			
All cardiorespiratory	133,753	1.09 (0.99,1.19)	0.073
All cardiovascular	72,471	1.07 (0.97,1.18)	0.156
Ischemic heart disease	29,990	1.06 (0.96,1.16)	0.235
Acute myocardial infarction	13,152	1.05 (0.95,1.17)	0.323
Cerebrovascular disease	23,411	1.08 (0.97,1.20)	0.137
Heart failure	5,731	1.07 (0.95,1.21)	0.245
All respiratory	61,282	1.09 (0.99,1.21)	0.089

Chronic obstructive pulmonary disease	12,728	1.02 (0.90,1.14)	0.788
Asthma	598	**1.21 (1.02,1.45)**	**0.031**
Pneumonia & Influenza	43,907	1.07 (0.95,1.20)	0.285
Lung cancer	26,097	1.03 (0.94,1.12)	0.545
Colorectal cancer	12,901	0.97 (0.90,1.05)	0.504
Breast cancer	3,980	**1.10 (1.01,1.22)**	**0.042**
Lymphoma & hematologic malignancies	5,302	1.02 (0.94,1.11)	0.556
Diabetes mellitus	3,103	1.06 (0.92,1.21)	0.446
Renal disease	10,754	1.02 (0.92,1.13)	0.750
Dementia	5,620	1.05 (0.88,1.27)	0.575

Remarks: bold font indicates significant results at the significance level of 0.05

4. Discussion

To the authors' knowledge our study is the first to examine the association between urban ventilation and a health outcome, in this case mortality. Our study found that geographic areas of Hong Kong with poorer urban air ventilation, as measured by frontal area density, had higher all-cause mortality rates after adjusting for area-level socioeconomic characteristics, green space, and population density. In general, the pattern of increases in the various cause-specific mortality rates with poorer ventilation were consistent with our a priori expectations. Risk for cardiorespiratory death, which has been found to be sensitive to both extreme temperatures[17-21] and air pollution levels[24], were higher in areas with poorer ventilation, with asthma mortality being particularly strongly elevated.

Mortality from colorectal cancer and lymphoma and hematologic malignancies were not expected to be associated with urban air ventilation and in fact a very weak, non-significant negative association was found for colorectal cancer and a very weak positive association was found for lymphoma and hematological malignancies. Lung cancer mortality was included as it is a quite common cause of death and to assess whether smoking could be an uncontrolled confounder. We found a weak non-significant elevated risk of lung cancer death in areas with higher FAD. Some increase was expected as pollution[25], but not extreme temperatures, are a risk factor for lung cancer. The fact that a stronger association was not found suggests that those living in areas with poorer ventilation did not have higher smoking rates as smoking is such a dominant risk factor for lung cancer. Surprising findings from our study include a significant positive association between breast cancer risk and FAD, and a weak non-significant association for COPD mortality. Prior studies have found evidence of an association between breast cancer risk and air pollution[26-27], although some studies have not found an association[27], and this could explain the association. As colorectal cancer is by far the most common cause of death among our three 'positive control' groups, taken as a whole the control groups don't show increased mortality as expected.

The FAD measurement we used in our study was specially developed for use in high-density cities predominantly with high-rise buildings [10]. Wind has been far less investigated in environmental epidemiological studies compared to temperature and rainfall. UHI has been found to be associated with increased health risk related to heat exposure, particularly during heatwaves [6-8]. A previous time-series study in Hong Kong found that low wind speeds were strongly associated with higher mortality in areas with higher urban heat island indices[6]. On average Hong Kong has high prevailing wind speed with the potential to lessen the impact of the UHI effect, but the densely built urban environment in some areas of the city prevents these winds from reaching parts of the city[10]. In addition, UHI effect will further elevate the urban air temperature under the various scenarios of global climate change [28] and thus could even worsen its progressive adverse heat-related heath impact. Both simulations and experimental studies have shown a negative association of wind speed with urban heat island intensity and air temperature [29,30]. Better urban design with lower FAD value indicating better air flow penetration is expected to decrease the UHI effect and could further reduce heat-related health risks.

Our study found a non-significant increased mortality risk from influenza/pneumonia in areas with poorer outdoor air ventilation. A systematic review by the World Health Organization has suggested that higher indoor ventilation flow rates could decrease infection rates or outbreaks of airborne diseases in healthcare settings and purpose-built openings such as windows and doors assure the improvement of indoor air quality by natural ventilation [31], and that the success of natural ventilation is dependent on natural forces including outdoor wind speed[32]. The interaction between outdoor environment, the building, and the ventilation system suggests that favorable outdoor air is the first prerequisite for clean and healthy air indoors [32,33]. In addition a recent WHO news release on the topic of Covid-19 and ventilation suggested that the use of natural ventilation through opening of windows should be considered as a way to improve ventilation in indoor public spaces and buildings[34].

Our study found that poorer urban air ventilation was strongly associated with asthma-caused mortality. Our prior study found that asthma hospitalizations in Hong Kong rose with both high and low temperatures and with higher ozone levels[35]. Hong Kong has a humid subtropical climate with mean monthly relative humidity over 70% throughout the year [36]. Indoor sources of moisture include cooking, cleaning, showering or bathing, and doing laundry, and ventilation usually will result in lower moisture levels indoors[37]. With non-ideal wind penetration and indoor ventilation, it’s likely to have high moisture level indoor and thus to develop residential mold that could possibly incur allergic symptoms[37].

Our subgroup analysis indicated that age and SES status were significant effect modifiers. It is possible that the younger generations and those who live in a high-income area facing greater urban life stress would be more vulnerable to worsened living conditions whereas aged people and those living in a less developed and non-wealthy districts could have already become resilient to the already disadvantageous environment. People in the younger age group may also be more frequently exposed to outdoor conditions, compared to those 75 or older who may mostly stay indoors.

Our study results have policy implications. There are many methods by which urban planners can increase the ventilation of densely populated cities, following the general principal that prevailing winds should be able to travel along breezeways and major roads and be able to penetrate into interior parts of the city[38]. New building complexes can be designed such that the axis of the buildings are parallel to the prevailing wind, the arrangement of towers are staggered to allow the towers behind the ‘front row’ facing the prevailing winds to receive the wind, and have adequately sized gaps between the buildings to allow the wind to penetrate[38].

Our study has some limitations. First, like all ecological studies the exposure measurements at the area-level do not apply equally to all individuals living in those areas. As air pollution monitoring data was not available at the TPU level we were unable to directly estimate the potential contribution that higher pollutant concentrations may have made to the higher mortality observed in TPUs with less wind penetration. We note that as there is considerable prior evidence that exposure to higher levels of ambient air pollution is associated with greater mortality for several causes of death. Based on this and the fact that air pollution concentrations in Hong Kong have been found to be higher in areas with less wind availability[15] we feel it is likely that some of the excess mortality observed in areas with less wind penetration is due to higher fine scale pollutant concentrations. However, further studies are needed to more precisely quantify the potential contribution of poorer air pollutant dispersal to increased mortality in areas with higher FAD. In addition, we assumed that the area-level variables, including FAD, NDVI, population density and SES factors, remained unchanged throughout our study period of 7 years. The GEE method we employed has advantage in the accountability of correlations among mortality counts from the same TPUs. However, at the individual level we were only able to control for age and gender. There are other potential individual level confounders such as smoking and diet that could influence mortality.

In conclusion, the present study revealed the association between mortality and indicator for urban wind penetration, particularly for certain causes of death and specific subgroups. With rapid urbanization and aging trend worldwide, strategic and healthy city planning is desired to alleviate the potential adverse impact of unfavorable environment to promote population health in a densely populated city on an evidence-based basis.

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Conflicts of interest

The authors declare they have no actual or potential competing interests.

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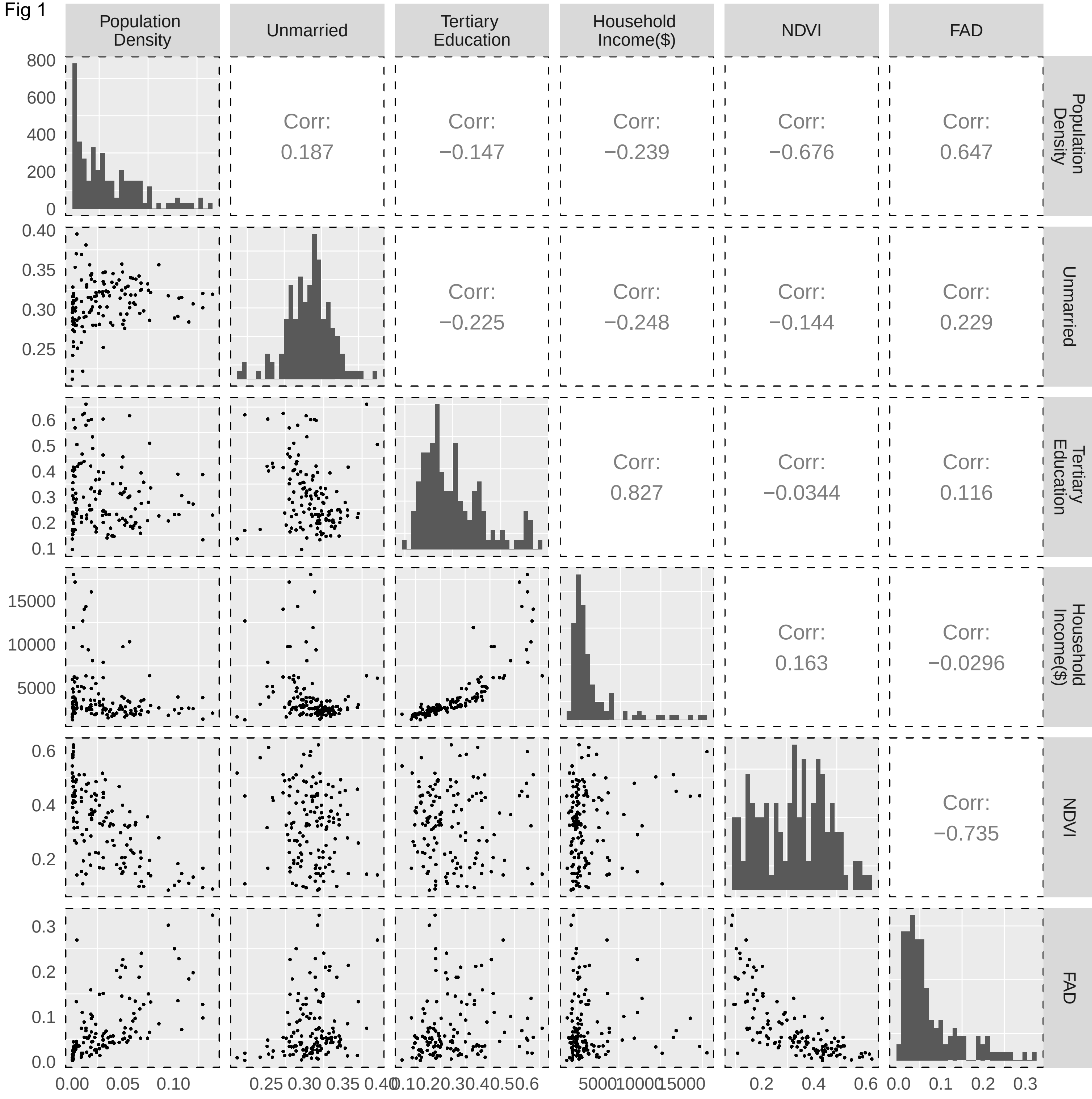
Fig 1


Population Density
Unmarried
Tertiary Education
Household Income($)
NDVI
FAD
Corr: 0.187
Corr: −0.147
Corr: −0.239
Corr: −0.676
Corr: 0.647
Corr: −0.225
Corr: −0.248
Corr: −0.144
Corr: 0.229
Corr: 0.827
Corr: −0.0344
Corr: 0.116
Corr: 0.163
Corr: −0.0296
Corr: −0.735

Graphical abstract

This figureshows the relative risks for mortality for an interquartile range increase in area level frontal area density corresponding to an interquartile range decrease in urban air ventilation.