Air quality in Tehran, Iran: Evaluating acute health effects and modeling the long-term spatial variability

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Dedication:

I would like to dedicate this PhD dissertation to my father, Mr. Rasoul Amini, and all other innocent victims of Sardasht 1987 chemical bombardment

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Abbreviations

AQCC	Air Quality Control Company
AQI	Air Quality Index
BTEX	Benzene, toluene, ethylbenzene, and xylenes
CI	Confidence interval
CO	Carbon monoxide
DLNM	Distributed lag non-linear modeling
DOE	Department of Environment
GIS	Geographic Information System
HIC	High income country
LMIC	Low and middle income country
LOOCV	Leave one out cross validation
LUR	Land use regression
MOH	Ministry of Health and Medical Education
NO2	Nitrogen dioxide
O3	Ozon
PM	Particulate matter
PM10	Particulate matter less than 10 µm
PM2.5	Particulate matter less than 2.5 µm
RMN	Regulatory monitoring network
RR	Relative risk
SO2	Sulfur dioxide
Tehran SEPEHR	Tehran Study of Exposure Prediction for Environmental Health Research
VOCs	Volatile organic compounds
WHO	World Health Organization

Abstract

The burden of disease due to air pollution can be very large because of its acute and chronic effects. This dissertation focused on these two key challenges in the megacity of Tehran, Iran. First, it assessed short-term exposure to ambient air pollutants and their association with daily mortality. Second, it assessed long-term exposures for different air pollutants, which is a prerequisite for the investigation of their chronic health effects. The first part found that the effect of air pollutants on mortality was immediate, and that it increased steadily over a period of weeks. The second part found that concentrations of various air pollutants were very high in Tehran, comparable with those reported for other megacities in Asia. Further, spatial land-use regression (LUR) models were developed for multiple pollutants, and showed that the city center was the most polluted area. Even so, more than 80% of Tehran had benzene concentrations above air quality standard of 5 $\mu g/m^3$ set by European Union and Iranian Government. The thesis also included a systematic review of the global literature on LUR models for volatile organic compounds and found that the study in Tehran has been the largest to assess all BTEX (benzene, toluene, ethylbenzene, and xylenes) species in a megacity. The methods and models developed for this PhD dissertation opened up new avenues for the next generation of air pollution monitoring, modelling, and epidemiology in Iran.

Introduction

A large body of research conducted primarily in Europe and North America—and not much yet from developing countries—demonstrated that cities with more air pollution have higher morbidity and mortality rates than those with less air pollution (Beelen et al., 2014; Krewski et al., 2000; Miller et al., 2007). More recent work has demonstrated that more polluted areas within cities have higher morbidity and mortality rates than less polluted areas (Hankey et al., 2012; Raaschou-Nielsen et al., 2013; Schwela, 2011). The related burden has been shown to be substantial for acute effects, such as heart failure, asthma attacks, and other morbidities (Künzli et al., 2000; Shah et al., 2013), and even larger for chronic outcomes, such as the development of asthma (Perez et al., 2013) and morbidities due to the development of atherosclerosis (Künzli et al., 2005).

Air pollution in cities of low- or middle-income countries, such as Tehran in Iran is higher than in cities of high-income countries and generated by a different balance of sources. Given that most of the peer-reviewed literature on air pollution exposure and its health effects reports on cities in high-income countries, it follows that the evidence may not be generalizable to Tehran. Though not all countries need to repeat research prior to implementing clean air policies, local research on air pollution and health supports the policy dialog and provides input in planning local clean air strategies. From a public health and research perspective, there are two key issues of air pollution relevant for Tehran: short-term effects and long-term effects.

Although they contribute less to the overall burden of disease, the short-term effects currently dominate the daily discussions about air pollution and the need for control policies in Tehran. Though there have been several studies in Iran that addressed acute health effects of air pollutants on hospital admissions and mortality due to various diseases, mainly cardiovascular and respiratory, in time-series or case-crossover designs (Gharehchahi et al., 2013; Hosseinpoor et al., 2005; Vahedian et al., 2017a, b), none exist on non-accidental mortality, to date. Daily air quality is communicated via an index generated very similarly to the United States Environmental Protection Agency Air Quality Index (AQI) (U.S. Environmental Protection Agency; Office of Air Quality Planning and Standards; Outreach and Information Division, 2014). The AQI is a single numerical value from 0 to 500 with 1 unit increment and has been reported daily since 2011 in Tehran. The AQI in Tehran is constructed in such a way that almost half of the days are labelled as "healthy" while at the end of the year, the long-term means are reported to be far higher than the WHO guideline values, which are adopted as standards in Iran. This discrepancy between acknowledging long-term air quality problems, while reporting healthy air on a daily level, results in ambiguous communication undermining trust of people in environmental monitoring. To date, it is not clear how this AQI value is correlated with health outcomes. Moreover, it summarizes air quality in categories while its health effects occur in a continuum. So far, there have been few studies investigating the ability of air quality indices to predict mortality, and they have been conducted in high-income countries (Chen et al., 2013; Stieb et al., 2005). As mortality has coherently been associated with air pollution concentrations in previous studies (Beelen et al., 2014; Dockery et al., 1993), this dissertation aims to evaluate how daily air pollutants and AQI value is associated with daily-registered mortality in Tehran.

The long-term effects of air pollution on chronic pathologies have been shown to contribute to a far larger burden of morbidity and mortality than the acute effects of daily fluctuations. Thus, it is particularly important to embark a research agenda for long-term effects. Recently, the government of Iran, namely the Ministry of Health and Medical Education (MOH) and Municipality of Tehran, has expressed interest in this issue. The MOH is dedicated to investing in long-term cohort studies in Tehran. To investigate the role of air pollution in such studies, it is essential to understand the long-term spatial distribution of air pollutants and estimate individual-scale exposures. In addition, in light of policy and technology changes, there is a need to monitor those spatial trends over time. Although studies in Canada and the Netherlands indicate substantial stability of spatial air pollutants patterns over several years (Wang et al., 2013), it is inappropriate to assume the same for Tehran where a range of specific policies are expected to result in rapid and substantial changes in the air pollution mixtures, distributions, and correlation among the pollutants. These policies could include implementation of WHO guidelines as national standards, offering clean diesel and petrol in terms of sulfur content in Tehran based on Europe standards, manufacturing vehicles, especially buses, equipped with catalyst and diesel particulate filters, developing public transportation and supporting zero emission transportation facilities (e.g. developing more metro routes and using electric trams, cars, motorcycles, etc.), modified tax policies on single-seat vehicles which entering high emission areas in the city, providing free parking and infrastructure throughout the city for zero- or low-emission vehicles, and so forth. This dissertation aims to address these challenges by conducting research that opens up new avenues to increase knowledge about air pollutant distributions in Tehran and their behavior over time, mainly through developing land use regression (LUR) models. The LUR is a geospatial-geostatistical technique that has been used to model within-city spatial and spatiotemporal variability for multiple air pollutants (Amini et al., 2014; Amini et al., 2013). There is no standard way of conducting LUR, but detailed descriptions of different approaches are published elsewhere (Hoek et al., 2008). In brief, a pollutant is measured at multiple sites around a city. Physical and geographic characteristics that might be associated with the pollutant concentrations are then determined around each site using a Geographic Information System (GIS). These potentially predictive variables typically describe site location, surrounding land use, population density, point sources, and traffic patterns. Multiple linear regression is used to correlate the measurements with the most predictive variables, and the resulting equation can be used to estimate pollutant concentrations wherever information about the predictors is available (Jerrett et al., 2004).

The most expensive part of LUR is the measurement activities for different pollutants. As a result, selection of pollutants to be measured is of crucial importance. Based on the previous research, particulate matter (PM), especially PM_{10} and $PM_{2.5}$ (PM less than 10 and 2.5 μm), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and benzene, toluene, ethyl-benzene, and xylenes (BTEX), are the key air pollutants in Tehran which have been in turn responsible to high AQI values in the past. Some studies indicate the gas oil combusted by diesel engine vehicles is sour in Iran and contains lots amounts of sulfur (Amini et al., 2014). The next important component to be considered for LUR modeling is the location of measurement sites. Under ideal circumstances, the sites are specifically selected to optimize the spatial variability in pollutant concentrations, but some studies have leveraged data from pre-existing monitoring networks. Currently, there are about 40 air pollution monitoring fixed-sites in Tehran, which measure criteria air pollutants, namely PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, BTEX, and carbon monoxide (CO) in an hourly basis, and could be used for development of LUR models. However, it is not known whether the sites are optimally selected to characterize spatial patterns relevant to people's exposure across the city and over time. Ideally, sites may be located in such a way that valid spatial models could be developed based on annual data to evaluate trends.

The current dissertation has two main parts to address these knowledge gaps in Iran. First in part I, evaluating acute effects of air pollutants and daily-reported AQI value on non-accidental mortality in a time-series analysis in Tehran, and second in part II, measurement and modeling the long-term spatial variability of air pollutants, again in Tehran.

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Goals of the dissertation

The overarching goals of this PhD dissertation are:

1. To examine the association between $PM_{2.5}$, NO_2, AQI and daily mortality as means to evaluate use of the AQI to communicate the public health relevance of daily air quality in Tehran, Iran
2. To model and estimate long-term spatial distribution of important air pollutants in Tehran, Iran, for use in future studies

Research questions

For the first goal, I would like to address three research questions (RQ):

RQ1.1. What is the association between the daily $PM_{2.5}$ and mortality in Tehran?

RQ1.2. What is the association between the daily NO_2 and mortality in Tehran?

RQ1.3. What is the association between the daily AQI and mortality in Tehran?

For the second goal, I would like to address two RQs:

RQ2.1. What are the levels of and the spatiotemporal associations between important ambient air pollutants in Tehran?

RQ2.2. What are the spatial patterns of these pollutants in Tehran?

Specific aims

In order to respond to the abovementioned questions, the dissertation will follow the following specific aims (SAs):

The SAs for the first goal are:

SA1.1. To evaluate the association between the daily $PM_{2.5}$ and mortality in Tehran?

SA1.2. To evaluate the association between the daily NO_2 and mortality in Tehran?

SA1.3. To evaluate the association between the daily AQI and mortality in Tehran?

The SAs for the second goal are:

SA2.1. To develop land use regression (LUR) models to estimate the annual and seasonal within-city spatial gradients of the monitored pollutants by the regulatory monitoring network, namely NO, NO_2, and NOx in Tehran, Iran

SA2.2. To monitor and describe the spatiotemporal variability of benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene (BTEX), and total BTEX in Tehran, Iran

SA2.3. To develop LUR models to estimate the annual within-city spatial gradients of the monitored BTEX compounds in Tehran, Iran

SA2.4. To conduct a systematic review of land use regression models for volatile organic compounds

PART I: Evaluating acute health effects

Article 1: Short-term associations between daily mortality and particulate matter, nitrogen dioxide, and the air quality index in a Middle Eastern megacity

This article is currently under review among co-authors.

Prepared to be submitted to a peer-reviewed scientific journal. The content of this article may change after the peer-review process by co-authors and journal's reviewers.

Short-term associations between daily mortality and particulate matter, nitrogen dioxide, and the air quality index in a Middle Eastern megacity

Abstract

There is limited evidence for short-term associations between mortality and ambient air pollution in the Middle East, and no studies examining the air quality index. We investigated short-term associations of non-accidental mortality with fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and the air quality index (AQI) from March 2011 through March 2014 in the megacity of Tehran, Iran. Generalized additive quasi-Poisson models were used within a distributed lag non-linear modeling (DLNM) framework to estimate the effects of $PM_{2.5}$, NO_2, and AQI up to a lag of 45 days. Positive associations were found in most models, with strong evidence of effect modification by sex, age, and season. The maximum cumulative relative risk rates (95% confidence interval) per inter-quartile range increment were: 1.19 (1.12, 1.28) for NO_2 at lag 45 (for males, all ages, in cooler months); 1.14 (1.07, 1.21) for $PM_{2.5}$ at lag 30; and 1.15 (1.08, 1.22) for AQI at lag 31 (both for females, all ages, in cooler months). The cumulative effects remained positive in multipollutant models. Overall, we found that the effect of $PM_{2.5}$, NO_2, and AQI on mortality in Tehran was immediate, and that it increased steadily over a period of weeks. This is the first study to report short-term association between non-accidental mortality and ambient air pollution in Iran.

Keywords: Air pollution, Air Quality Index (AQI), DLNM, mortality, multi-pollutant model, nitrogen dioxide, particulate matter, short-term

INTRODUCTION

Air pollution is composed of a complex mixture of gases and small particles, which varies depending on the sources of the primary emissions and the environmental conditions leading to secondary reactions. Air pollution contributes substantially to a range of acute and chronic diseases and has large public health impacts (1-4). Of the health outcomes associated with air pollution, mortality has been most studied because the data are most readily available (3). Of all of the constituents of the complex ambient air pollution mixture, the strongest and most consistent predictors of population mortality have been particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2) (2, 5). Although there is a large body of evidence on the associations between daily death and $PM_{2.5}$ and NO_2 concentrations, there are some important limitations of this literature when considering its generalizability for low- and middle-income countries (LMICs).

First, the number of studies conducted in LMICs is small compared with the number conducted in high-income countries, meaning that any meta-analyses are weighted towards the high-income context (6, 7). Second, some studies have reported evidence of effect modification by age and sex (8-10), but pooled estimates for gender-based effect modification have been weak and almost nothing is known about this question in LMICs (3). Furthermore, not many studies on mortality have investigated the short-term associations beyond lag 7, i.e. air pollution exposure up to 7 days prior to death, and few looked into lags of more than 30 days (11, 12). In addition, multi-pollutant models over distributed lags, especially in LMICs, are rare.

The Middle Eastern country of Iran has a population of approximately 80 million people who are exposed to air pollution from natural dust storms and anthropogenic sources (13). Although many studies have quantified the health burden attributable to air pollution in Iran (14-16), all have been based on the World Health Organization (WHO) software called "AirQ" (which was recently upgraded to "AirQ+"). However, these Iranian applications of AirQ have used relative risks (RR) and 95% confidence intervals (CI) estimated from the international literature rather than from the Iranian studies. These RRs and CIs are heavily driven by studies conducted in high-income countries, which usually have much lower levels of air pollution than LMICs and possibly different sources of pollution. Furthermore, these studies do not account for lag structures that may differ between locations nor consider effect modification by age, sex, and season. Indeed, a recent study in Tehran, the capital of Iran, showed that the composition of $PM_{2.5}$ varied substantially between colder and warmer seasons. For example, the dust component of $PM_{2.5}$ was 7% in the colder season while it increased to 56% during the warmer season. In contrast, organic matter and elemental carbon contributed 44% to $PM_{2.5}$ during the warmer season, which increased to 70% in the colder (17). To date, no study in Iran has reported on the short-term association between ambient air pollution and daily non-accidental mortality.

The Tehran Air Quality Control Company (AQCC), which is a subsidiary of the Tehran Municipality, reports a daily air quality index (AQI) value to the public, constructed from air pollution measurements taken across the regulatory monitoring network. This AQI is very similar to the AQI constructed by the US Environmental Protection Agency (EPA), with values ranging from 0 – 500 (18). However, there is one key difference: the daily city-wide AQI for Tehran is reported as the *mean* of the daily maximum AQI values at each reporting station, rather than as the maximum of these values as is done by the US EPA. At present the Iran Ministry of Health recommends following US EPA procedure, which has led to local debate on the issue. Regardless of this debate, no study to date has evaluated whether the AQI as reported by Tehran AQCC is an effective tool for risk communication by assessing whether it can predict daily morbidity or mortality. Indeed, such studies on the relationship between air quality indices and health outcomes are rare on the global scale. Our objective with this study is to address some of these research gaps by quantifying the short-term association between daily non-accidental mortality and $PM_{2.5}$, NO_2, and AQI in the megacity of Tehran, Iran. In addition, we evaluate the cumulative effects of lags up to 45 days, and the difference in effects by sex, age, and season.

METHODS

Tehran is the capital of Iran, with an area of about 613 km^2. It is considered to be a megacity, with a resident population of almost 9 million people and an estimated transient population of 3 million people who commute into the city daily from outside areas (19). Tehran is surrounded by Alborz Mountains in the north and a desert in the south (19, 20). The climate is semi-arid, with an annual mean temperature of 18.3°C for the study period of March 2011 to March 2014. The extremes rose up to 36.9°C in July and went down to −5.7 °C in January for the same period. There are many hours of bright sunshine in Tehran, with an annual precipitation of approximately 220 mm. The annual mean relative humidity (RH) is 35%, ranging from 9.5% up to 92%, and the annual mean air pressure is 880 hPa, ranging from 868.4 up to 893.6 hPa. The elevation of Tehran is approximately 1000 m above sea level in the south, increasing to 1800 m in the north (21, 22).

Hourly $PM_{2.5}$ and NO_2 measurements for the period March 21, 2011 through March 20 2014 were obtained from 40 air quality monitoring stations operated by the Tehran AQCC and the Tehran Department of Environment. We calculated the daily mean value for each site if at least 50% of the hourly measurements over the entire study period were available. This criterion led to the exclusion of eight stations, leaving us with 32 for all further analyses. The AQI reported by the Tehran AQCC calculated as follows: (a) the hourly AQI value for each pollutant (for ozone, PM_{10}, $PM_{2.5}$, CO, SO_2, and NO_2 if it was above 200 ppm) at each monitoring site is calculated according to US EPA methods (23); (b) the maximum hourly AQI for each monitoring site is reported as the AQI for that site on that day; and (c) the *mean* of the maximum daily AQIs among all monitoring sites is reported as the AQI for the entire city (23). This method differs slightly from the US EPA method, which reports the *maximum* of the maximum daily AQIs among all monitoring sites for step (c). We obtained daily AQI values reported by Tehran AQCC for the study period. Daily counts of non-accidental mortality data by sex and age were obtained from the Behesht-e-Zahra Cemetery Organization, which is a subsidiary of Tehran Municipality, where all mortality data are registered (24).

For the statistical analysis, we first calculated descriptive statistics including mean, standard deviation (SD), min, max, interquartile range (IQR), 25^{th}, 50^{th}, and 75^{th} percentiles, for daily non-accidental mortality, weather parameters, air pollutants, and the AQI. The same statistics were calculated separately for the warmer (April–September) and cooler months (October–March). We also calculated the temporal Spearman correlations for daily $PM_{2.5}$, NO_2, AQI, and weather parameters.

Generalized additive quasi-Poisson models were used within a distributed lag non-linear modeling (DLNM) framework to estimate the effects of NO_2, $PM_{2.5}$, and AQI on non-accidental mortality, lagged out to 45 days and controlling for measured and unmeasured time-varying covariates. The unmeasured confounders were seasonality and temporal trend, which we captured by thin plate spline functions with six degrees of freedom (df) per year. The appropriate df value was selected based on visually inspected residuals partial autocorrelation function plots (PACF) and lower generalized cross-validation (GCV) values. We added an autoregressive term to the model if we were unable to adequately remove partial autocorrelation at lag 0.

For the measured meteorological confounders we included temperature, relative humidity (RH), and air pressure (AP). We evaluated the effect of temperature on mortality for single lags and cumulative lags up to seven days, and found the highest impact for a cumulative lag of four days. This is consistent with findings of a recent multi-country multi-community study of the effects of heat waves on mortality (Guo et al 2017). We used three df per year and it turned out that adaptive smoothers provide better results for meteorological confounders with lower GCV values. We used the same df and smoothing functions for the RH and AP covariates. In addition, we included day of week as a categorical variable and created a Boolean indicator for all holidays. After building core models that removed the effect of the confounders, the $PM_{2.5}$, NO_2, and AQI variables were added separately. Multi-pollutant models were also run for the combined effects of NO_2 and $PM_{2.5}$. Finally, the RR (CI) for lag 0 and cumulative RR (CI) for each of the preceding 45 days were extracted for an interquartile range (IQR) increase (and 10-unit increase in the supplemental information) in each of $PM_{2.5}$, NO_2, and the AQI.

In addition to the overall analyses, all models were also stratified data by sex, and age groups (>65, 18-65, and <18). To address the issue of different sources of air pollution in cooler vs warmer months, the analyses were further stratified by season. All analysis were performed and plotted in R statistical software (25), using the *dlnm* (26), *nlme* (27), *mgcv* (28), *splines* (25), and *Hmisc* (29) packages.

RESULTS

Over the March 2011 – March 2014 study period, the mean (SD) daily death count in Tehran was 111.7 (15.8) with a range from 52 to 165 (Table 1). This value increased to 117.9 (15.6) during the cooler months compared with 105.6 (13.5) in the warmer months (Table 2). The daily number of deaths was higher for males than females, at 61.2 compared with 48.8. The overall daily mean (SD) temperature (°C), RH (%), and AP (hPa) were 18.3 (10.2), 35.2% (18.2%), 880.0 (4.6), respectively (Table 1). These values in cooler vs warmer months were 10.2 (7.0) vs 26.0 (5.9), 46.5% (17.8%) vs 24.2% (10.2%), and 882.7 (4.1) vs 877.3 (3.3), respectively (Table 2). The overall daily mean (SD) $PM_{2.5}$ and NO_2 concentrations and AQI value were 40.0 (15.4) $\mu g/m^3$, 42.4 (9.6) ppb, and 100.4 (25.7), respectively (Table 1). Average concentrations were slightly higher in the cooler months (Table 2). The Spearman correlation between daily $PM_{2.5}$ and NO_2 was 0.53. Between $PM_{2.5}$ and the AQI it was 0.83, and between NO_2 and the AQI it was 0.40. The temporal correlations between markers of pollution and weather parameters were very low (Table 3).

An IQR increase in $PM_{2.5}$ (18.8 μg/m^3) was associated with a small increase in same day (lag0) non-accidental mortality, with a RR (CI) of 1.004 (1.001, 1.007). At longer lags the cumulative RR rose steadily until lag 37, reaching a maximum value of 1.044 (1.007, 1.083) before decreasing (Figure 1 and supplementary Table S1). Similarly, an IQR increase in NO_2 had an RR (CI) of 1.003 (0.999, 1.007) at lag 0, which rose steadily to a maximum of 1.060 (1.012, 1.108) at lag 29. Finally, an IQR increase in the AQI had an RR (CI) of 1.003 (1.000, 1.007) at lag 0, which rose steadily to a maximum of 1.043 (1.008, 1.079) at lag 38 (Figure 1 and supplementary Tables S2–S3).

We found strong evidence of effect modification by sex and age, with stronger associations in females and in the >65 years age category. For females (all ages), the maximum RRs (CI) per IQR increases reached 1.069 (1.024, 1.116) at lag 31 for $PM_{2.5}$; 1.081 (1.026, 1.140) at lag 27 for NO_2; and 1.063 (1.019, 1.1087) at lag 35 for the AQI (Figure 1 and supplementary Tables S6–S11). For age group >65 years (both sexes), the maximum RRs (CI) per IQR increases were: 1.053 (1.014, 1.094) at lag 30 for $PM_{2.5}$; 1.081 (1.023, 1.142) at lag 30 for NO_2; and 1.055 (1.015, 1.096) at lag 35 for the AQI (Figure 2 and supplemental Tables S12–S14). Positive associations were also found for men and for the <18 and 18–65 age categories (Figure 2 and supplementary Tables S15–S20). The multi-pollutant model results were similar to single pollutant models (supplementary Tables S4-S5).

We also observed larger associations in the cooler months than in the warmer months (supplementary Figures S1–S3). In the warmer months, the associations remained positive up to a lag of ~20 days for most models (supplementary Figures S1–S3 and Tables S21–S40). In the cooler months, associations were positive and stronger than associations during the warmer months for most models. In fact, the maximum RRs (CIs) per IQR were found during the cooler months, including: 1.14 (1.07, 1.21) among all subjects at lag 30 for $PM_{2.5}$; 1.19 (1.12, 1.28) among all males at lag 45 for NO_2; and 1.15 (1.08, 1.22) among all subjects at lag 31 for the AQI (supplementary Figures S1–S3 and Tables S41–S60). The cumulative effects remained positive in multi-pollutant models (supplementary Tables S24, S25, S44, and S45).

DISCUSSION

Here we provide a first-ever report on the association between daily non-accidental mortality and air pollution in Tehran, Iran, including evaluation of the local AQI. Although the previous research on PM with aerodynamic diameter ≤ 10 μm (PM_{10}) has shown that the short-term effects on mortality can persist up to 30-40 days (11, 12), to the best of our knowledge, no study reported lag structures of acute effects up to 45 days for $PM_{2.5}$, NO_2, and AQI.

The RR (CI) for the association between $PM_{2.5}$ and overall non-accidental mortality in Tehran at lag 0 was 1.002 (1.000, 1.004) per each 10 $\mu g/m^3$ increase, which is consistent with the pooled global findings. Atkinson and colleagues (2014) conducted a systematic review and meta-analysis of the association between $PM_{2.5}$ and all-cause mortality in 23 studies and an RR (CI) of 1.010 (1.005, 1.056) per each 10 $\mu g/m^3$ increment. However, most of the studies assessed were conducted in high income countries (30). Another meta-analysis conducted only on studies from Chinese cities reported a RR (CI) of 1.004 (1.002, 1.006) for the same association, which is more comparable with our results (7). The $PM_{2.5}$ effect estimates from the multi-pollutant models ($PM_{2.5}$ + NO_2) were similar to those from the single-pollutant model, with an overall RR (CI) of 1.002 (1.000, 1.004) at lag 0 up to a maximum cumulative RR (CI) of 1.023 (1.003, 1.044) at lag 37 per each 10 $\mu g/m^3$ increment.

Most studies conducted to date have considered short lag periods, and studies that have evaluated the effect of $PM_{2.5}$ beyond seven days are rare. Neuberger et al. (2007) evaluated the association between $PM_{2.5}$ and mortality in Vienna (Austria) for lags 0–1, 0–7, and 0–14 days. Similar to our results, the RR (CI) values rose steadily with the longer lags, increasing from 1.005 (0.994, 1.015) for 0-1, to 1.018 (1.000, 1.037) for 0-7, to 1.026 (1.011, 1.041) for 0-14 per each 10 $\mu g/m^3$ increment (31). The equivalent values in Tehran were 1.004 (1.001, 1.007) for 0-1 days, 1.011 (1.003, 1.020) for 0-7 days, and 1.016 (1.005, 1.028) for 0-14 days. They did not reach a maximum of 1.023 (1.003, 1.043) until the 0-37 day lag. Two other studies on the relationship between PM_{10} and mortality have reported on lags of up to 40 days, and have also observed that effect estimates were more than doubled for the longest lags (11, 12). We did not find any other studies that considered the effects of $PM_{2.5}$ on mortality for lags as long as 45 days.

The RR (CI) for the association between NO_2 and overall non-accidental mortality in Tehran at lag 0 was 1.002 (0.999, 1.006) for a 10 ppb increase, with the cumulative effects increasing steadily to 1.047 (1.011, 1.085) at a lag of 29 days. Once again, the multi-pollutant estimates (NO_2 + $PM_{2.5}$) for NO_2 were similar. A national Swiss study, conducted in 21 out of 26 cantons, reported a RR (CI) of 1.007 (1.001, 1.013) for the association of a 2-day average of NO_2 and any natural cause of death per 10 $\mu g/m^3$ (32). This value is very similar to what we observed in Tehran for cumulative lag of 2 where RR (CI) was 1.007 (0.999, 1.016) per 10 ppb increment in NO_2. As for $PM_{2.5}$, the aforementioned study in Vienna also considered NO_2 in the lagged mortality analyses, and reported an RR (CI) of 1.008 (1.000, 1.016) for 0–1 days, 1.021 (1.008, 1.035) for 0–7 days, and 1.029 (1.016, 1.041) for 0–14 days per each 10 $\mu g/m^3$ increment (31). These equivalent values in Tehran were 1.005 (0.999, 1.011) for 0-1 days, 1.019 (1.002, 1.035) for 0-7 days, and 1.033 (1.010, 1.057) for 0-14 days per each 10 ppb increment. Again, we did not find any other studies to consider longer cumulative lags for the association between NO_2 and mortality.

The RR (CI) for the association between AQI and overall non-accidental mortality in Tehran was 1.001 (1.000, 1.002) at lag 0, and the cumulative effect had an upward trend to 38 days, where the RR (CI) was 1.014 (1.003, 1.025) for a 10-unit increase. To date, very few studies have reported on the association between air quality indices and mortality (33), and none have considered long lag periods. Li and colleagues (2015) evaluated the association between mortality and the AQI (calculated using an approach similar to the US EPA) in Guangzhou (China), and reported RRs (CI) of 1.006 (1.003, 1.008) at lag 0 and 1.010 (1.003, 1.018) at lag 0–15 for each 10-unit increase (33). Other studies have evaluated the Canadian Air Quality Health Index (AQHI), but they are not directly comparable with our findings because the index construction and communication are different from the AQI used here (34, 35).

There is some local controversy about the application of the AQI in Tehran, because authorities report the average of maximum AQI values of each regulatory monitoring station rather than the maximum AQI value among all sites. Tehran is a highly polluted megacity, and some of the monitoring sites in the regulatory network are located close to traffic intersections. If the daily maximum AQI was reported as the maximum among all sites, the values would be dominated by measurements at such locations, and might not represent the general exposure of people in such a large city. In addition, reporting the AQI with US EPA procedure could lead to more days with poor air quality, which could have other consequences. It would be ideal to use a data-driven approach to the problem, testing different algorithms to evaluate which would be most effective for communicating risk to the public. Overall, we found that the effect of PM2.5, NO2, and AQI on mortality in Tehran was immediate, and that it increased steadily over a period of weeks.

We generally found larger effects in females, in those older than >65 years, and in the cooler months, which is consistent with the findings of several other studies (9, 33, 36-38). Franklin et al. (2007) evaluated the association between $PM_{2.5}$ and mortality in 27 US communities and reported that the pooled RR (CI) for lag 1 in females was 1.013 (1.004, 1.023) compared with 1.011 (1.007, 1.021) in males. Similarly, for the >75 age group the value was 1.017 (1.006, 1.027) compared with 1.006 (0.997, 1.015) in age group <75 (36). Similar estimates have been found in several studies for NO_2 and AQI (33, 39). The role of season (cooler vs warmer months) has been evaluated in a number of studies and estimates depend on local conditions. In Tehran we found larger estimates in cooler months, when the organic matter and elemental carbon components of $PM_{2.5}$ are increased and the dust component is decreased (17). Studies in the US have reported higher estimates in the warmer season for Detroit, but for the cooler season in Seattle (40). Zhu et al. (2017) also reported more pronounced effects in cooler season in Wuxi (China) (41).

In conclusion, we observed positive associations between $PM_{2.5}$, NO_2, and AQI and daily non-accidental mortality in Tehran. Although the effects were immediately apparent, their maximum impacts were typically observed when cumulated over a period of weeks. This has important implications for risk communication, impact assessment, and health protection. On the communication side, we did find that the reported AQI showed similar association with mortality as measured by $PM_{2.5}$ and NO_2, suggesting this can be an effective tool. However, design and implementation of appropriate science-based abatement policies is necessary to protect public health in Tehran by enforcing the air quality targets proposed by WHO (42). We further observed evidence of effect modification by sex, age, and season where the overall estimates were larger in females, older age groups, and the cooler months.

SUPPLEMENTARY INFORMATION

The document contains 64 additional pages including 3 additional figures and 60 additional tables.

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TABLES

Table 1- Summary statistics for daily non-accidental mortality, meteorological parameters, air pollutants, and the air quality index (AQI) from March 2011 through March 2014 in Tehran, Iran.

							Percentiles		
		Mean	SD	Min	Max	IQR	25th	50th	75th
Daily non-accidental mortality	Total (both sexes; all ages)	111.7	15.8	52	165	21	101	111	122
	Males	61.2	10.3	29	95	14	54	61	68
	Females	48.8	8.6	21	80	11	43	48	54
	> 65 years of age	71.9	12.2	33	112	15	64	71	79
	18 – 65 years of age	33.9	6.8	16	56	9	29	34	38
	< 18 years of age	6.0	3.5	1	22	5	3	5	8
Meteorological parameters	Temperature (°C)	18.3	10.2	–5.7	36.9	18.5	9.1	18.8	27.6
	Relative humidity (%)	35.2	18.2	9.5	92.0	26.5	20.5	30.1	47.0
	Air pressure (hPa)	880.0	4.6	868.4	893.6	6.5	876.8	879.8	883.3
Air pollutants	$PM_{2.5}$ (µg/m^3)	40.0	15.4	10.1	126.9	18.8	29.1	37.7	47.9
	NO_2 (ppb)	42.4	9.6	21.4	74.7	12.6	35.6	41.1	48.2
Air Quality Index (AQI)		100.4	25.7	31	278	31.5	83.5	99.0	115.0

Table 2- Summary statistics for daily non-accidental mortality, meteorological parameters, air pollutants, and the air quality index (AQI) during cooler and warmer months from March 2011 through March 2014 in Tehran, Iran.

							Percentiles		
		Mean	SD	Min	Max	IQR	25^{th}	50^{th}	75^{th}
Daily non-accidental mortality	Total (both sexes; all ages) in cooler months	117.9	15.6	74	165	21	107	118	128
	Total (both sexes; all ages) in warmer months	105.6	13.5	52	147	17	97	106	114
meteorological parameters	Temperature in cooler months (°C)	10.2	7.0	–5.7	27.9	9.5	5.0	9.0	14.5
	Temperature in warmer months (°C)	26.0	5.9	7.8	36.9	8.7	21.9	27.5	30.6
	Relative humidity in cooler months (%)	46.5	17.8	12.3	92.0	26.6	33.4	45.0	60.0
	Relative humidity in warmer months (%)	24.2	10.2	9.4	78.4	12.3	16.7	21.7	29.0
	Air pressure in cooler months (hPa)	882.7	4.1	868.4	893.5	5.3	880.1	882.9	885.4
	Air pressure in warmer months (hPa)	877.3	3.3	868.5	889.6	4.4	875.2	877.4	879.6
Air pollutants	$PM_{2.5}$ in cooler months (µg/m^3)	40.9	16	10.1	121.3	21.3	28.9	38.9	50.2
	$PM_{2.5}$ in warmer months (µg/m^3)	39.0	14.8	13.3	126.9	16.7	29.2	37.0	45.9
	NO_2 in cooler months (ppb)	45.2	10.1	22.3	74.7	14.4	37.9	43.8	52.3
	NO_2 in warmer months (ppb)	39.7	8.3	21.4	70.2	11	33.6	38.9	44.6
Air Quality Index (AQI)	Cooler months	102.8	26.4	31	180	34	85	102	119
	Warmer months	98.2	24.8	48	278	27	83	96	110

Table 3- Spearman correlation between $PM_{2.5}$, NO_2, the air quality index (AQI), and meteorological parameters during the March 2011 to March 2014 study period in Tehran, Iran.

	$PM_{2.5}$	NO_2	AQI	Temperature	Relative humidity	Air pressure
$PM_{2.5}$	1					
NO_2	0.53	1				
AQI	0.83	0.40	1			
Temperature	0.11	–0.16	0.04	1		
Relative humidity	–0.11	0.06	–0.04	–0.81	1	
Air pressure	0.01	0.21	0.002	–0.62	0.49	1

FIGURES

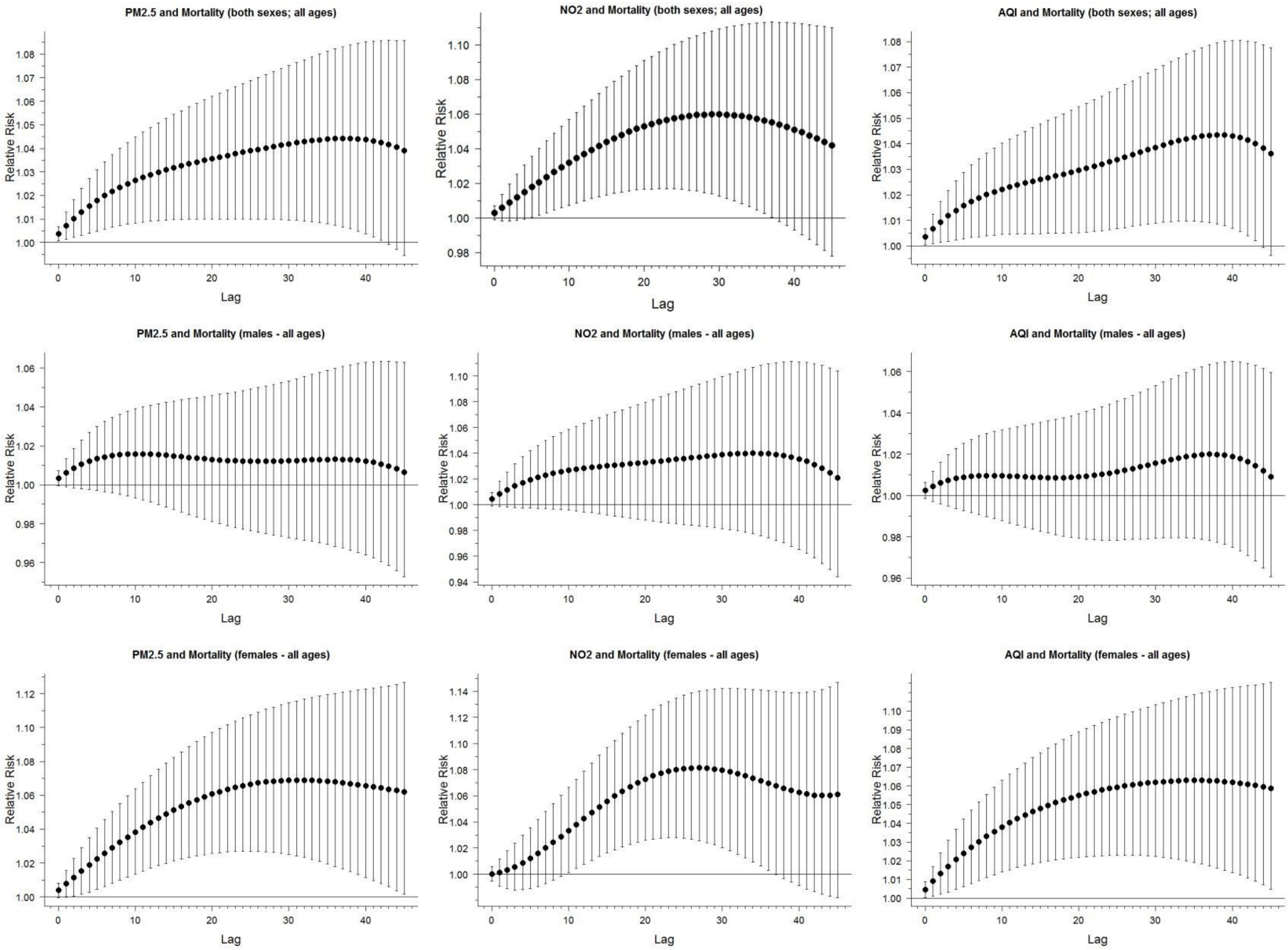

Figure 1- The cumulative associations (lag 0 to lag 45 days) between $PM_{2.5}$, NO_2, and AQI (per IQR) and overall and sex-specific non-accidental mortality from March 2011 to March 2014 in Tehran, Iran. All strata-specific lag-response point estimates for increments of 10 $\mu g/m^3$ of $PM_{2.5}$, 10 ppb of NO_2, and 10 units of AQI are available in the online supplement.

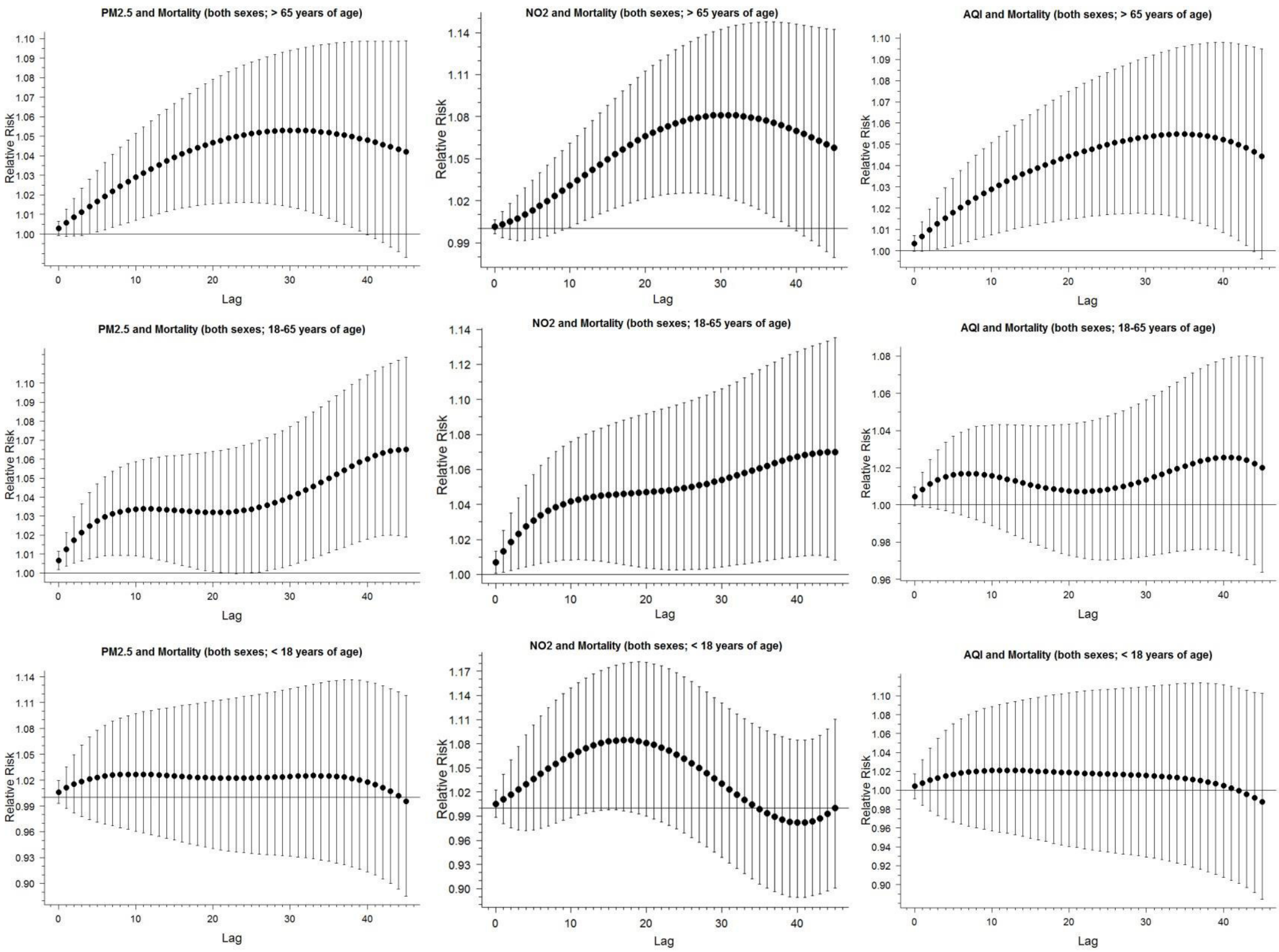

Figure 2- The cumulative associations (lag 0 to lag 45 days) between $PM_{2.5}$, NO_2, and the AQI (per IQR) and age-specific (>65, 18–65, and <18 years of age) non-accidental mortality from March 2011 to March 2014 in Tehran, Iran. All strata-specific lag-response point estimates for increments of 10 μg/m^3 of $PM_{2.5}$, 10 ppb of NO_2, and 10 units of AQI are available in the online supplement.

Supplementary information to:

Short-term associations between daily mortality and particulate matter, nitrogen dioxide, and the air quality index in a Middle Eastern megacity

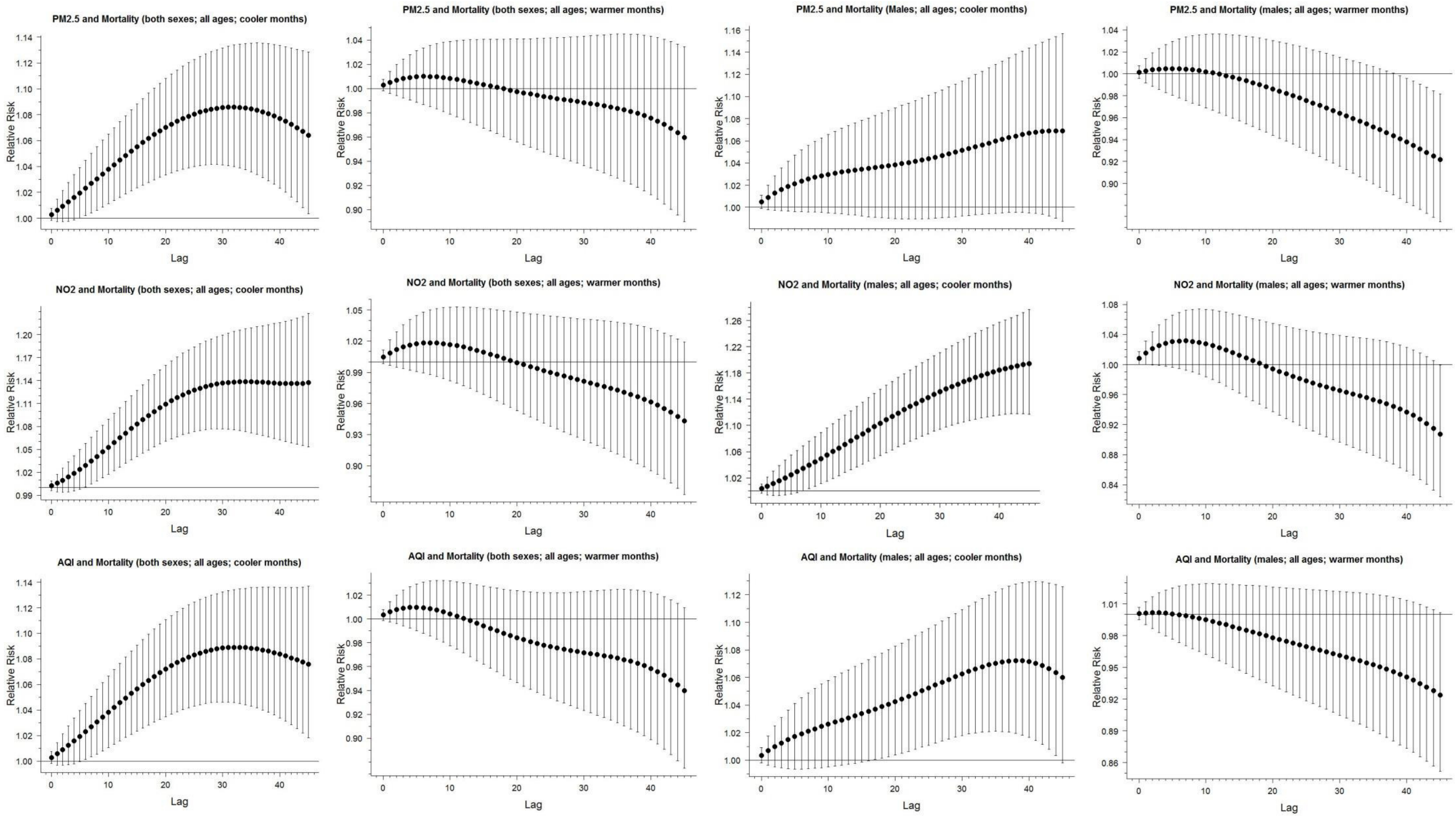

Figure S1- The cumulative associations (lag 0 to lag 45 days) between $PM_{2.5}$, NO_2, and AQI (per IQR) and overall and sex-specific non-accidental mortality during cooler and warmer months from March 2011 through March 2014 in Tehran, Iran.

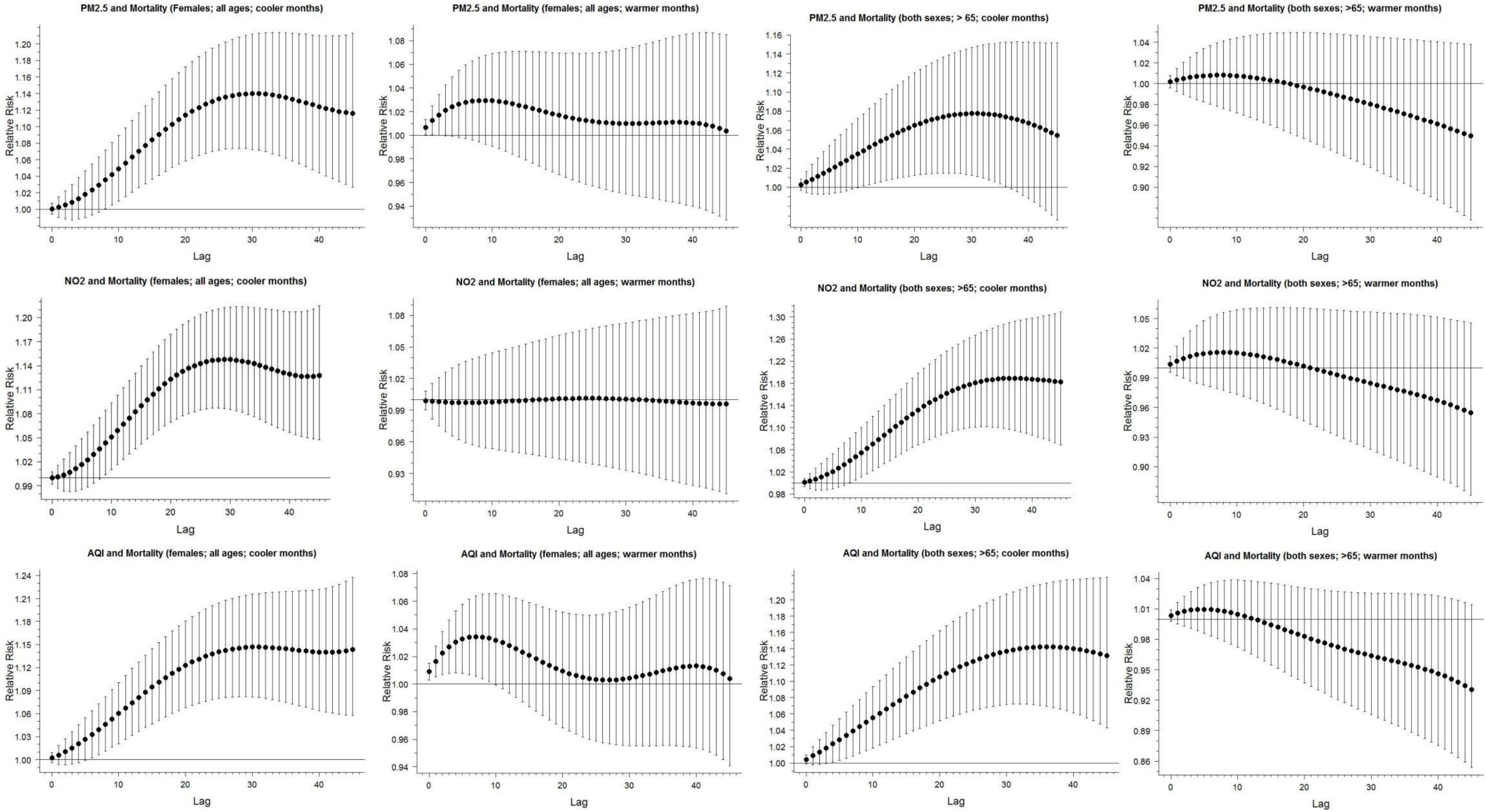

Figure S2- The cumulative associations (lag 0 to lag 45 days) between $PM_{2.5}$, NO_2, and AQI (per IQR) and sex-age-specific (females and >65 years of age) non-accidental mortality during cooler and warmer months from March 2011 through March 2014 in Tehran, Iran.

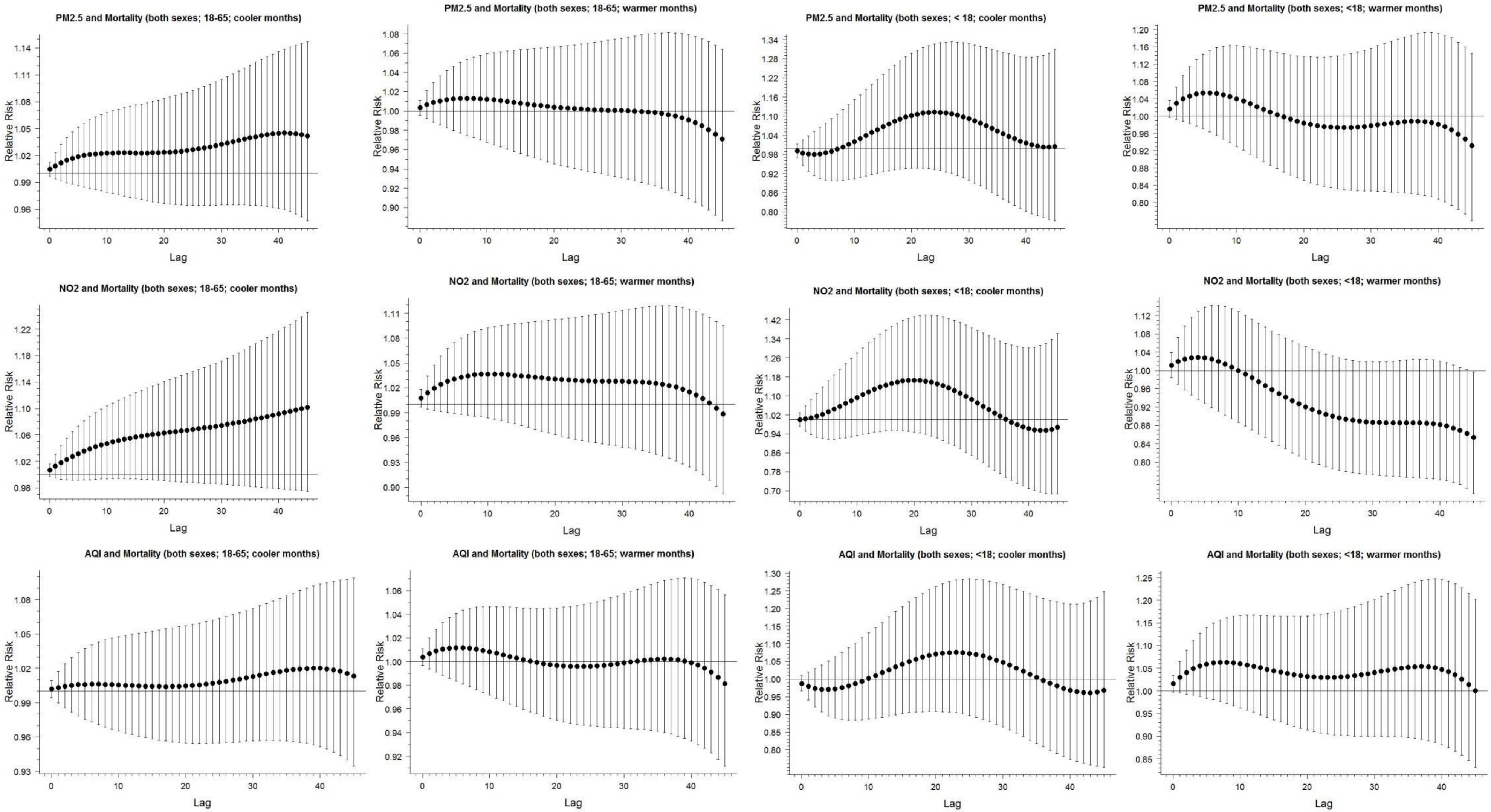

Figure S3- The cumulative associations (lag 0 to lag 45 days) between $PM_{2.5}$, NO_2, and AQI (per IQR) and age-specific (18–65 and <18 years of age) non-accidental mortality during cooler/warmer months from March 2011 through March 2014 in Tehran, Iran.

Table S1- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran (point estimates from the figures).

	Per IQR			Per 10 $\mu g/m^3$		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003726	1.000659	1.006802	1.001981	1.00035	1.003613
Lag 1	1.007118	1.001419	1.012849	1.003781	1.000755	1.006816
Lag 2	1.0102	1.002248	1.018215	1.005414	1.001195	1.009651
Lag 3	1.012997	1.003117	1.022974	1.006894	1.001657	1.012158
Lag 4	1.01553	1.003996	1.027196	1.008233	1.002124	1.014379
Lag 5	1.017823	1.004861	1.030952	1.009444	1.002583	1.016351
Lag 6	1.019897	1.005688	1.034306	1.010537	1.003022	1.018109
Lag 7	1.021772	1.006458	1.037318	1.011525	1.003431	1.019685
Lag 8	1.023468	1.007156	1.040044	1.012418	1.003801	1.02111
Lag 9	1.025004	1.007772	1.042531	1.013227	1.004128	1.022408
Lag 10	1.026398	1.008299	1.044821	1.013959	1.004407	1.023603
Lag 11	1.027666	1.008737	1.04695	1.014626	1.004639	1.024712
Lag 12	1.028824	1.009088	1.048947	1.015234	1.004825	1.025751
Lag 13	1.029887	1.009358	1.050833	1.015792	1.004968	1.026732
Lag 14	1.030868	1.009558	1.052628	1.016307	1.005074	1.027665
Lag 15	1.031779	1.009696	1.054345	1.016785	1.005147	1.028557
Lag 16	1.032632	1.009787	1.055994	1.017232	1.005195	1.029412
Lag 17	1.033436	1.009841	1.057583	1.017653	1.005224	1.030236
Lag 18	1.034201	1.00987	1.059118	1.018054	1.005239	1.031031
Lag 19	1.034933	1.009884	1.060605	1.018437	1.005247	1.031801
Lag 20	1.03564	1.00989	1.062048	1.018807	1.00525	1.032548
Lag 21	1.036327	1.009894	1.063453	1.019167	1.005252	1.033274
Lag 22	1.036998	1.009899	1.064824	1.019517	1.005255	1.033983
Lag 23	1.037655	1.009906	1.066166	1.019861	1.005258	1.034676
Lag 24	1.0383	1.009912	1.067486	1.020199	1.005262	1.035358
Lag 25	1.038934	1.009914	1.068788	1.02053	1.005263	1.036029
Lag 26	1.039557	1.009906	1.070078	1.020855	1.005259	1.036694
Lag 27	1.040165	1.00988	1.071358	1.021173	1.005245	1.037354
Lag 28	1.040756	1.009827	1.072632	1.021482	1.005216	1.03801
Lag 29	1.041325	1.009737	1.073901	1.021779	1.005169	1.038663
Lag 30	1.041867	1.009601	1.075164	1.022062	1.005097	1.039313
Lag 31	1.042375	1.009409	1.076417	1.022327	1.004995	1.039957
Lag 32	1.04284	1.009152	1.077653	1.02257	1.004859	1.040592
Lag 33	1.043254	1.008822	1.078862	1.022786	1.004684	1.041213
Lag 34	1.043606	1.00841	1.08003	1.022969	1.004466	1.041813
Lag 35	1.043883	1.007908	1.081142	1.023114	1.0042	1.042383
Lag 36	1.044073	1.00731	1.082179	1.023213	1.003883	1.042915
Lag 37	1.044162	1.006605	1.083121	1.023259	1.003509	1.043398
Lag 38	1.044135	1.005784	1.083948	1.023245	1.003073	1.043822
Lag 39	1.043974	1.004831	1.084641	1.023161	1.002568	1.044177
Lag 40	1.043661	1.003728	1.085183	1.022998	1.001982	1.044455
Lag 41	1.043179	1.002447	1.085565	1.022746	1.001301	1.04465
Lag 42	1.042506	1.000953	1.085784	1.022395	1.000507	1.044762
Lag 43	1.041622	0.999197	1.085849	1.021934	0.999573	1.044795
Lag 44	1.040505	0.997114	1.085784	1.021351	0.998464	1.044762
Lag 45	1.039131	0.994623	1.085631	1.020633	0.997135	1.044684

Table S2- The cumulative effect between NO_2 and overall non-accidental mortality (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002968	0.998842	1.007111	1.002366	0.999076	1.005666
Lag 1	1.005957	0.9983	1.013672	1.004746	0.998645	1.010886
Lag 2	1.008955	0.998281	1.019743	1.007133	0.998629	1.015709
Lag 3	1.01195	0.998694	1.025382	1.009516	0.998959	1.020185
Lag 4	1.014932	0.999456	1.030648	1.011887	0.999566	1.024361
Lag 5	1.01789	1.000486	1.035596	1.014238	1.000388	1.028279
Lag 6	1.020812	1.001714	1.040274	1.016559	1.001366	1.031981
Lag 7	1.02369	1.003073	1.04473	1.018842	1.002449	1.035504
Lag 8	1.026512	1.004504	1.049002	1.021081	1.003589	1.038878
Lag 9	1.02927	1.005958	1.053121	1.023268	1.004748	1.04213
Lag 10	1.031954	1.007394	1.057113	1.025395	1.005891	1.045278
Lag 11	1.034556	1.008778	1.060992	1.027456	1.006993	1.048335
Lag 12	1.037067	1.010086	1.064769	1.029444	1.008033	1.051309
Lag 13	1.03948	1.011298	1.068447	1.031353	1.008997	1.054203
Lag 14	1.041786	1.012403	1.072021	1.033177	1.009877	1.057014
Lag 15	1.043979	1.013395	1.075486	1.03491	1.010665	1.059737
Lag 16	1.046052	1.014268	1.078832	1.036549	1.011359	1.062365
Lag 17	1.047999	1.015021	1.082048	1.038086	1.011958	1.064889
Lag 18	1.049814	1.015653	1.085123	1.039519	1.012461	1.067301
Lag 19	1.051491	1.016164	1.088047	1.040844	1.012867	1.069593
Lag 20	1.053027	1.016553	1.09081	1.042055	1.013175	1.071758
Lag 21	1.054416	1.016817	1.093406	1.043151	1.013385	1.073792
Lag 22	1.055656	1.016953	1.095831	1.044129	1.013493	1.07569
Lag 23	1.056741	1.016957	1.098082	1.044985	1.013496	1.077452
Lag 24	1.057671	1.016822	1.100161	1.045718	1.01339	1.079077
Lag 25	1.058442	1.016543	1.102068	1.046326	1.013168	1.080569
Lag 26	1.059053	1.016112	1.103809	1.046807	1.012825	1.081929
Lag 27	1.059503	1.015523	1.105389	1.047162	1.012357	1.083164
Lag 28	1.059791	1.014768	1.106812	1.047389	1.011757	1.084276
Lag 29	1.059917	1.013842	1.108086	1.047488	1.011021	1.08527
Lag 30	1.059881	1.012743	1.109214	1.04746	1.010147	1.086151
Lag 31	1.059685	1.011468	1.1102	1.047305	1.009133	1.086921
Lag 32	1.05933	1.010019	1.111047	1.047025	1.00798	1.087582
Lag 33	1.058817	1.0084	1.111754	1.046621	1.006692	1.088134
Lag 34	1.05815	1.006617	1.112321	1.046095	1.005272	1.088576
Lag 35	1.057332	1.004679	1.112743	1.04545	1.003729	1.088906
Lag 36	1.056365	1.002596	1.113019	1.044688	1.002069	1.08912
Lag 37	1.055255	1.000378	1.113143	1.043813	1.000302	1.089217
Lag 38	1.054007	0.998037	1.113115	1.042828	0.998435	1.089195
Lag 39	1.052624	0.99558	1.112936	1.041737	0.996474	1.089056
Lag 40	1.051113	0.993009	1.112616	1.040545	0.994422	1.088806
Lag 41	1.04948	0.990322	1.112172	1.039256	0.992276	1.088459
Lag 42	1.047731	0.987503	1.111633	1.037875	0.990023	1.088039
Lag 43	1.045874	0.984524	1.111046	1.036408	0.987642	1.087581
Lag 44	1.043915	0.98134	1.110481	1.03486	0.985094	1.08714
Lag 45	1.041864	0.977884	1.11003	1.033238	0.982327	1.086788

Table S3- The cumulative effect between AQI and overall non-accidental mortality (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003502	1.000406	1.006609	1.001119	1.00013	1.00211
Lag 1	1.006606	1.000862	1.012382	1.002109	1.000276	1.003946
Lag 2	1.009345	1.001349	1.017405	1.002981	1.000431	1.005537
Lag 3	1.011757	1.001847	1.021765	1.003747	1.000591	1.006914
Lag 4	1.013875	1.002339	1.025544	1.004419	1.000748	1.008104
Lag 5	1.015731	1.002807	1.028822	1.005007	1.000897	1.009134
Lag 6	1.017358	1.003239	1.031675	1.005522	1.001035	1.010029
Lag 7	1.018784	1.003622	1.034175	1.005973	1.001158	1.010811
Lag 8	1.020038	1.00395	1.036385	1.006369	1.001262	1.011502
Lag 9	1.021147	1.004217	1.038363	1.006719	1.001347	1.012119
Lag 10	1.022135	1.004424	1.040159	1.007031	1.001413	1.012679
Lag 11	1.023026	1.004574	1.041817	1.007311	1.001461	1.013196
Lag 12	1.02384	1.004675	1.043371	1.007568	1.001494	1.013679
Lag 13	1.024598	1.004737	1.044851	1.007806	1.001513	1.014139
Lag 14	1.025316	1.004773	1.04628	1.008032	1.001525	1.014582
Lag 15	1.026011	1.004797	1.047674	1.008251	1.001532	1.015015
Lag 16	1.026696	1.004822	1.049047	1.008466	1.001541	1.01544
Lag 17	1.027384	1.004864	1.050409	1.008683	1.001554	1.015862
Lag 18	1.028085	1.004934	1.051769	1.008903	1.001576	1.016283
Lag 19	1.028806	1.005043	1.053131	1.009129	1.001611	1.016704
Lag 20	1.029554	1.005198	1.0545	1.009364	1.00166	1.017126
Lag 21	1.030334	1.005405	1.055881	1.009608	1.001726	1.017552
Lag 22	1.031148	1.005665	1.057277	1.009864	1.001809	1.017983
Lag 23	1.031997	1.005977	1.05869	1.01013	1.001909	1.018418
Lag 24	1.03288	1.006336	1.060124	1.010406	1.002023	1.018859
Lag 25	1.033793	1.006733	1.061581	1.010692	1.00215	1.019307
Lag 26	1.034731	1.007157	1.06306	1.010985	1.002285	1.019761
Lag 27	1.035688	1.007597	1.064562	1.011284	1.002425	1.020222
Lag 28	1.036653	1.008036	1.066083	1.011586	1.002564	1.020688
Lag 29	1.037617	1.008457	1.06762	1.011887	1.002699	1.021159
Lag 30	1.038566	1.008845	1.069163	1.012183	1.002822	1.021631
Lag 31	1.039485	1.00918	1.070701	1.012469	1.002928	1.022101
Lag 32	1.040358	1.009444	1.072217	1.012741	1.003013	1.022564
Lag 33	1.041164	1.009621	1.073693	1.012992	1.003069	1.023014
Lag 34	1.041884	1.009692	1.075103	1.013217	1.003091	1.023444
Lag 35	1.042495	1.00964	1.07642	1.013407	1.003075	1.023845
Lag 36	1.042972	1.009446	1.077611	1.013555	1.003013	1.024207
Lag 37	1.043287	1.009091	1.078642	1.013653	1.0029	1.024521
Lag 38	1.043412	1.008552	1.079477	1.013692	1.002729	1.024774
Lag 39	1.043317	1.007803	1.080082	1.013662	1.002491	1.024958
Lag 40	1.042969	1.006812	1.080425	1.013554	1.002175	1.025062
Lag 41	1.042335	1.005537	1.080479	1.013357	1.001769	1.025079
Lag 42	1.041377	1.003926	1.080225	1.013059	1.001255	1.025002
Lag 43	1.04006	1.001913	1.079659	1.012648	1.000612	1.02483
Lag 44	1.038344	0.999414	1.078791	1.012113	0.999812	1.024566
Lag 45	1.03619	0.996322	1.077652	1.011441	0.998822	1.02422

Table S4- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for both sexes and all ages) adjusted for NO_2 from March 2011 through March 2014 in Tehran, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.00362	1.000349	1.006901	1.001924	1.000186	1.003666
Lag 1	1.006924	1.000849	1.013036	1.003678	1.000452	1.006915
Lag 2	1.009935	1.001463	1.018479	1.005274	1.000778	1.00979
Lag 3	1.012676	1.002159	1.023304	1.006725	1.001148	1.012332
Lag 4	1.015169	1.002904	1.027583	1.008042	1.001544	1.014582
Lag 5	1.017433	1.00367	1.031385	1.009238	1.001951	1.016578
Lag 6	1.01949	1.00443	1.034776	1.010323	1.002355	1.018355
Lag 7	1.021359	1.005163	1.037816	1.011308	1.002744	1.019946
Lag 8	1.023058	1.005848	1.040563	1.012203	1.003107	1.021381
Lag 9	1.024606	1.006472	1.043066	1.013017	1.003439	1.022687
Lag 10	1.026018	1.007026	1.045368	1.01376	1.003732	1.023887
Lag 11	1.02731	1.007503	1.047506	1.014439	1.003985	1.025001
Lag 12	1.028497	1.007903	1.049511	1.015062	1.004197	1.026045
Lag 13	1.029592	1.00823	1.051407	1.015637	1.00437	1.027031
Lag 14	1.030609	1.008489	1.053214	1.016171	1.004508	1.027969
Lag 15	1.031558	1.008689	1.054946	1.016669	1.004614	1.028868
Lag 16	1.03245	1.008839	1.056613	1.017136	1.004693	1.029733
Lag 17	1.033294	1.008951	1.058223	1.017578	1.004753	1.030568
Lag 18	1.034098	1.009033	1.059784	1.017999	1.004796	1.031376
Lag 19	1.034869	1.009095	1.0613	1.018403	1.004829	1.032161
Lag 20	1.035613	1.009144	1.062776	1.018793	1.004855	1.032924
Lag 21	1.036335	1.009185	1.064215	1.019171	1.004876	1.033668
Lag 22	1.037038	1.00922	1.065623	1.019539	1.004895	1.034396
Lag 23	1.037725	1.00925	1.067004	1.019898	1.004911	1.035108
Lag 24	1.038398	1.009274	1.068362	1.02025	1.004924	1.035809
Lag 25	1.039055	1.009287	1.069701	1.020593	1.004931	1.0365
Lag 26	1.039697	1.009283	1.071027	1.020929	1.004929	1.037183
Lag 27	1.040321	1.009256	1.072342	1.021255	1.004914	1.037861
Lag 28	1.040924	1.009196	1.073649	1.021569	1.004882	1.038534
Lag 29	1.041501	1.009095	1.074948	1.021871	1.004829	1.039202
Lag 30	1.042046	1.008943	1.076236	1.022155	1.004748	1.039864
Lag 31	1.042554	1.008732	1.07751	1.02242	1.004636	1.040519
Lag 32	1.043015	1.008453	1.078761	1.022661	1.004489	1.041162
Lag 33	1.043421	1.008099	1.07998	1.022872	1.004301	1.041787
Lag 34	1.043761	1.007663	1.081151	1.02305	1.00407	1.042388
Lag 35	1.044023	1.007138	1.082259	1.023187	1.003792	1.042956
Lag 36	1.044196	1.006518	1.083284	1.023277	1.003462	1.043482
Lag 37	1.044264	1.005794	1.084206	1.023312	1.003079	1.043954
Lag 38	1.044214	1.004959	1.085003	1.023286	1.002635	1.044363
Lag 39	1.044029	1.003998	1.085657	1.02319	1.002125	1.044697
Lag 40	1.043692	1.002894	1.08615	1.023014	1.001539	1.04495
Lag 41	1.043184	1.001622	1.086472	1.022749	1.000862	1.045114
Lag 42	1.042487	1.000146	1.086621	1.022385	1.000078	1.045191
Lag 43	1.04158	0.998419	1.086606	1.021912	0.999159	1.045183
Lag 44	1.040441	0.996378	1.086453	1.021317	0.998071	1.045105
Lag 45	1.039049	0.993937	1.086208	1.02059	0.99677	1.044979

Table S5- The cumulative effect between NO_2 and overall non-accidental mortality (for both sexes and all ages) adjusted for $PM_{2.5}$ from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.00221	0.997831	1.006608	1.001762	0.99827	1.005265
Lag 1	1.004558	0.99645	1.012733	1.003633	0.997169	1.010139
Lag 2	1.007024	0.995746	1.018428	1.005596	0.996607	1.014665
Lag 3	1.009584	0.995615	1.023748	1.007633	0.996503	1.018889
Lag 4	1.012218	0.995959	1.028743	1.009729	0.996777	1.02285
Lag 5	1.014907	0.996684	1.033463	1.011867	0.997355	1.02659
Lag 6	1.017631	0.997706	1.037954	1.014032	0.99817	1.030145
Lag 7	1.020371	0.998945	1.042256	1.016208	0.999159	1.033549
Lag 8	1.02311	1.000333	1.046407	1.018383	1.000265	1.036829
Lag 9	1.025831	1.001805	1.050434	1.020542	1.001439	1.040009
Lag 10	1.028518	1.003309	1.054359	1.022672	1.002638	1.043106
Lag 11	1.031154	1.004802	1.058198	1.024761	1.003826	1.046133
Lag 12	1.033726	1.006246	1.061956	1.026798	1.004976	1.049094
Lag 13	1.036219	1.007614	1.065635	1.028772	1.006066	1.051991
Lag 14	1.03862	1.008887	1.069228	1.030672	1.007079	1.054818
Lag 15	1.040917	1.01005	1.072727	1.03249	1.008005	1.057569
Lag 16	1.043099	1.011093	1.076118	1.034215	1.008834	1.060234
Lag 17	1.045155	1.012008	1.079387	1.03584	1.009563	1.062801
Lag 18	1.047076	1.012793	1.08252	1.037357	1.010186	1.065259
Lag 19	1.048853	1.013442	1.085501	1.038761	1.010703	1.067598
Lag 20	1.050479	1.013953	1.08832	1.040044	1.011109	1.069808
Lag 21	1.051946	1.014322	1.090967	1.041203	1.011402	1.071882
Lag 22	1.05325	1.014544	1.093434	1.042232	1.011578	1.073814
Lag 23	1.054386	1.014614	1.095717	1.043128	1.011634	1.075601
Lag 24	1.05535	1.014527	1.097816	1.043888	1.011565	1.077243
Lag 25	1.05614	1.014276	1.099731	1.04451	1.011366	1.078741
Lag 26	1.056753	1.013855	1.101467	1.044994	1.011031	1.080098
Lag 27	1.057191	1.013258	1.103028	1.045339	1.010556	1.081319
Lag 28	1.057452	1.01248	1.104421	1.045545	1.009938	1.082408
Lag 29	1.05754	1.011519	1.105654	1.045614	1.009173	1.083371
Lag 30	1.057456	1.010372	1.106733	1.045548	1.008261	1.084213
Lag 31	1.057204	1.009043	1.107664	1.04535	1.007203	1.084941
Lag 32	1.056789	1.007535	1.108452	1.045023	1.006003	1.085556
Lag 33	1.056218	1.005857	1.109101	1.044572	1.004667	1.086063
Lag 34	1.055496	1.004019	1.109613	1.044003	1.003203	1.086463
Lag 35	1.054633	1.002036	1.10999	1.043322	1.001623	1.086757
Lag 36	1.053635	0.999923	1.110232	1.042535	0.999939	1.086946
Lag 37	1.052514	0.997698	1.110342	1.041651	0.998164	1.087032
Lag 38	1.05128	0.995376	1.110324	1.040677	0.996312	1.087018
Lag 39	1.049946	0.992974	1.110186	1.039624	0.994394	1.08691
Lag 40	1.048523	0.9905	1.109944	1.0385	0.992418	1.086721
Lag 41	1.047025	0.987957	1.109623	1.037317	0.990387	1.086471
Lag 42	1.045467	0.98534	1.109263	1.036086	0.988294	1.086189
Lag 43	1.043864	0.982624	1.10892	1.034819	0.986122	1.085921
Lag 44	1.042232	0.979772	1.108675	1.033529	0.983839	1.08573
Lag 45	1.040589	0.976719	1.108635	1.03223	0.981394	1.085699

Table S6- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003321	0.999427	1.00723	1.001766	0.999695	1.003841
Lag 1	1.00615	0.998924	1.013427	1.003267	0.999428	1.007122
Lag 2	1.008526	0.99846	1.018694	1.004527	0.99918	1.009903
Lag 3	1.010491	0.998003	1.023136	1.005568	0.998937	1.012244
Lag 4	1.012084	0.997528	1.026853	1.006411	0.998684	1.014198
Lag 5	1.013343	0.997009	1.029943	1.007077	0.998408	1.015822
Lag 6	1.014304	0.996427	1.032501	1.007585	0.998097	1.017163
Lag 7	1.015002	0.995764	1.034613	1.007954	0.997744	1.018269
Lag 8	1.015472	0.995009	1.036356	1.008203	0.997341	1.019182
Lag 9	1.015745	0.994157	1.037803	1.008347	0.996887	1.019939
Lag 10	1.015852	0.993206	1.039014	1.008403	0.99638	1.020571
Lag 11	1.015819	0.992163	1.04004	1.008386	0.995822	1.021108
Lag 12	1.015675	0.991037	1.040926	1.00831	0.995221	1.02157
Lag 13	1.015442	0.989842	1.041705	1.008187	0.994583	1.021977
Lag 14	1.015145	0.988597	1.042406	1.00803	0.993917	1.022343
Lag 15	1.014803	0.987319	1.043051	1.007849	0.993233	1.02268
Lag 16	1.014435	0.98603	1.043657	1.007654	0.992543	1.022996
Lag 17	1.014057	0.984749	1.044238	1.007455	0.991856	1.023299
Lag 18	1.013685	0.983493	1.044804	1.007258	0.991183	1.023594
Lag 19	1.013331	0.982277	1.045367	1.007071	0.990531	1.023887
Lag 20	1.013006	0.981116	1.045933	1.006899	0.989908	1.024182
Lag 21	1.012719	0.980017	1.046512	1.006747	0.989318	1.024484
Lag 22	1.012477	0.978987	1.047112	1.006619	0.988765	1.024796
Lag 23	1.012285	0.978029	1.04774	1.006517	0.988249	1.025123
Lag 24	1.012145	0.97714	1.048404	1.006444	0.987771	1.025469
Lag 25	1.012059	0.976316	1.049111	1.006398	0.987328	1.025837
Lag 26	1.012027	0.975551	1.049868	1.006381	0.986916	1.02623
Lag 27	1.012046	0.974833	1.050678	1.006391	0.98653	1.026652
Lag 28	1.01211	0.974152	1.051546	1.006425	0.986163	1.027103
Lag 29	1.012214	0.973496	1.052471	1.00648	0.98581	1.027584
Lag 30	1.012348	0.972849	1.053451	1.006551	0.985461	1.028092
Lag 31	1.012504	0.972199	1.054479	1.006633	0.985111	1.028626
Lag 32	1.012667	0.971531	1.055544	1.00672	0.984751	1.029179
Lag 33	1.012825	0.970833	1.056632	1.006803	0.984374	1.029743
Lag 34	1.01296	0.970092	1.057722	1.006875	0.983974	1.030308
Lag 35	1.013055	0.969293	1.058792	1.006925	0.983543	1.030862
Lag 36	1.013089	0.968424	1.059814	1.006943	0.983074	1.031392
Lag 37	1.013041	0.96747	1.060759	1.006918	0.982558	1.031881
Lag 38	1.012887	0.966411	1.061597	1.006836	0.981986	1.032315
Lag 39	1.0126	0.965225	1.0623	1.006684	0.981345	1.032678
Lag 40	1.012153	0.963883	1.062841	1.006448	0.980618	1.032958
Lag 41	1.011517	0.962345	1.063202	1.006111	0.979786	1.033145
Lag 42	1.010661	0.96056	1.063374	1.005658	0.978818	1.033234
Lag 43	1.009551	0.958461	1.063364	1.00507	0.977679	1.033228
Lag 44	1.008153	0.955959	1.063196	1.004329	0.976321	1.033142
Lag 45	1.006431	0.952946	1.062918	1.003416	0.974682	1.032998

Table S7- The cumulative effect between NO_2 and overall non-accidental mortality (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004386	0.999143	1.009656	1.003495	0.999316	1.007691
Lag 1	1.008251	0.998517	1.01808	1.006573	0.998818	1.014389
Lag 2	1.011642	0.99807	1.025398	1.009271	0.998461	1.020198
Lag 3	1.014601	0.99775	1.031737	1.011624	0.998206	1.025223
Lag 4	1.017172	0.997509	1.037223	1.013668	0.998014	1.029567
Lag 5	1.019395	0.997304	1.041976	1.015434	0.99785	1.033327
Lag 6	1.021311	0.997095	1.046114	1.016954	0.997683	1.036598
Lag 7	1.022955	0.99685	1.049744	1.01826	0.997488	1.039465
Lag 8	1.024365	0.996543	1.052964	1.019378	0.997242	1.042006
Lag 9	1.025573	0.996156	1.055859	1.020337	0.996934	1.044289
Lag 10	1.026611	0.995679	1.058505	1.02116	0.996553	1.046375
Lag 11	1.027508	0.99511	1.060961	1.021871	0.996099	1.048311
Lag 12	1.028291	0.994454	1.063279	1.022492	0.995575	1.050136
Lag 13	1.028983	0.993722	1.065497	1.023041	0.994991	1.051882
Lag 14	1.029608	0.992929	1.067642	1.023536	0.994358	1.05357
Lag 15	1.030184	0.992094	1.069738	1.023993	0.993691	1.055219
Lag 16	1.03073	0.991236	1.071797	1.024425	0.993006	1.056838
Lag 17	1.031258	0.990373	1.073831	1.024844	0.992317	1.058437
Lag 18	1.031783	0.989524	1.075846	1.025259	0.991639	1.06002
Lag 19	1.032313	0.988702	1.077848	1.025679	0.990982	1.061592
Lag 20	1.032856	0.987917	1.079838	1.026109	0.990355	1.063155
Lag 21	1.033416	0.987176	1.081822	1.026553	0.989762	1.064712
Lag 22	1.033997	0.986481	1.083802	1.027013	0.989207	1.066265
Lag 23	1.034598	0.985828	1.085779	1.027489	0.988685	1.067816
Lag 24	1.035216	0.985211	1.087758	1.027978	0.988191	1.069367
Lag 25	1.035846	0.984618	1.089739	1.028477	0.987717	1.070919
Lag 26	1.036481	0.984034	1.091722	1.02898	0.98725	1.072473
Lag 27	1.03711	0.983442	1.093706	1.029478	0.986776	1.074027
Lag 28	1.037721	0.982821	1.095687	1.029961	0.986279	1.075578
Lag 29	1.038298	0.982149	1.097657	1.030418	0.985742	1.077119
Lag 30	1.038824	0.981405	1.099603	1.030834	0.985146	1.078641
Lag 31	1.039279	0.980566	1.101507	1.031194	0.984475	1.08013
Lag 32	1.039639	0.979609	1.103347	1.031479	0.983709	1.081568
Lag 33	1.03988	0.978514	1.105093	1.031669	0.982832	1.082933
Lag 34	1.039972	0.977259	1.10671	1.031743	0.981827	1.084196
Lag 35	1.039888	0.975824	1.108158	1.031675	0.980677	1.085326
Lag 36	1.039592	0.974186	1.10939	1.031442	0.979364	1.086288
Lag 37	1.039051	0.972323	1.110358	1.031014	0.977871	1.087044
Lag 38	1.038227	0.970209	1.111013	1.030362	0.976176	1.087555
Lag 39	1.03708	0.967813	1.111305	1.029454	0.974253	1.087784
Lag 40	1.03557	0.965094	1.111192	1.028259	0.97207	1.087695
Lag 41	1.033652	0.962003	1.110637	1.02674	0.969587	1.087262
Lag 42	1.031281	0.958474	1.109618	1.024862	0.96675	1.086467
Lag 43	1.028411	0.954423	1.108134	1.022587	0.963491	1.085308
Lag 44	1.024994	0.949743	1.106206	1.019877	0.959723	1.083802
Lag 45	1.020981	0.944299	1.10389	1.016692	0.955334	1.081992

Table S8- The cumulative effect between AQI and overall non-accidental mortality (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002451	0.998533	1.006385	1.000784	0.99953	1.002039
Lag 1	1.004451	0.997204	1.01175	1.001422	0.999104	1.003745
Lag 2	1.006048	0.995986	1.016211	1.001931	0.998714	1.005159
Lag 3	1.00729	0.994855	1.01988	1.002327	0.998351	1.006319
Lag 4	1.008222	0.993787	1.022866	1.002624	0.998008	1.007261
Lag 5	1.008887	0.992761	1.025275	1.002835	0.997678	1.008019
Lag 6	1.009326	0.991757	1.027207	1.002975	0.997355	1.008627
Lag 7	1.009578	0.99076	1.028754	1.003055	0.997034	1.009113
Lag 8	1.00968	0.989761	1.030001	1.003088	0.996712	1.009504
Lag 9	1.009666	0.988751	1.031023	1.003083	0.996386	1.009824
Lag 10	1.009566	0.98773	1.031884	1.003051	0.996057	1.010094
Lag 11	1.00941	0.986702	1.03264	1.003001	0.995725	1.010331
Lag 12	1.009224	0.985674	1.033336	1.002942	0.995393	1.010549
Lag 13	1.009031	0.984658	1.034008	1.002881	0.995065	1.010759
Lag 14	1.008855	0.98367	1.034684	1.002825	0.994745	1.010971
Lag 15	1.008712	0.982726	1.035385	1.00278	0.994439	1.01119
Lag 16	1.008619	0.981843	1.036125	1.00275	0.994153	1.011421
Lag 17	1.00859	0.981037	1.036916	1.002741	0.993892	1.011668
Lag 18	1.008635	0.980323	1.037765	1.002755	0.993661	1.011933
Lag 19	1.008764	0.979712	1.038678	1.002796	0.993463	1.012218
Lag 20	1.008983	0.979213	1.039657	1.002866	0.993301	1.012523
Lag 21	1.009294	0.97883	1.040706	1.002965	0.993176	1.01285
Lag 22	1.009699	0.978563	1.041826	1.003094	0.99309	1.013198
Lag 23	1.010197	0.978409	1.043018	1.003252	0.993039	1.013569
Lag 24	1.010783	0.978358	1.044283	1.003438	0.993023	1.013962
Lag 25	1.011451	0.978399	1.045621	1.00365	0.993036	1.014378
Lag 26	1.012192	0.978515	1.047029	1.003885	0.993074	1.014815
Lag 27	1.012994	0.978687	1.048504	1.00414	0.99313	1.015272
Lag 28	1.013843	0.978895	1.050039	1.004409	0.993197	1.015748
Lag 29	1.014722	0.979114	1.051626	1.004688	0.993268	1.016238
Lag 30	1.015612	0.97932	1.053249	1.00497	0.993335	1.01674
Lag 31	1.01649	0.979487	1.054891	1.005248	0.99339	1.017247
Lag 32	1.017333	0.97959	1.056529	1.005514	0.993423	1.017752
Lag 33	1.018111	0.979604	1.058132	1.00576	0.993428	1.018246
Lag 34	1.018797	0.979503	1.059666	1.005977	0.993395	1.018718
Lag 35	1.019356	0.979262	1.061091	1.006154	0.993317	1.019156
Lag 36	1.019754	0.978855	1.062362	1.006279	0.993184	1.019547
Lag 37	1.019953	0.978252	1.063431	1.006342	0.992989	1.019875
Lag 38	1.019913	0.977424	1.064248	1.006329	0.992719	1.020126
Lag 39	1.01959	0.976333	1.064764	1.006228	0.992365	1.020284
Lag 40	1.018941	0.974934	1.064934	1.006022	0.99191	1.020336
Lag 41	1.017918	0.973173	1.064719	1.005699	0.991336	1.02027
Lag 42	1.016471	0.970981	1.064092	1.005242	0.990621	1.020078
Lag 43	1.014551	0.968271	1.063043	1.004633	0.989735	1.019756
Lag 44	1.012104	0.964932	1.061581	1.003857	0.988642	1.019307
Lag 45	1.009076	0.960831	1.059744	1.002896	0.987295	1.018742

Table S9- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.00389	0.999633	1.008164	1.002068	0.999805	1.004336
Lag 1	1.007722	0.999824	1.015682	1.004101	0.999906	1.008313
Lag 2	1.011488	1.000484	1.022613	1.006096	1.000257	1.011968
Lag 3	1.01518	1.001526	1.029019	1.008048	1.000812	1.015337
Lag 4	1.01879	1.002872	1.034961	1.009954	1.001527	1.018452
Lag 5	1.022311	1.004445	1.040495	1.01181	1.002363	1.021346
Lag 6	1.025737	1.006178	1.045676	1.013612	1.003282	1.024048
Lag 7	1.029059	1.008007	1.050551	1.015358	1.004252	1.026586
Lag 8	1.032273	1.009877	1.055166	1.017044	1.005243	1.028983
Lag 9	1.035373	1.011741	1.059557	1.018667	1.00623	1.031258
Lag 10	1.038353	1.01356	1.063752	1.020226	1.007192	1.033429
Lag 11	1.041208	1.015302	1.067775	1.021718	1.008113	1.035507
Lag 12	1.043934	1.016945	1.07164	1.02314	1.00898	1.037499
Lag 13	1.046528	1.018472	1.075356	1.024492	1.009786	1.039412
Lag 14	1.048984	1.019875	1.078925	1.025771	1.010526	1.041246
Lag 15	1.051302	1.021148	1.082347	1.026976	1.011197	1.043001
Lag 16	1.053477	1.02229	1.085617	1.028106	1.011798	1.044677
Lag 17	1.055509	1.023303	1.088729	1.029161	1.012331	1.046269
Lag 18	1.057396	1.024189	1.091679	1.030139	1.012798	1.047776
Lag 19	1.059136	1.024951	1.09446	1.03104	1.013199	1.049196
Lag 20	1.060729	1.025592	1.09707	1.031865	1.013536	1.050526
Lag 21	1.062175	1.026112	1.099506	1.032614	1.013809	1.051767
Lag 22	1.063476	1.026512	1.10177	1.033286	1.01402	1.052919
Lag 23	1.064631	1.026791	1.103866	1.033883	1.014166	1.053984
Lag 24	1.065643	1.026944	1.105801	1.034406	1.014246	1.054966
Lag 25	1.066514	1.026968	1.107582	1.034856	1.014259	1.05587
Lag 26	1.067246	1.026859	1.109222	1.035234	1.014202	1.056702
Lag 27	1.067844	1.026611	1.110732	1.035542	1.014072	1.057467
Lag 28	1.068309	1.02622	1.112124	1.035782	1.013866	1.058172
Lag 29	1.068648	1.025683	1.113412	1.035957	1.013584	1.058824
Lag 30	1.068864	1.024998	1.114607	1.036068	1.013224	1.059428
Lag 31	1.068963	1.024166	1.115719	1.036119	1.012786	1.05999
Lag 32	1.06895	1.023192	1.116756	1.036113	1.012273	1.060514
Lag 33	1.068833	1.022081	1.117724	1.036052	1.011688	1.061003
Lag 34	1.068617	1.020843	1.118627	1.035941	1.011036	1.061459
Lag 35	1.068311	1.019492	1.119467	1.035783	1.010324	1.061883
Lag 36	1.067921	1.018041	1.120244	1.035582	1.009559	1.062275
Lag 37	1.067456	1.016505	1.120961	1.035342	1.008748	1.062637
Lag 38	1.066924	1.014897	1.121619	1.035067	1.007899	1.062969
Lag 39	1.066336	1.013229	1.122226	1.034764	1.007017	1.063275
Lag 40	1.0657	1.011506	1.122797	1.034435	1.006105	1.063563
Lag 41	1.065026	1.009725	1.123356	1.034087	1.005163	1.063844
Lag 42	1.064325	1.007871	1.123942	1.033725	1.00418	1.06414
Lag 43	1.063609	1.005913	1.124614	1.033355	1.003142	1.064478
Lag 44	1.062887	1.003798	1.125453	1.032982	1.002019	1.064901
Lag 45	1.062172	1.001453	1.126572	1.032612	1.000773	1.065464

Table S10- The cumulative effect between NO_2 and overall non-accidental mortality (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.000274	0.994656	1.005925	1.000219	0.995737	1.004721
Lag 1	1.001369	0.991	1.011846	1.001091	0.992818	1.009433
Lag 2	1.003184	0.988802	1.017775	1.002538	0.991062	1.014146
Lag 3	1.005627	0.987849	1.023725	1.004484	0.990301	1.018871
Lag 4	1.008611	0.987945	1.029708	1.006859	0.990377	1.023615
Lag 5	1.01205	0.988908	1.035733	1.009595	0.991147	1.028387
Lag 6	1.015865	0.99057	1.041806	1.012629	0.992474	1.033193
Lag 7	1.01998	0.992775	1.047931	1.015898	0.994235	1.038033
Lag 8	1.024324	0.995384	1.054105	1.019346	0.996318	1.042906
Lag 9	1.028826	0.99827	1.060317	1.022916	0.998621	1.047803
Lag 10	1.033422	1.001322	1.066551	1.026558	1.001054	1.052711
Lag 11	1.03805	1.004444	1.07278	1.030221	1.003541	1.057611
Lag 12	1.042651	1.007552	1.078972	1.033861	1.006017	1.062475
Lag 13	1.047171	1.01058	1.085088	1.037433	1.008426	1.067274
Lag 14	1.05156	1.013469	1.091082	1.040898	1.010724	1.071972
Lag 15	1.05577	1.016175	1.096907	1.044219	1.012875	1.076532
Lag 16	1.059758	1.01866	1.102514	1.047363	1.014849	1.080917
Lag 17	1.063486	1.020894	1.107856	1.050299	1.016623	1.085091
Lag 18	1.066921	1.022853	1.112888	1.053003	1.018178	1.089018
Lag 19	1.070032	1.024516	1.11757	1.05545	1.019498	1.09267
Lag 20	1.072796	1.025867	1.12187	1.057623	1.02057	1.096021
Lag 21	1.075191	1.026892	1.125763	1.059506	1.021383	1.099052
Lag 22	1.077205	1.027578	1.12923	1.061088	1.021927	1.101749
Lag 23	1.078828	1.027915	1.132262	1.062362	1.022194	1.104108
Lag 24	1.080054	1.027896	1.134859	1.063325	1.022179	1.106126
Lag 25	1.080886	1.027516	1.137028	1.063978	1.021878	1.107812
Lag 26	1.08133	1.026774	1.138785	1.064326	1.021289	1.109176
Lag 27	1.081397	1.025672	1.140149	1.064378	1.020415	1.110235
Lag 28	1.081104	1.024217	1.14115	1.064148	1.019261	1.111012
Lag 29	1.080473	1.022424	1.141819	1.063653	1.017838	1.111531
Lag 30	1.079532	1.020311	1.142191	1.062915	1.016161	1.11182
Lag 31	1.078313	1.017906	1.142305	1.061958	1.01425	1.111909
Lag 32	1.076853	1.015243	1.142201	1.060811	1.012135	1.111828
Lag 33	1.075194	1.012365	1.141921	1.059507	1.009846	1.11161
Lag 34	1.073382	1.009322	1.141507	1.058084	1.007425	1.111289
Lag 35	1.071469	1.00617	1.141005	1.05658	1.004916	1.1109
Lag 36	1.069511	1.002972	1.140463	1.05504	1.002369	1.110479
Lag 37	1.067567	0.999794	1.139934	1.053511	0.999836	1.110068
Lag 38	1.065703	0.996705	1.139478	1.052044	0.997372	1.109714
Lag 39	1.063987	0.993772	1.139163	1.050693	0.995031	1.10947
Lag 40	1.062492	0.991058	1.139075	1.049516	0.992864	1.109401
Lag 41	1.061296	0.988619	1.139316	1.048574	0.990915	1.109588
Lag 42	1.060481	0.986496	1.140015	1.047932	0.989219	1.110131
Lag 43	1.060135	0.984714	1.141332	1.047659	0.987794	1.111153
Lag 44	1.060349	0.983271	1.143469	1.047828	0.98664	1.112812
Lag 45	1.061222	0.982135	1.146676	1.048516	0.985731	1.1153

Table S11- The cumulative effect between AQI and overall non-accidental mortality (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004644	1.000352	1.008955	1.001484	1.000113	1.002857
Lag 1	1.009019	1.001066	1.017035	1.002877	1.000341	1.00542
Lag 2	1.013135	1.002073	1.024318	1.004184	1.000663	1.007718
Lag 3	1.017003	1.00331	1.030884	1.00541	1.001058	1.009781
Lag 4	1.020636	1.004714	1.036811	1.006558	1.001506	1.011635
Lag 5	1.024044	1.006229	1.042175	1.007632	1.001989	1.013307
Lag 6	1.027238	1.007802	1.047049	1.008637	1.00249	1.014821
Lag 7	1.030228	1.009387	1.0515	1.009575	1.002994	1.016199
Lag 8	1.033025	1.010943	1.055589	1.010452	1.003489	1.017462
Lag 9	1.035639	1.012437	1.059372	1.011269	1.003963	1.018628
Lag 10	1.038079	1.013843	1.062895	1.012031	1.004409	1.019711
Lag 11	1.040356	1.015142	1.066196	1.012741	1.004821	1.020723
Lag 12	1.042477	1.016323	1.069305	1.013401	1.005195	1.021674
Lag 13	1.044452	1.017381	1.072244	1.014015	1.005529	1.022572
Lag 14	1.04629	1.018319	1.07503	1.014586	1.005826	1.023421
Lag 15	1.047998	1.019141	1.077672	1.015115	1.006086	1.024226
Lag 16	1.049583	1.019855	1.080177	1.015606	1.006311	1.024987
Lag 17	1.051052	1.020473	1.082548	1.016061	1.006506	1.025707
Lag 18	1.052413	1.021004	1.084788	1.016482	1.006674	1.026385
Lag 19	1.053671	1.02146	1.086899	1.016871	1.006818	1.027024
Lag 20	1.054833	1.021847	1.088883	1.017229	1.00694	1.027623
Lag 21	1.055902	1.022173	1.090744	1.017559	1.007043	1.028185
Lag 22	1.056884	1.022442	1.092487	1.017862	1.007127	1.028711
Lag 23	1.057784	1.022654	1.094121	1.018139	1.007194	1.029203
Lag 24	1.058604	1.022808	1.095653	1.018391	1.007243	1.029664
Lag 25	1.059348	1.0229	1.097095	1.01862	1.007272	1.030097
Lag 26	1.060019	1.022925	1.098458	1.018827	1.00728	1.030506
Lag 27	1.060619	1.022875	1.099755	1.019011	1.007264	1.030896
Lag 28	1.061149	1.022743	1.100998	1.019174	1.007222	1.031268
Lag 29	1.061611	1.02252	1.102196	1.019316	1.007152	1.031627
Lag 30	1.062005	1.022201	1.103359	1.019437	1.007051	1.031976
Lag 31	1.062332	1.021781	1.104492	1.019538	1.006919	1.032315
Lag 32	1.062591	1.021256	1.105598	1.019617	1.006753	1.032645
Lag 33	1.06278	1.020628	1.106674	1.019675	1.006555	1.032967
Lag 34	1.062899	1.019897	1.107715	1.019712	1.006325	1.033277
Lag 35	1.062946	1.01907	1.108712	1.019726	1.006063	1.033575
Lag 36	1.062918	1.018151	1.109653	1.019718	1.005773	1.033856
Lag 37	1.062812	1.017148	1.110526	1.019685	1.005456	1.034116
Lag 38	1.062624	1.016063	1.111318	1.019627	1.005112	1.034352
Lag 39	1.062351	1.014898	1.112021	1.019543	1.004744	1.034561
Lag 40	1.061987	1.013647	1.112632	1.019432	1.004347	1.034743
Lag 41	1.061528	1.012291	1.113159	1.019291	1.003917	1.0349
Lag 42	1.060968	1.0108	1.113626	1.019119	1.003443	1.035039
Lag 43	1.060301	1.009122	1.114076	1.018913	1.00291	1.035172
Lag 44	1.05952	1.00718	1.11458	1.018673	1.002292	1.035322
Lag 45	1.058619	1.004871	1.115241	1.018396	1.001556	1.035519

Table S12- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.00287	0.999161	1.006592	1.001526	0.999554	1.003502
Lag 1	1.005711	0.998826	1.012643	1.003035	0.999375	1.006707
Lag 2	1.008517	0.998916	1.018211	1.004523	0.999423	1.009649
Lag 3	1.011282	0.999356	1.023351	1.005987	0.999657	1.012357
Lag 4	1.013999	1.000077	1.028115	1.007424	1.000041	1.014862
Lag 5	1.016662	1.001013	1.032554	1.008831	1.000539	1.017191
Lag 6	1.019264	1.002106	1.036716	1.010204	1.00112	1.01937
Lag 7	1.021801	1.003302	1.040642	1.011541	1.001755	1.021422
Lag 8	1.024267	1.004553	1.044369	1.012839	1.00242	1.023367
Lag 9	1.026657	1.005819	1.047927	1.014096	1.003092	1.02522
Lag 10	1.028966	1.007067	1.051341	1.015308	1.003754	1.026996
Lag 11	1.031189	1.008271	1.054627	1.016475	1.004392	1.028703
Lag 12	1.033321	1.009411	1.057798	1.017593	1.004996	1.030347
Lag 13	1.03536	1.010474	1.060859	1.01866	1.005559	1.031932
Lag 14	1.0373	1.01145	1.06381	1.019675	1.006076	1.033459
Lag 15	1.039138	1.012335	1.066651	1.020637	1.006544	1.034926
Lag 16	1.040871	1.013127	1.069376	1.021542	1.006963	1.036332
Lag 17	1.042497	1.013825	1.071979	1.02239	1.007332	1.037674
Lag 18	1.044011	1.014431	1.074454	1.02318	1.007653	1.038947
Lag 19	1.045413	1.014945	1.076795	1.023911	1.007924	1.040151
Lag 20	1.046699	1.015367	1.078998	1.024581	1.008147	1.041283
Lag 21	1.047869	1.015696	1.081061	1.02519	1.008321	1.042342
Lag 22	1.04892	1.015929	1.082983	1.025737	1.008444	1.043328
Lag 23	1.049852	1.016063	1.084765	1.026222	1.008515	1.044241
Lag 24	1.050664	1.016094	1.086411	1.026644	1.008531	1.045083
Lag 25	1.051355	1.016014	1.087926	1.027004	1.008489	1.045858
Lag 26	1.051926	1.015819	1.089316	1.0273	1.008386	1.046569
Lag 27	1.052376	1.015501	1.09059	1.027534	1.008218	1.04722
Lag 28	1.052706	1.015054	1.091754	1.027705	1.007981	1.047815
Lag 29	1.052916	1.014472	1.092817	1.027815	1.007674	1.048358
Lag 30	1.053009	1.013753	1.093785	1.027863	1.007294	1.048852
Lag 31	1.052985	1.012894	1.094664	1.027851	1.00684	1.0493
Lag 32	1.052847	1.011896	1.095456	1.027779	1.006312	1.049704
Lag 33	1.052596	1.010761	1.096163	1.027648	1.005711	1.050064
Lag 34	1.052235	1.009495	1.096785	1.027461	1.005041	1.050381
Lag 35	1.051767	1.008106	1.097319	1.027218	1.004305	1.050653
Lag 36	1.051195	1.006602	1.097763	1.02692	1.003507	1.050879
Lag 37	1.050522	1.004993	1.098114	1.02657	1.002653	1.051058
Lag 38	1.049752	1.003286	1.098369	1.02617	1.001747	1.051188
Lag 39	1.048889	1.00149	1.098531	1.025721	1.000792	1.051271
Lag 40	1.047937	0.999603	1.098608	1.025226	0.999789	1.05131
Lag 41	1.046902	0.997622	1.098616	1.024687	0.998734	1.051314
Lag 42	1.045787	0.995529	1.098582	1.024106	0.997619	1.051296
Lag 43	1.044598	0.993296	1.09855	1.023486	0.996428	1.05128
Lag 44	1.043341	0.990877	1.098583	1.022831	0.995136	1.051297
Lag 45	1.042021	0.988204	1.09877	1.022142	0.993706	1.051392

Table S13- The cumulative effect between NO_2 and overall non-accidental mortality (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.001218	0.996225	1.006236	1.000971	0.996989	1.004968
Lag 1	1.002884	0.993637	1.012217	1.002299	0.994924	1.009729
Lag 2	1.004952	0.99208	1.01799	1.003946	0.99368	1.014317
Lag 3	1.007374	0.991406	1.023599	1.005875	0.993142	1.018771
Lag 4	1.010107	0.991479	1.029086	1.00805	0.9932	1.023122
Lag 5	1.013109	0.992171	1.034489	1.010438	0.993753	1.027403
Lag 6	1.016338	0.993365	1.039843	1.013005	0.994706	1.03164
Lag 7	1.019755	0.994953	1.045177	1.01572	0.995974	1.035857
Lag 8	1.023323	0.996838	1.050511	1.018551	0.997478	1.04007
Lag 9	1.027003	0.998935	1.05586	1.021471	0.999151	1.04429
Lag 10	1.030762	1.001169	1.061229	1.02445	1.000932	1.048521
Lag 11	1.034564	1.003477	1.066614	1.027462	1.002771	1.052762
Lag 12	1.038378	1.005805	1.072005	1.030481	1.004625	1.057002
Lag 13	1.042171	1.008111	1.077383	1.033481	1.006461	1.061227
Lag 14	1.045916	1.01036	1.082723	1.036441	1.008251	1.065419
Lag 15	1.049582	1.012523	1.087997	1.039336	1.009972	1.069554
Lag 16	1.053144	1.014579	1.093174	1.042147	1.011607	1.07361
Lag 17	1.056575	1.016507	1.098223	1.044854	1.013139	1.077562
Lag 18	1.059854	1.018292	1.103112	1.047438	1.014557	1.081384
Lag 19	1.062957	1.019918	1.107812	1.049882	1.015849	1.085056
Lag 20	1.065865	1.021371	1.112297	1.052172	1.017002	1.088557
Lag 21	1.068559	1.022636	1.116545	1.054292	1.018006	1.09187
Lag 22	1.071023	1.023698	1.120537	1.05623	1.018849	1.094982
Lag 23	1.073243	1.024542	1.12426	1.057975	1.019519	1.097881
Lag 24	1.075207	1.025154	1.127703	1.059518	1.020004	1.100561
Lag 25	1.076903	1.025518	1.130862	1.06085	1.020293	1.103019
Lag 26	1.078323	1.025621	1.133734	1.061966	1.020375	1.105252
Lag 27	1.079462	1.025449	1.136321	1.06286	1.020239	1.107262
Lag 28	1.080316	1.024993	1.138625	1.06353	1.019877	1.109051
Lag 29	1.080882	1.024244	1.140651	1.063974	1.019283	1.110625
Lag 30	1.08116	1.023199	1.142405	1.064193	1.018453	1.111986
Lag 31	1.081154	1.021857	1.143893	1.064188	1.017388	1.113141
Lag 32	1.080868	1.020222	1.145119	1.063963	1.01609	1.114092
Lag 33	1.080309	1.018305	1.146089	1.063524	1.014567	1.114844
Lag 34	1.079485	1.016117	1.146805	1.062878	1.012829	1.1154
Lag 35	1.078409	1.013678	1.147273	1.062033	1.010891	1.115762
Lag 36	1.077092	1.011008	1.147495	1.060999	1.008767	1.115935
Lag 37	1.075551	1.00813	1.14748	1.059788	1.006477	1.115922
Lag 38	1.073801	1.005068	1.147236	1.058414	1.004038	1.115733
Lag 39	1.071864	1.001843	1.14678	1.056891	1.001469	1.11538
Lag 40	1.069759	0.998472	1.146137	1.055236	0.998782	1.114881
Lag 41	1.06751	0.994966	1.145344	1.053467	0.995984	1.114267
Lag 42	1.065142	0.991323	1.144458	1.051603	0.993075	1.113579
Lag 43	1.06268	0.987525	1.143554	1.049664	0.990041	1.112878
Lag 44	1.060153	0.983537	1.142738	1.047674	0.986852	1.112244
Lag 45	1.057591	0.979297	1.142146	1.045655	0.983458	1.111785

Table S14- The cumulative effect between AQI and overall non-accidental mortality (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003454	0.999698	1.007224	1.001104	0.999903	1.002306
Lag 1	1.006706	0.999743	1.013718	1.002141	0.999918	1.004369
Lag 2	1.009771	1.000078	1.019558	1.003116	1.000025	1.006217
Lag 3	1.01266	1.000647	1.024817	1.004034	1.000207	1.007875
Lag 4	1.015386	1.0014	1.029567	1.004898	1.000448	1.009368
Lag 5	1.01796	1.002289	1.033876	1.005713	1.000732	1.010718
Lag 6	1.020395	1.003271	1.037811	1.006482	1.001045	1.011947
Lag 7	1.022699	1.004305	1.041429	1.007208	1.001376	1.013075
Lag 8	1.024883	1.00536	1.044786	1.007896	1.001712	1.014118
Lag 9	1.026957	1.006407	1.047926	1.008548	1.002046	1.015093
Lag 10	1.028928	1.007424	1.050891	1.009167	1.00237	1.016011
Lag 11	1.030805	1.008396	1.053712	1.009756	1.002679	1.016883
Lag 12	1.032594	1.009313	1.056412	1.010317	1.002971	1.017716
Lag 13	1.034303	1.010171	1.059011	1.010851	1.003243	1.018517
Lag 14	1.035936	1.010969	1.061519	1.011362	1.003497	1.019288
Lag 15	1.037499	1.011711	1.063945	1.01185	1.003733	1.020033
Lag 16	1.038996	1.012401	1.06629	1.012317	1.003952	1.020752
Lag 17	1.040431	1.013046	1.068556	1.012764	1.004156	1.021445
Lag 18	1.041806	1.013651	1.070743	1.013192	1.004348	1.022114
Lag 19	1.043122	1.01422	1.072848	1.013602	1.004529	1.022756
Lag 20	1.044382	1.014758	1.074871	1.013993	1.004699	1.023373
Lag 21	1.045586	1.015265	1.076812	1.014367	1.00486	1.023964
Lag 22	1.046732	1.01574	1.07867	1.014723	1.00501	1.024529
Lag 23	1.047821	1.01618	1.080447	1.01506	1.005149	1.025069
Lag 24	1.048849	1.016577	1.082146	1.015379	1.005275	1.025584
Lag 25	1.049814	1.016923	1.083769	1.015678	1.005384	1.026077
Lag 26	1.050713	1.017207	1.085322	1.015956	1.005474	1.026547
Lag 27	1.05154	1.017418	1.086807	1.016212	1.005541	1.026996
Lag 28	1.052291	1.017542	1.088227	1.016444	1.00558	1.027425
Lag 29	1.05296	1.017567	1.089583	1.016651	1.005588	1.027835
Lag 30	1.053539	1.01748	1.090876	1.01683	1.005561	1.028225
Lag 31	1.054021	1.01727	1.0921	1.016979	1.005494	1.028594
Lag 32	1.054398	1.016928	1.09325	1.017095	1.005386	1.02894
Lag 33	1.054661	1.016444	1.094314	1.017176	1.005233	1.029261
Lag 34	1.054799	1.015814	1.09528	1.017219	1.005033	1.029551
Lag 35	1.054801	1.015031	1.096129	1.017219	1.004786	1.029807
Lag 36	1.054656	1.014094	1.096841	1.017175	1.004489	1.030021
Lag 37	1.054352	1.012996	1.097396	1.017081	1.004141	1.030188
Lag 38	1.053876	1.011734	1.097773	1.016934	1.00374	1.030301
Lag 39	1.053213	1.010297	1.097953	1.016729	1.003283	1.030355
Lag 40	1.05235	1.00867	1.097922	1.016462	1.002766	1.030346
Lag 41	1.051272	1.006829	1.097676	1.016129	1.00218	1.030272
Lag 42	1.049962	1.004738	1.097221	1.015724	1.001514	1.030135
Lag 43	1.048405	1.002345	1.096582	1.015241	1.00075	1.029943
Lag 44	1.046584	0.999575	1.095803	1.014677	0.999864	1.029709
Lag 45	1.044481	0.996332	1.094956	1.014024	0.998825	1.029454

Table S15- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.006703	1.001925	1.011503	1.003561	1.001024	1.006104
Lag 1	1.012456	1.003649	1.021341	1.006608	1.00194	1.011299
Lag 2	1.017335	1.005161	1.029656	1.009186	1.002743	1.015671
Lag 3	1.021412	1.006453	1.036594	1.011336	1.003428	1.019306
Lag 4	1.024763	1.007516	1.042305	1.0131	1.003992	1.02229
Lag 5	1.02746	1.008344	1.046939	1.014518	1.004431	1.024706
Lag 6	1.029576	1.008932	1.050642	1.015629	1.004742	1.026633
Lag 7	1.03118	1.00928	1.053556	1.01647	1.004927	1.028147
Lag 8	1.03234	1.00939	1.055813	1.017079	1.004985	1.029318
Lag 9	1.033122	1.009272	1.057535	1.017488	1.004922	1.030211
Lag 10	1.033585	1.008938	1.058834	1.017731	1.004746	1.030884
Lag 11	1.03379	1.008412	1.059807	1.017838	1.004467	1.031388
Lag 12	1.033791	1.007719	1.060538	1.017839	1.004099	1.031766
Lag 13	1.03364	1.006893	1.061098	1.01776	1.003662	1.032056
Lag 14	1.033385	1.005972	1.061545	1.017626	1.003173	1.032288
Lag 15	1.03307	1.004997	1.061928	1.017461	1.002655	1.032486
Lag 16	1.032736	1.004009	1.062285	1.017286	1.002131	1.03267
Lag 17	1.03242	1.003052	1.062648	1.01712	1.001623	1.032858
Lag 18	1.032155	1.002163	1.063044	1.016981	1.00115	1.033063
Lag 19	1.031969	1.001379	1.063494	1.016884	1.000733	1.033296
Lag 20	1.03189	1.00073	1.064021	1.016843	1.000388	1.033568
Lag 21	1.031939	1.00024	1.064643	1.016868	1.000128	1.033889
Lag 22	1.032135	0.99993	1.065378	1.016971	0.999963	1.034269
Lag 23	1.032492	0.999809	1.066244	1.017158	0.999898	1.034716
Lag 24	1.033023	0.999885	1.067259	1.017436	0.999939	1.03524
Lag 25	1.033733	1.000156	1.068438	1.017809	1.000083	1.035848
Lag 26	1.034629	1.000617	1.069797	1.018278	1.000328	1.036549
Lag 27	1.035709	1.001256	1.071348	1.018843	1.000668	1.037349
Lag 28	1.036972	1.00206	1.073102	1.019504	1.001095	1.038252
Lag 29	1.038411	1.00301	1.075062	1.020257	1.0016	1.03926
Lag 30	1.040015	1.004088	1.077228	1.021095	1.002173	1.040374
Lag 31	1.04177	1.005275	1.079591	1.022011	1.002803	1.041587
Lag 32	1.043659	1.006552	1.082135	1.022997	1.003481	1.042893
Lag 33	1.04566	1.0079	1.084835	1.02404	1.004196	1.044276
Lag 34	1.047748	1.009304	1.087656	1.025127	1.004939	1.04572
Lag 35	1.049893	1.010745	1.090557	1.026243	1.005703	1.047203
Lag 36	1.052062	1.012207	1.093486	1.027371	1.006476	1.048699
Lag 37	1.054218	1.013669	1.096388	1.02849	1.00725	1.050179
Lag 38	1.056319	1.015105	1.099206	1.029581	1.008009	1.051614
Lag 39	1.05832	1.01648	1.101882	1.030618	1.008735	1.052975
Lag 40	1.060172	1.017745	1.104367	1.031577	1.009402	1.054238
Lag 41	1.06182	1.018829	1.106625	1.03243	1.009974	1.055384
Lag 42	1.063207	1.019634	1.108641	1.033147	1.010399	1.056407
Lag 43	1.064271	1.020026	1.110436	1.033697	1.010605	1.057317
Lag 44	1.064948	1.019822	1.112072	1.034047	1.010498	1.058145
Lag 45	1.065168	1.018787	1.113661	1.034161	1.009952	1.058949

Table S16- The cumulative effect between NO_2 and overall non-accidental mortality (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.006952	1.000537	1.013408	1.005539	1.000428	1.010675
Lag 1	1.013106	1.001297	1.025054	1.010436	1.001034	1.019925
Lag 2	1.018518	1.002214	1.035087	1.014736	1.001765	1.027876
Lag 3	1.023242	1.003222	1.04366	1.018487	1.002568	1.034659
Lag 4	1.027333	1.004262	1.050934	1.021733	1.003397	1.040404
Lag 5	1.030848	1.005277	1.057069	1.024519	1.004205	1.045243
Lag 6	1.03384	1.006215	1.062223	1.026889	1.004952	1.049304
Lag 7	1.036362	1.007031	1.066546	1.028885	1.005602	1.052708
Lag 8	1.038465	1.007688	1.070181	1.03055	1.006125	1.055568
Lag 9	1.040199	1.00816	1.073257	1.031922	1.0065	1.057986
Lag 10	1.041613	1.008429	1.075889	1.03304	1.006715	1.060054
Lag 11	1.042751	1.008493	1.078173	1.03394	1.006766	1.061848
Lag 12	1.043657	1.008359	1.080191	1.034656	1.006659	1.063431
Lag 13	1.044372	1.008047	1.082006	1.035221	1.006411	1.064856
Lag 14	1.044934	1.007586	1.083667	1.035665	1.006043	1.066159
Lag 15	1.045379	1.007009	1.08521	1.036016	1.005584	1.06737
Lag 16	1.045739	1.006357	1.086663	1.036301	1.005065	1.068508
Lag 17	1.046046	1.005671	1.088043	1.036544	1.004519	1.06959
Lag 18	1.046327	1.004989	1.089366	1.036766	1.003976	1.070627
Lag 19	1.046607	1.004348	1.090644	1.036987	1.003465	1.071629
Lag 20	1.046908	1.00378	1.09189	1.037225	1.003013	1.072604
Lag 21	1.04725	1.00331	1.093115	1.037495	1.002638	1.073564
Lag 22	1.047649	1.002955	1.094335	1.03781	1.002355	1.074519
Lag 23	1.04812	1.002728	1.095566	1.038182	1.002174	1.075483
Lag 24	1.048673	1.002633	1.096826	1.038618	1.002099	1.076469
Lag 25	1.049317	1.002669	1.098136	1.039127	1.002127	1.077493
Lag 26	1.050058	1.002827	1.099514	1.039712	1.002253	1.078571
Lag 27	1.050899	1.003095	1.100982	1.040376	1.002467	1.079719
Lag 28	1.05184	1.003457	1.102556	1.041119	1.002756	1.08095
Lag 29	1.05288	1.003897	1.104252	1.041939	1.003106	1.082275
Lag 30	1.054011	1.004397	1.106077	1.042832	1.003504	1.083701
Lag 31	1.055228	1.00494	1.108032	1.043791	1.003937	1.085228
Lag 32	1.056518	1.005514	1.11011	1.044809	1.004394	1.086851
Lag 33	1.057869	1.006107	1.112294	1.045874	1.004866	1.088555
Lag 34	1.059263	1.006713	1.114556	1.046973	1.005349	1.09032
Lag 35	1.060682	1.007329	1.11686	1.04809	1.005839	1.092116
Lag 36	1.062102	1.007952	1.119161	1.049209	1.006335	1.09391
Lag 37	1.0635	1.008579	1.121411	1.05031	1.006834	1.095663
Lag 38	1.064846	1.009201	1.12356	1.05137	1.007329	1.097336
Lag 39	1.06611	1.009798	1.125562	1.052365	1.007804	1.098895
Lag 40	1.067257	1.010336	1.127385	1.053267	1.008232	1.100314
Lag 41	1.068251	1.010753	1.12902	1.054049	1.008564	1.101586
Lag 42	1.069051	1.010949	1.130493	1.054679	1.00872	1.102732
Lag 43	1.069615	1.010774	1.131882	1.055123	1.008581	1.103812
Lag 44	1.069898	1.010017	1.133329	1.055345	1.007979	1.104937
Lag 45	1.06985	1.008392	1.135055	1.055307	1.006685	1.106278

Table S17- The cumulative effect between AQI and overall non-accidental mortality (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004602	0.999576	1.009653	1.00147	0.999864	1.003079
Lag 1	1.008328	0.999052	1.017691	1.002658	0.999696	1.005627
Lag 2	1.011263	0.99842	1.024271	1.00359	0.999494	1.007704
Lag 3	1.013487	0.997672	1.029554	1.004296	0.999254	1.009364
Lag 4	1.015082	0.9968	1.0337	1.004802	0.998975	1.010663
Lag 5	1.016124	0.995798	1.036866	1.005132	0.998653	1.011652
Lag 6	1.016689	0.994662	1.039204	1.005311	0.998289	1.012382
Lag 7	1.016849	0.993393	1.040858	1.005361	0.997881	1.012897
Lag 8	1.016671	0.991994	1.041963	1.005305	0.997431	1.013241
Lag 9	1.016221	0.990473	1.042638	1.005162	0.996941	1.013451
Lag 10	1.015558	0.988845	1.042993	1.004953	0.996417	1.013561
Lag 11	1.014739	0.987129	1.043122	1.004693	0.995863	1.013601
Lag 12	1.013817	0.985352	1.043104	1.004401	0.995289	1.013596
Lag 13	1.012838	0.983543	1.043005	1.00409	0.994704	1.013565
Lag 14	1.011846	0.981736	1.04288	1.003776	0.994119	1.013526
Lag 15	1.010882	0.979966	1.042772	1.003469	0.993545	1.013493
Lag 16	1.009978	0.978269	1.042715	1.003182	0.992994	1.013475
Lag 17	1.009168	0.97668	1.042736	1.002925	0.992478	1.013481
Lag 18	1.008476	0.975228	1.042857	1.002704	0.992005	1.013519
Lag 19	1.007925	0.973942	1.043094	1.002529	0.991586	1.013593
Lag 20	1.007535	0.972842	1.043464	1.002405	0.991228	1.013708
Lag 21	1.007318	0.971945	1.043979	1.002336	0.990935	1.013868
Lag 22	1.007285	0.971258	1.044649	1.002326	0.990711	1.014076
Lag 23	1.007443	0.970785	1.045486	1.002376	0.990557	1.014336
Lag 24	1.007794	0.970521	1.046499	1.002488	0.990471	1.01465
Lag 25	1.008336	0.970456	1.047694	1.00266	0.990449	1.015021
Lag 26	1.009062	0.970574	1.049077	1.002891	0.990488	1.01545
Lag 27	1.009964	0.970854	1.050651	1.003178	0.990579	1.015937
Lag 28	1.011028	0.97127	1.052413	1.003516	0.990715	1.016482
Lag 29	1.012235	0.971795	1.054358	1.003899	0.990887	1.017082
Lag 30	1.013564	0.972398	1.056472	1.004321	0.991083	1.017735
Lag 31	1.014988	0.973046	1.058737	1.004772	0.991295	1.018432
Lag 32	1.016476	0.973708	1.061122	1.005243	0.99151	1.019166
Lag 33	1.017994	0.974351	1.063592	1.005723	0.99172	1.019925
Lag 34	1.019503	0.974941	1.066101	1.0062	0.991912	1.020694
Lag 35	1.020958	0.975446	1.068594	1.006659	0.992076	1.021457
Lag 36	1.022312	0.97583	1.071009	1.007086	0.992201	1.022195
Lag 37	1.023513	0.976054	1.073279	1.007465	0.992274	1.022888
Lag 38	1.024503	0.976076	1.075333	1.007777	0.992281	1.023514
Lag 39	1.025222	0.975842	1.077101	1.008003	0.992205	1.024052
Lag 40	1.025604	0.975288	1.078515	1.008123	0.992025	1.024482
Lag 41	1.02558	0.974334	1.079521	1.008115	0.991714	1.024788
Lag 42	1.025077	0.972877	1.080079	1.007957	0.991239	1.024957
Lag 43	1.024019	0.970786	1.080172	1.007624	0.990557	1.024985
Lag 44	1.022327	0.967898	1.079816	1.007091	0.989613	1.024877
Lag 45	1.019917	0.964013	1.079064	1.006331	0.98834	1.024649

Table S18- The cumulative effect between $PM_{2.5}$ and overall non-accidental mortality (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.005934	0.992804	1.019237	1.003153	0.996165	1.01019
Lag 1	1.010931	0.986827	1.035625	1.005801	0.992969	1.018799
Lag 2	1.015074	0.981876	1.049395	1.007992	0.990316	1.025984
Lag 3	1.018444	0.977775	1.060805	1.009771	0.988113	1.031905
Lag 4	1.021121	0.974359	1.070128	1.011183	0.986274	1.03672
Lag 5	1.023184	0.971476	1.077644	1.012269	0.984721	1.040588
Lag 6	1.024707	0.968988	1.08363	1.013071	0.983378	1.043659
Lag 7	1.025764	0.966772	1.088355	1.013626	0.982181	1.046078
Lag 8	1.026422	0.964721	1.092069	1.013972	0.981072	1.047976
Lag 9	1.026747	0.962748	1.095	1.014143	0.980004	1.049471
Lag 10	1.026799	0.960786	1.097348	1.014171	0.978941	1.050668
Lag 11	1.026636	0.95879	1.099282	1.014085	0.977858	1.051653
Lag 12	1.026308	0.956738	1.100938	1.013912	0.976744	1.052495
Lag 13	1.025864	0.954625	1.102419	1.013679	0.975596	1.053249
Lag 14	1.025347	0.952468	1.103801	1.013407	0.974422	1.053951
Lag 15	1.024794	0.950294	1.105134	1.013116	0.973238	1.054628
Lag 16	1.024239	0.94814	1.106446	1.012824	0.972064	1.055294
Lag 17	1.023712	0.946047	1.107754	1.012547	0.970922	1.055957
Lag 18	1.023237	0.944055	1.109061	1.012297	0.969833	1.05662
Lag 19	1.022834	0.9422	1.110369	1.012085	0.968819	1.057283
Lag 20	1.022518	0.940511	1.111676	1.011919	0.967895	1.057945
Lag 21	1.0223	0.939008	1.112981	1.011804	0.967071	1.058605
Lag 22	1.022186	0.937697	1.114289	1.011744	0.966353	1.059267
Lag 23	1.022178	0.936575	1.115605	1.011739	0.965737	1.059933
Lag 24	1.022273	0.935627	1.116943	1.01179	0.965217	1.060609
Lag 25	1.022464	0.934827	1.118317	1.01189	0.964778	1.061303
Lag 26	1.022739	0.934139	1.119742	1.012035	0.9644	1.062022
Lag 27	1.023081	0.93352	1.121235	1.012215	0.96406	1.062775
Lag 28	1.023471	0.932922	1.122808	1.01242	0.963731	1.063568
Lag 29	1.023881	0.932294	1.124465	1.012636	0.963386	1.064403
Lag 30	1.024283	0.931589	1.126199	1.012847	0.962999	1.065276
Lag 31	1.024641	0.930762	1.127989	1.013036	0.962543	1.066176
Lag 32	1.024916	0.929772	1.129796	1.01318	0.961999	1.067085
Lag 33	1.025065	0.928591	1.131562	1.013259	0.961348	1.067972
Lag 34	1.025038	0.927194	1.133208	1.013245	0.960578	1.068799
Lag 35	1.024784	0.925565	1.134639	1.013111	0.95968	1.069516
Lag 36	1.024245	0.923691	1.135744	1.012827	0.958646	1.07007
Lag 37	1.023359	0.92156	1.136402	1.012361	0.957469	1.0704
Lag 38	1.022061	0.919149	1.136495	1.011678	0.956135	1.070447
Lag 39	1.020281	0.91642	1.135913	1.01074	0.954624	1.070155
Lag 40	1.017948	0.913307	1.134578	1.00951	0.952897	1.069486
Lag 41	1.014985	0.909698	1.132458	1.007945	0.950892	1.068422
Lag 42	1.011315	0.905421	1.129593	1.006004	0.948511	1.066983
Lag 43	1.006857	0.900219	1.126126	1.003642	0.945607	1.065239
Lag 44	1.00153	0.893732	1.122329	1.000814	0.941975	1.063327
Lag 45	0.995252	0.885484	1.118627	0.997471	0.93734	1.061459

Table S19- The cumulative effect between NO_2 and overall non-accidental mortality (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.005107	0.988375	1.022124	1.00407	0.99072	1.0176
Lag 1	1.010749	0.9803	1.042143	1.008561	0.984262	1.033459
Lag 2	1.016792	0.975201	1.060157	1.013366	0.980178	1.047677
Lag 3	1.023112	0.972562	1.07629	1.018384	0.978062	1.060368
Lag 4	1.029587	0.971915	1.090681	1.023519	0.977544	1.071657
Lag 5	1.036102	0.972835	1.103484	1.02868	0.978281	1.081675
Lag 6	1.042548	0.974925	1.114863	1.03378	0.979956	1.090559
Lag 7	1.048822	0.97782	1.12498	1.038736	0.982276	1.098442
Lag 8	1.054826	0.981186	1.133992	1.043474	0.984971	1.105452
Lag 9	1.060469	0.984721	1.142044	1.047923	0.987799	1.111706
Lag 10	1.065669	0.98816	1.149258	1.052017	0.990548	1.117301
Lag 11	1.07035	0.99128	1.155727	1.0557	0.993041	1.122312
Lag 12	1.074445	0.993905	1.161511	1.058919	0.995138	1.126788
Lag 13	1.077895	0.995907	1.166634	1.06163	0.996735	1.130749
Lag 14	1.080653	0.997203	1.171086	1.063794	0.99777	1.134188
Lag 15	1.082678	0.997755	1.17483	1.065384	0.99821	1.137078
Lag 16	1.083942	0.997558	1.177808	1.066375	0.998052	1.139375
Lag 17	1.084427	0.996634	1.179953	1.066755	0.997315	1.14103
Lag 18	1.084123	0.995024	1.181201	1.066517	0.99603	1.141992
Lag 19	1.083034	0.992778	1.181495	1.065663	0.994238	1.142219
Lag 20	1.081172	0.98995	1.180801	1.064202	0.991979	1.141683
Lag 21	1.078562	0.986592	1.179106	1.062153	0.989296	1.140377
Lag 22	1.075238	0.982753	1.176426	1.059542	0.986225	1.13831
Lag 23	1.071242	0.978471	1.172808	1.056401	0.982797	1.135518
Lag 24	1.066628	0.973781	1.168327	1.052772	0.97904	1.132057
Lag 25	1.061459	0.96871	1.163087	1.048702	0.974973	1.128007
Lag 26	1.055805	0.963282	1.157214	1.044246	0.970615	1.123464
Lag 27	1.049746	0.95752	1.150854	1.039466	0.965983	1.118538
Lag 28	1.043367	0.95145	1.144164	1.034427	0.961098	1.113351
Lag 29	1.036763	0.94511	1.137304	1.029203	0.955988	1.108025
Lag 30	1.030033	0.938552	1.13043	1.023873	0.950695	1.102683
Lag 31	1.023282	0.931847	1.123689	1.018519	0.945276	1.097437
Lag 32	1.016623	0.925094	1.117207	1.013231	0.93981	1.092387
Lag 33	1.010171	0.918418	1.111092	1.008101	0.934399	1.087617
Lag 34	1.00405	0.911971	1.105427	1.003228	0.929166	1.083194
Lag 35	0.998387	0.90593	1.100281	0.998714	0.924255	1.079171
Lag 36	0.993316	0.900491	1.095709	0.994667	0.919828	1.075595
Lag 37	0.988975	0.895859	1.091769	0.9912	0.916054	1.07251
Lag 38	0.985511	0.892238	1.088534	0.988431	0.913101	1.069975
Lag 39	0.983078	0.889815	1.086117	0.986485	0.911123	1.068081
Lag 40	0.981841	0.888736	1.0847	0.985495	0.910242	1.066969
Lag 41	0.981974	0.889076	1.084578	0.985601	0.91052	1.066874
Lag 42	0.983665	0.890792	1.086221	0.986954	0.911921	1.068162
Lag 43	0.987119	0.893661	1.09035	0.989717	0.914262	1.071398
Lag 44	0.992561	0.897225	1.098026	0.994064	0.917168	1.077408
Lag 45	1.000239	0.900762	1.110701	1.00019	0.920049	1.087312

Table S20- The cumulative effect between AQI and overall non-accidental mortality (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004097	0.990995	1.017372	1.001309	0.997109	1.005527
Lag 1	1.007619	0.983655	1.032166	1.002432	0.99474	1.010182
Lag 2	1.010612	0.97773	1.044601	1.003384	0.992819	1.014061
Lag 3	1.013125	0.972986	1.054919	1.004181	0.991275	1.017256
Lag 4	1.015201	0.969212	1.063372	1.004839	0.990043	1.019857
Lag 5	1.016885	0.96621	1.070218	1.005373	0.989061	1.021954
Lag 6	1.018219	0.963801	1.075711	1.005794	0.988271	1.023629
Lag 7	1.019244	0.961821	1.080095	1.006118	0.987621	1.024962
Lag 8	1.019997	0.960128	1.083599	1.006356	0.987064	1.026025
Lag 9	1.020515	0.958601	1.086429	1.00652	0.986561	1.026882
Lag 10	1.020832	0.95714	1.088762	1.006619	0.98608	1.027587
Lag 11	1.020979	0.955673	1.090746	1.006666	0.985596	1.028186
Lag 12	1.020985	0.954153	1.092498	1.006668	0.985094	1.028714
Lag 13	1.020877	0.952555	1.0941	1.006634	0.984566	1.029196
Lag 14	1.02068	0.950879	1.095606	1.006572	0.984011	1.02965
Lag 15	1.020416	0.949138	1.097046	1.006488	0.983434	1.030082
Lag 16	1.020103	0.947362	1.098429	1.00639	0.982845	1.030498
Lag 17	1.019759	0.945584	1.099752	1.006281	0.982255	1.030895
Lag 18	1.019397	0.943841	1.101002	1.006167	0.981675	1.03127
Lag 19	1.019031	0.942167	1.102165	1.006051	0.981117	1.031618
Lag 20	1.018668	0.94059	1.103228	1.005936	0.980591	1.031936
Lag 21	1.018316	0.939128	1.104182	1.005825	0.980104	1.032222
Lag 22	1.01798	0.937792	1.105024	1.005719	0.979657	1.032474
Lag 23	1.01766	0.936578	1.105762	1.005618	0.979251	1.032694
Lag 24	1.017357	0.935474	1.106407	1.005522	0.978881	1.032887
Lag 25	1.017066	0.934455	1.106981	1.00543	0.97854	1.033058
Lag 26	1.016783	0.933489	1.10751	1.00534	0.978216	1.033216
Lag 27	1.0165	0.932536	1.108024	1.005251	0.977897	1.03337
Lag 28	1.016205	0.931553	1.10855	1.005157	0.977567	1.033527
Lag 29	1.015886	0.930494	1.109115	1.005056	0.977211	1.033695
Lag 30	1.015528	0.929318	1.109734	1.004943	0.976816	1.03388
Lag 31	1.015111	0.92799	1.110412	1.004811	0.976369	1.034082
Lag 32	1.014616	0.926483	1.111134	1.004654	0.975861	1.034297
Lag 33	1.014021	0.924781	1.111872	1.004465	0.975287	1.034517
Lag 34	1.013299	0.922881	1.112575	1.004237	0.974646	1.034726
Lag 35	1.012423	0.92079	1.113176	1.003959	0.973938	1.034905
Lag 36	1.011364	0.91852	1.113593	1.003622	0.973169	1.035029
Lag 37	1.010089	0.916086	1.113737	1.003217	0.972343	1.035072
Lag 38	1.008563	0.913499	1.11352	1.002732	0.971464	1.035007
Lag 39	1.006751	0.910753	1.112867	1.002155	0.970528	1.034813
Lag 40	1.004614	0.907815	1.111734	1.001474	0.969525	1.034476
Lag 41	1.002112	0.904607	1.110126	1.000675	0.968427	1.033997
Lag 42	0.999202	0.900984	1.108127	0.999745	0.967185	1.033401
Lag 43	0.995843	0.896717	1.105926	0.998668	0.965717	1.032743
Lag 44	0.991988	0.891462	1.10385	0.997429	0.963902	1.032122
Lag 45	0.987593	0.884755	1.102386	0.996013	0.961575	1.031684

Table S21- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002914	0.998241	1.007608	1.001367	0.999174	1.003565
Lag 1	1.005994	0.997342	1.014721	1.00281	0.998751	1.006885
Lag 2	1.009219	0.997186	1.021396	1.004317	0.998678	1.009989
Lag 3	1.012567	0.997667	1.02769	1.00588	0.998904	1.012906
Lag 4	1.016018	0.998682	1.033655	1.007489	0.999381	1.015662
Lag 5	1.019552	1.000136	1.039345	1.009132	1.000064	1.018283
Lag 6	1.023148	1.001941	1.044804	1.010802	1.000911	1.020791
Lag 7	1.026788	1.004016	1.050077	1.012488	1.001883	1.023206
Lag 8	1.030452	1.006288	1.055197	1.014183	1.002947	1.025545
Lag 9	1.034122	1.008693	1.060193	1.015877	1.004072	1.027822
Lag 10	1.03778	1.011175	1.065086	1.017563	1.005231	1.030046
Lag 11	1.041409	1.013687	1.069889	1.019232	1.006403	1.032224
Lag 12	1.044991	1.016191	1.074606	1.020876	1.007569	1.034358
Lag 13	1.048509	1.018657	1.079235	1.022488	1.008716	1.036448
Lag 14	1.051948	1.021062	1.083768	1.024061	1.009834	1.038489
Lag 15	1.055292	1.023388	1.088191	1.025589	1.010913	1.040477
Lag 16	1.058527	1.025622	1.092488	1.027063	1.011948	1.042404
Lag 17	1.061638	1.027752	1.09664	1.028479	1.012935	1.044262
Lag 18	1.064611	1.029771	1.100628	1.02983	1.013868	1.046043
Lag 19	1.067433	1.031671	1.104435	1.031111	1.014746	1.04774
Lag 20	1.070092	1.033441	1.108043	1.032316	1.015563	1.049346
Lag 21	1.072576	1.035073	1.111439	1.033441	1.016316	1.050854
Lag 22	1.074875	1.036555	1.114612	1.03448	1.016999	1.052262
Lag 23	1.076978	1.037875	1.117555	1.03543	1.017607	1.053565
Lag 24	1.078876	1.039018	1.120264	1.036286	1.018132	1.054763
Lag 25	1.080561	1.039968	1.122738	1.037045	1.018569	1.055856
Lag 26	1.082024	1.040708	1.124979	1.037704	1.01891	1.056845
Lag 27	1.083258	1.041222	1.126991	1.03826	1.019146	1.057733
Lag 28	1.084259	1.041493	1.12878	1.03871	1.01927	1.058521
Lag 29	1.08502	1.041506	1.130352	1.039052	1.019276	1.059212
Lag 30	1.085537	1.041248	1.131711	1.039285	1.019158	1.05981
Lag 31	1.085808	1.040709	1.132862	1.039407	1.01891	1.060316
Lag 32	1.08583	1.039883	1.133806	1.039416	1.01853	1.060731
Lag 33	1.0856	1.038768	1.134544	1.039313	1.018017	1.061055
Lag 34	1.08512	1.037366	1.135072	1.039097	1.017372	1.061287
Lag 35	1.084389	1.035681	1.135387	1.038769	1.016596	1.061425
Lag 36	1.083408	1.033721	1.135483	1.038327	1.015692	1.061467
Lag 37	1.08218	1.031495	1.135356	1.037775	1.014665	1.061411
Lag 38	1.080708	1.02901	1.135004	1.037112	1.013516	1.061257
Lag 39	1.078997	1.026269	1.134433	1.03634	1.012248	1.061006
Lag 40	1.07705	1.023269	1.133657	1.035462	1.010858	1.060665
Lag 41	1.074874	1.019997	1.132703	1.034479	1.009339	1.060246
Lag 42	1.072475	1.016425	1.131617	1.033395	1.007678	1.059769
Lag 43	1.069862	1.012504	1.13047	1.032212	1.005851	1.059264
Lag 44	1.067043	1.008164	1.12936	1.030934	1.003825	1.058775
Lag 45	1.064026	1.003309	1.128417	1.029564	1.001552	1.05836

Table S22- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002551	0.996419	1.00872	1.001771	0.997512	1.006047
Lag 1	1.005755	0.994393	1.017247	1.003993	0.996103	1.011946
Lag 2	1.00954	0.99372	1.025611	1.006615	0.995635	1.017717
Lag 3	1.013834	0.994217	1.033838	1.009587	0.99598	1.023379
Lag 4	1.018571	0.995712	1.041955	1.01286	0.99702	1.028952
Lag 5	1.023686	0.998046	1.049985	1.01639	0.998643	1.034452
Lag 6	1.029117	1.001072	1.057947	1.020131	1.000745	1.039893
Lag 7	1.034804	1.004654	1.065858	1.024043	1.00323	1.045287
Lag 8	1.040689	1.008667	1.073727	1.028084	1.006011	1.05064
Lag 9	1.046717	1.012998	1.081559	1.032216	1.009009	1.055956
Lag 10	1.052836	1.017547	1.089349	1.036402	1.012153	1.061233
Lag 11	1.058994	1.022223	1.097089	1.040608	1.015381	1.066463
Lag 12	1.065144	1.02695	1.104759	1.044801	1.018639	1.071635
Lag 13	1.071239	1.031661	1.112335	1.048949	1.021882	1.076733
Lag 14	1.077236	1.036302	1.119786	1.053023	1.025072	1.081737
Lag 15	1.083094	1.040825	1.127079	1.056997	1.028177	1.086624
Lag 16	1.088775	1.045192	1.134177	1.060844	1.031171	1.091372
Lag 17	1.094246	1.049369	1.141042	1.064543	1.034031	1.095955
Lag 18	1.099473	1.05333	1.147638	1.068072	1.03674	1.100351
Lag 19	1.10443	1.05705	1.153933	1.071413	1.039281	1.104539
Lag 20	1.10909	1.060508	1.159898	1.074551	1.041641	1.108501
Lag 21	1.113433	1.063682	1.165511	1.077471	1.043805	1.112223
Lag 22	1.117441	1.066555	1.170754	1.080163	1.045762	1.115696
Lag 23	1.1211	1.069109	1.17562	1.082618	1.0475	1.118913
Lag 24	1.124401	1.071326	1.180105	1.084831	1.049008	1.121876
Lag 25	1.127338	1.073192	1.184215	1.086798	1.050277	1.124588
Lag 26	1.129908	1.074693	1.187961	1.088518	1.051296	1.127057
Lag 27	1.132116	1.075818	1.19136	1.089994	1.052061	1.129295
Lag 28	1.133966	1.076562	1.194431	1.091231	1.052566	1.131317
Lag 29	1.135471	1.076924	1.197201	1.092237	1.052812	1.133138
Lag 30	1.136645	1.076908	1.199696	1.093021	1.052801	1.134777
Lag 31	1.137507	1.076527	1.201942	1.093596	1.052542	1.136252
Lag 32	1.138082	1.075801	1.203967	1.09398	1.052049	1.137581
Lag 33	1.138395	1.074758	1.205799	1.094189	1.051341	1.138783
Lag 34	1.138479	1.073435	1.207464	1.094245	1.050442	1.139875
Lag 35	1.138369	1.071874	1.208989	1.094172	1.049381	1.140874
Lag 36	1.138104	1.070124	1.210403	1.093995	1.048191	1.141801
Lag 37	1.137728	1.06824	1.211737	1.093744	1.046909	1.142674
Lag 38	1.137288	1.066276	1.213029	1.09345	1.045572	1.14352
Lag 39	1.136833	1.064285	1.214327	1.093146	1.044216	1.14437
Lag 40	1.13642	1.062315	1.215694	1.09287	1.042873	1.145264
Lag 41	1.136105	1.060404	1.217209	1.09266	1.04157	1.146255
Lag 42	1.13595	1.058575	1.21898	1.092556	1.040322	1.147413
Lag 43	1.136022	1.056829	1.221149	1.092604	1.03913	1.148831
Lag 44	1.136389	1.055138	1.223897	1.09285	1.037976	1.150625
Lag 45	1.137126	1.053444	1.227456	1.093342	1.036818	1.152948

Table S23- The cumulative effect between AQI and non-accidental mortality in cooler months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002719	0.998025	1.007435	1.000799	0.999419	1.002181
Lag 1	1.005671	0.996952	1.014466	1.001665	0.999103	1.004233
Lag 2	1.008827	0.996661	1.021142	1.002588	0.999017	1.006172
Lag 3	1.012158	0.997038	1.027508	1.003561	0.999128	1.008013
Lag 4	1.015637	0.997978	1.033608	1.004574	0.999405	1.00977
Lag 5	1.019236	0.999383	1.039483	1.00562	0.999818	1.011454
Lag 6	1.022929	1.001163	1.045169	1.00669	1.000342	1.013078
Lag 7	1.026692	1.003236	1.050695	1.007778	1.000951	1.014651
Lag 8	1.030499	1.005531	1.056087	1.008875	1.001624	1.01618
Lag 9	1.034328	1.007982	1.061362	1.009976	1.002341	1.01767
Lag 10	1.038155	1.010536	1.066529	1.011074	1.003087	1.019125
Lag 11	1.04196	1.013145	1.071594	1.012163	1.003848	1.020546
Lag 12	1.04572	1.015772	1.076552	1.013236	1.004613	1.021932
Lag 13	1.049417	1.018386	1.081394	1.014288	1.005373	1.023282
Lag 14	1.053031	1.020963	1.086106	1.015314	1.006121	1.024591
Lag 15	1.056545	1.023485	1.090672	1.016309	1.006851	1.025856
Lag 16	1.05994	1.025935	1.095072	1.017269	1.007559	1.027072
Lag 17	1.063203	1.028303	1.099286	1.018189	1.008243	1.028233
Lag 18	1.066317	1.030578	1.103295	1.019065	1.008898	1.029334
Lag 19	1.069269	1.032749	1.107081	1.019894	1.009523	1.030372
Lag 20	1.072047	1.034807	1.110628	1.020673	1.010114	1.031342
Lag 21	1.074641	1.036741	1.113925	1.021398	1.010669	1.032241
Lag 22	1.077038	1.038539	1.116965	1.022068	1.011184	1.033069
Lag 23	1.079233	1.040189	1.119742	1.02268	1.011656	1.033824
Lag 24	1.081216	1.041674	1.122259	1.023232	1.012081	1.034507
Lag 25	1.082982	1.042979	1.124519	1.023724	1.012454	1.035119
Lag 26	1.084527	1.044088	1.126532	1.024153	1.01277	1.035664
Lag 27	1.085847	1.044982	1.128309	1.024519	1.013025	1.036144
Lag 28	1.08694	1.045647	1.129864	1.024823	1.013215	1.036564
Lag 29	1.087807	1.046066	1.131213	1.025063	1.013334	1.036927
Lag 30	1.088447	1.046227	1.132371	1.02524	1.01338	1.037239
Lag 31	1.088865	1.046122	1.133353	1.025356	1.01335	1.037504
Lag 32	1.089062	1.045745	1.134174	1.025411	1.013243	1.037725
Lag 33	1.089046	1.045096	1.134844	1.025406	1.013058	1.037905
Lag 34	1.088821	1.044179	1.135372	1.025344	1.012796	1.038047
Lag 35	1.088398	1.043004	1.135767	1.025227	1.012461	1.038153
Lag 36	1.087784	1.041582	1.136034	1.025057	1.012055	1.038225
Lag 37	1.086991	1.039929	1.136182	1.024837	1.011582	1.038265
Lag 38	1.08603	1.038057	1.136221	1.02457	1.011046	1.038275
Lag 39	1.084916	1.035977	1.136167	1.024261	1.01045	1.038261
Lag 40	1.083663	1.033692	1.13605	1.023913	1.009794	1.03823
Lag 41	1.082287	1.031195	1.135911	1.02353	1.009076	1.038192
Lag 42	1.080805	1.028464	1.135811	1.023118	1.008289	1.038165
Lag 43	1.079236	1.025455	1.135838	1.022681	1.007421	1.038172
Lag 44	1.077599	1.022103	1.136108	1.022224	1.006451	1.038245
Lag 45	1.075915	1.018316	1.136771	1.021754	1.005353	1.038423

Table S24- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran, adjusted for NO_2.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.001999	0.99701	1.007014	1.000938	0.998595	1.003287
Lag 1	1.004269	0.995029	1.013594	1.002002	0.997663	1.00636
Lag 2	1.006779	0.99393	1.019795	1.003177	0.997145	1.009245
Lag 3	1.0095	0.993589	1.025666	1.004449	0.996985	1.011969
Lag 4	1.012403	0.993895	1.031256	1.005804	0.997129	1.014554
Lag 5	1.015461	0.994741	1.036612	1.007229	0.997527	1.017025
Lag 6	1.018646	0.996031	1.041776	1.008711	0.998134	1.0194
Lag 7	1.021934	0.997674	1.046785	1.010239	0.998907	1.021698
Lag 8	1.0253	0.99959	1.051671	1.011799	0.999808	1.023934
Lag 9	1.028719	1.001707	1.056459	1.013382	1.000801	1.02612
Lag 10	1.032168	1.003961	1.061167	1.014975	1.001858	1.028265
Lag 11	1.035625	1.006298	1.065806	1.01657	1.002952	1.030373
Lag 12	1.039068	1.008673	1.070379	1.018155	1.004062	1.032446
Lag 13	1.042478	1.011049	1.074884	1.019723	1.005172	1.034484
Lag 14	1.045834	1.013396	1.07931	1.021263	1.006267	1.036482
Lag 15	1.049118	1.015691	1.083645	1.022767	1.007336	1.038434
Lag 16	1.052313	1.017917	1.087871	1.024228	1.008372	1.040333
Lag 17	1.055402	1.020059	1.091969	1.025638	1.009368	1.042171
Lag 18	1.058369	1.022104	1.09592	1.026991	1.010317	1.04394
Lag 19	1.0612	1.024043	1.099706	1.02828	1.011217	1.045632
Lag 20	1.063883	1.025865	1.10331	1.0295	1.012061	1.047239
Lag 21	1.066404	1.027559	1.106717	1.030644	1.012845	1.048756
Lag 22	1.068753	1.029115	1.109919	1.03171	1.013565	1.050179
Lag 23	1.070921	1.030519	1.112907	1.032692	1.014214	1.051506
Lag 24	1.072899	1.031759	1.115679	1.033586	1.014787	1.052734
Lag 25	1.074679	1.03282	1.118235	1.034391	1.015276	1.053866
Lag 26	1.076257	1.033687	1.12058	1.035104	1.015677	1.054903
Lag 27	1.077627	1.034347	1.122719	1.035723	1.015981	1.055848
Lag 28	1.078787	1.034785	1.124661	1.036246	1.016183	1.056705
Lag 29	1.079735	1.034988	1.126417	1.036673	1.016277	1.057479
Lag 30	1.08047	1.034949	1.127994	1.037005	1.016258	1.058174
Lag 31	1.080994	1.03466	1.129403	1.037241	1.016125	1.058795
Lag 32	1.081308	1.034119	1.130651	1.037382	1.015876	1.059344
Lag 33	1.081417	1.033328	1.131744	1.037431	1.015511	1.059824
Lag 34	1.081325	1.032292	1.132687	1.03739	1.015033	1.060239
Lag 35	1.081039	1.031021	1.133484	1.037261	1.014446	1.060589
Lag 36	1.080567	1.029527	1.134138	1.037048	1.013756	1.060876
Lag 37	1.079918	1.027823	1.134654	1.036756	1.012967	1.061103
Lag 38	1.079102	1.02592	1.135041	1.036388	1.012086	1.061273
Lag 39	1.078131	1.023826	1.135316	1.03595	1.011116	1.061394
Lag 40	1.077018	1.021544	1.135505	1.035448	1.010057	1.061476
Lag 41	1.075777	1.019064	1.135647	1.034887	1.008905	1.061539
Lag 42	1.074424	1.016361	1.135804	1.034276	1.007648	1.061608
Lag 43	1.072975	1.013394	1.13606	1.033621	1.006266	1.06172
Lag 44	1.071449	1.010094	1.136529	1.03293	1.004727	1.061926
Lag 45	1.069863	1.006372	1.13736	1.032212	1.002986	1.06229

Table S25- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran, adjusted for $PM_{2.5}$.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.000033	0.993329	1.006782	1.000023	0.995363	1.004705
Lag 1	1.001107	0.988714	1.013655	1.000768	0.992149	1.009463
Lag 2	1.00311	0.985897	1.020622	1.002158	0.990185	1.014276
Lag 3	1.005938	0.984649	1.027688	1.00412	0.989314	1.019148
Lag 4	1.009494	0.984755	1.034856	1.006584	0.989388	1.024078
Lag 5	1.013685	0.98602	1.042125	1.009483	0.990271	1.029069
Lag 6	1.01842	0.988264	1.049497	1.012756	0.991835	1.034118
Lag 7	1.023617	0.99132	1.056966	1.016342	0.993964	1.039224
Lag 8	1.029192	0.995033	1.064524	1.020183	0.996548	1.044379
Lag 9	1.03507	0.999263	1.072161	1.024226	0.999488	1.049576
Lag 10	1.041176	1.003881	1.079856	1.028418	1.002693	1.054802
Lag 11	1.047438	1.00877	1.087588	1.032709	1.006082	1.06004
Lag 12	1.053788	1.013827	1.095325	1.037053	1.009582	1.065272
Lag 13	1.060163	1.01896	1.103032	1.041406	1.013129	1.070472
Lag 14	1.066502	1.02409	1.11067	1.045726	1.016668	1.075614
Lag 15	1.072746	1.029146	1.118193	1.049973	1.020151	1.080667
Lag 16	1.078842	1.034068	1.125553	1.054113	1.023537	1.085603
Lag 17	1.08474	1.038806	1.132705	1.058112	1.026792	1.090388
Lag 18	1.090395	1.043315	1.1396	1.06194	1.029884	1.094993
Lag 19	1.095766	1.047555	1.146196	1.06557	1.032789	1.099391
Lag 20	1.100816	1.051493	1.152454	1.068978	1.035484	1.103555
Lag 21	1.105514	1.055098	1.15834	1.072144	1.037948	1.107467
Lag 22	1.109834	1.058343	1.16383	1.075051	1.040163	1.111109
Lag 23	1.113753	1.061203	1.168905	1.077686	1.042115	1.114471
Lag 24	1.117257	1.063658	1.173556	1.080039	1.043789	1.117549
Lag 25	1.120335	1.065689	1.177783	1.082105	1.045172	1.120342
Lag 26	1.122982	1.06728	1.18159	1.08388	1.046256	1.122857
Lag 27	1.1252	1.068423	1.184994	1.085366	1.047034	1.125101
Lag 28	1.126996	1.069113	1.188013	1.086569	1.047503	1.127091
Lag 29	1.128383	1.069352	1.190672	1.087497	1.047666	1.128843
Lag 30	1.12938	1.069151	1.193001	1.088164	1.047529	1.130376
Lag 31	1.13001	1.068527	1.195031	1.088586	1.047104	1.131711
Lag 32	1.130305	1.067509	1.196796	1.088783	1.046411	1.132871
Lag 33	1.130301	1.066134	1.19833	1.088781	1.045475	1.13388
Lag 34	1.130039	1.064449	1.199669	1.088605	1.044328	1.13476
Lag 35	1.129565	1.06251	1.200853	1.088288	1.043006	1.135537
Lag 36	1.128933	1.060378	1.20192	1.087865	1.041552	1.136238
Lag 37	1.1282	1.058123	1.202918	1.087375	1.040014	1.136893
Lag 38	1.127429	1.055815	1.2039	1.086859	1.038438	1.137537
Lag 39	1.126687	1.053525	1.20493	1.086362	1.036873	1.138213
Lag 40	1.126049	1.051321	1.206088	1.085934	1.035366	1.138972
Lag 41	1.125591	1.049262	1.207473	1.085628	1.033957	1.13988
Lag 42	1.125398	1.047392	1.209213	1.085498	1.032678	1.141021
Lag 43	1.125558	1.045739	1.211469	1.085606	1.031546	1.142499
Lag 44	1.126166	1.044302	1.214447	1.086013	1.030561	1.144449
Lag 45	1.127322	1.043048	1.218405	1.086787	1.029701	1.147037

Table S26- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004761	0.998811	1.010747	1.002233	0.999442	1.005031
Lag 1	1.008983	0.997937	1.020153	1.004208	0.999031	1.009411
Lag 2	1.012711	0.997311	1.028348	1.005948	0.998737	1.01321
Lag 3	1.015988	0.996873	1.035469	1.007475	0.998531	1.016498
Lag 4	1.018857	0.996563	1.04165	1.008809	0.998385	1.019342
Lag 5	1.021361	0.996331	1.04702	1.009972	0.998276	1.021806
Lag 6	1.02354	0.996128	1.051705	1.010983	0.99818	1.02395
Lag 7	1.025432	0.995918	1.055822	1.011861	0.998081	1.02583
Lag 8	1.027077	0.995669	1.059475	1.012622	0.997964	1.027495
Lag 9	1.028509	0.995361	1.06276	1.013285	0.997819	1.028989
Lag 10	1.029762	0.994982	1.065757	1.013864	0.997641	1.030351
Lag 11	1.030868	0.99453	1.068535	1.014375	0.997428	1.031611
Lag 12	1.031858	0.994009	1.071148	1.014832	0.997183	1.032794
Lag 13	1.032759	0.993435	1.07364	1.015248	0.996912	1.033922
Lag 14	1.033598	0.992825	1.076045	1.015635	0.996625	1.035008
Lag 15	1.034397	0.992202	1.078387	1.016004	0.996331	1.036065
Lag 16	1.035179	0.99159	1.080684	1.016365	0.996043	1.037101
Lag 17	1.035963	0.991014	1.082951	1.016726	0.995771	1.038122
Lag 18	1.036767	0.990498	1.085198	1.017096	0.995527	1.039132
Lag 19	1.037606	0.99006	1.087434	1.017482	0.995321	1.040137
Lag 20	1.038492	0.98972	1.089667	1.01789	0.99516	1.041139
Lag 21	1.039437	0.989488	1.091907	1.018325	0.995051	1.042143
Lag 22	1.040449	0.989373	1.094161	1.01879	0.994996	1.043153
Lag 23	1.041535	0.989377	1.096441	1.019289	0.994999	1.044173
Lag 24	1.042698	0.989499	1.098758	1.019824	0.995056	1.045208
Lag 25	1.043943	0.989733	1.101122	1.020395	0.995166	1.046263
Lag 26	1.045267	0.990066	1.103545	1.021003	0.995324	1.047344
Lag 27	1.046669	0.990486	1.106039	1.021645	0.995522	1.048454
Lag 28	1.048144	0.990975	1.108612	1.022321	0.995753	1.049599
Lag 29	1.049686	0.991515	1.111271	1.023027	0.996007	1.05078
Lag 30	1.051286	0.992085	1.114019	1.023759	0.996276	1.051999
Lag 31	1.052931	0.992666	1.116855	1.024511	0.99655	1.053256
Lag 32	1.054609	0.993237	1.119773	1.025277	0.996819	1.054547
Lag 33	1.056304	0.99378	1.12276	1.02605	0.997075	1.055866
Lag 34	1.057996	0.994276	1.125799	1.026821	0.997309	1.057207
Lag 35	1.059666	0.994707	1.128866	1.027582	0.997512	1.058558
Lag 36	1.061289	0.995054	1.131934	1.028321	0.997675	1.059908
Lag 37	1.062842	0.995295	1.134973	1.029027	0.997788	1.061243
Lag 38	1.064295	0.995404	1.137954	1.029687	0.997839	1.06255
Lag 39	1.065618	0.995347	1.14085	1.030288	0.997813	1.063819
Lag 40	1.066778	0.99508	1.143643	1.030814	0.997687	1.065041
Lag 41	1.067741	0.994541	1.146329	1.031251	0.997433	1.066215
Lag 42	1.068469	0.993649	1.148924	1.031581	0.997013	1.067347
Lag 43	1.068923	0.992295	1.151467	1.031786	0.996375	1.068456
Lag 44	1.069059	0.990341	1.154034	1.031848	0.995454	1.069574
Lag 45	1.068835	0.987612	1.156738	1.031747	0.994165	1.070749

Table S27- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003512	0.996282	1.010794	1.002438	0.997417	1.007484
Lag 1	1.007275	0.993954	1.020775	1.005046	0.995797	1.014381
Lag 2	1.011269	0.992844	1.030037	1.007813	0.995025	1.020765
Lag 3	1.015477	0.992794	1.038678	1.010723	0.99499	1.026704
Lag 4	1.01988	0.993658	1.046794	1.013764	0.995591	1.032268
Lag 5	1.024459	0.995297	1.054475	1.016923	0.996732	1.037523
Lag 6	1.029198	0.997587	1.061811	1.020187	0.998324	1.04253
Lag 7	1.03408	1.000411	1.068883	1.023545	1.000285	1.047346
Lag 8	1.039087	1.003663	1.075762	1.026985	1.002542	1.052023
Lag 9	1.044204	1.00725	1.082513	1.030494	1.005029	1.056603
Lag 10	1.049413	1.011091	1.089187	1.034061	1.007689	1.061123
Lag 11	1.054699	1.015119	1.095823	1.037676	1.010475	1.065608
Lag 12	1.060047	1.019278	1.102448	1.041327	1.013348	1.070078
Lag 13	1.065441	1.023525	1.109074	1.045004	1.016279	1.07454
Lag 14	1.070867	1.02783	1.115706	1.048696	1.019245	1.078998
Lag 15	1.076309	1.032171	1.122335	1.052394	1.022233	1.083446
Lag 16	1.081754	1.036533	1.128947	1.056089	1.025231	1.087875
Lag 17	1.087187	1.040909	1.135523	1.05977	1.028235	1.092272
Lag 18	1.092596	1.045292	1.142041	1.063428	1.031239	1.096621
Lag 19	1.097967	1.049678	1.148477	1.067055	1.034242	1.10091
Lag 20	1.103287	1.054061	1.154813	1.070643	1.037239	1.105123
Lag 21	1.108545	1.058433	1.16103	1.074184	1.040225	1.109252
Lag 22	1.113728	1.062782	1.167116	1.077669	1.043192	1.113286
Lag 23	1.118825	1.067094	1.173064	1.081092	1.046129	1.117223
Lag 24	1.123826	1.07135	1.178872	1.084445	1.049025	1.121062
Lag 25	1.12872	1.075526	1.184545	1.087723	1.051862	1.124806
Lag 26	1.133498	1.079596	1.190091	1.090918	1.054625	1.12846
Lag 27	1.13815	1.083532	1.195522	1.094026	1.057294	1.132034
Lag 28	1.142669	1.087306	1.200851	1.09704	1.05985	1.135535
Lag 29	1.147045	1.09089	1.206091	1.099956	1.062275	1.138974
Lag 30	1.151273	1.094263	1.211254	1.10277	1.064554	1.142358
Lag 31	1.155345	1.097404	1.216345	1.105477	1.066676	1.14569
Lag 32	1.159256	1.100304	1.221366	1.108075	1.068633	1.148973
Lag 33	1.163001	1.10296	1.226309	1.110559	1.070423	1.1522
Lag 34	1.166574	1.105376	1.23116	1.112928	1.072051	1.155363
Lag 35	1.169973	1.107565	1.235898	1.115179	1.073525	1.158449
Lag 36	1.173195	1.109545	1.240496	1.11731	1.074857	1.16144
Lag 37	1.176237	1.111336	1.244929	1.119322	1.076061	1.164321
Lag 38	1.179099	1.112955	1.249174	1.121212	1.07715	1.167076
Lag 39	1.181779	1.114411	1.253219	1.122981	1.078128	1.169699
Lag 40	1.184278	1.115699	1.257072	1.124629	1.078993	1.172196
Lag 41	1.186597	1.116785	1.260772	1.126158	1.079723	1.174591
Lag 42	1.188737	1.117601	1.264402	1.127569	1.08027	1.176938
Lag 43	1.190702	1.118027	1.268102	1.128863	1.080556	1.179329
Lag 44	1.192496	1.117882	1.272089	1.130043	1.080459	1.181902
Lag 45	1.194121	1.116915	1.276664	1.131113	1.07981	1.184852

Table S28- The cumulative effect between AQI and non-accidental mortality in cooler months (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003642	0.997915	1.009401	1.00107	0.999386	1.002756
Lag 1	1.006918	0.996328	1.01762	1.00203	0.998919	1.00515
Lag 2	1.009869	0.995174	1.024781	1.002893	0.998578	1.007226
Lag 3	1.012536	0.994394	1.031009	1.003671	0.998348	1.009022
Lag 4	1.014954	0.993928	1.036423	1.004375	0.99821	1.010578
Lag 5	1.017159	0.993727	1.041144	1.005016	0.998151	1.011929
Lag 6	1.019186	0.993741	1.045282	1.005605	0.998155	1.013111
Lag 7	1.021065	0.993928	1.048943	1.00615	0.99821	1.014153
Lag 8	1.022827	0.994251	1.052224	1.00666	0.998306	1.015085
Lag 9	1.024498	0.994681	1.05521	1.007144	0.998433	1.015931
Lag 10	1.026105	0.995193	1.057977	1.007608	0.998584	1.016714
Lag 11	1.027669	0.995773	1.060587	1.00806	0.998755	1.017451
Lag 12	1.029212	0.996409	1.063094	1.008505	0.998943	1.018158
Lag 13	1.030751	0.997099	1.065539	1.008948	0.999146	1.018846
Lag 14	1.032303	0.997844	1.067953	1.009395	0.999365	1.019524
Lag 15	1.033882	0.998649	1.070357	1.009848	0.999602	1.020199
Lag 16	1.035498	0.999521	1.072769	1.010312	0.999859	1.020875
Lag 17	1.03716	1.00047	1.075196	1.010789	1.000138	1.021553
Lag 18	1.038876	1.001502	1.077644	1.01128	1.000441	1.022237
Lag 19	1.040648	1.002622	1.080116	1.011788	1.00077	1.022926
Lag 20	1.042479	1.003832	1.082614	1.012311	1.001126	1.023621
Lag 21	1.044368	1.005131	1.085137	1.01285	1.001506	1.024322
Lag 22	1.046312	1.00651	1.087687	1.013404	1.00191	1.02503
Lag 23	1.048304	1.007958	1.090266	1.013971	1.002334	1.025744
Lag 24	1.050337	1.009456	1.092874	1.014549	1.002772	1.026465
Lag 25	1.0524	1.010982	1.095514	1.015135	1.003218	1.027194
Lag 26	1.054479	1.012509	1.098188	1.015724	1.003663	1.02793
Lag 27	1.056558	1.014006	1.100894	1.016313	1.004099	1.028675
Lag 28	1.058618	1.015441	1.103631	1.016895	1.004517	1.029426
Lag 29	1.060639	1.016779	1.106391	1.017466	1.004906	1.030183
Lag 30	1.062596	1.017985	1.109162	1.018018	1.005257	1.030941
Lag 31	1.064462	1.019028	1.111923	1.018543	1.005559	1.031695
Lag 32	1.066209	1.019876	1.114648	1.019035	1.005805	1.032438
Lag 33	1.067804	1.020501	1.1173	1.019483	1.005986	1.03316
Lag 34	1.069212	1.020877	1.119836	1.019878	1.006096	1.033849
Lag 35	1.070397	1.020981	1.122205	1.02021	1.006126	1.034492
Lag 36	1.071317	1.020788	1.124348	1.020468	1.00607	1.035073
Lag 37	1.071932	1.020275	1.126205	1.02064	1.005921	1.035575
Lag 38	1.072195	1.01941	1.127715	1.020714	1.00567	1.035983
Lag 39	1.072061	1.018155	1.128821	1.020676	1.005306	1.036282
Lag 40	1.071479	1.016461	1.129476	1.020514	1.004814	1.036459
Lag 41	1.0704	1.014259	1.129648	1.020211	1.004173	1.036505
Lag 42	1.068769	1.011455	1.12933	1.019754	1.003356	1.03642
Lag 43	1.066533	1.007929	1.128545	1.019126	1.002326	1.036208
Lag 44	1.063638	1.003521	1.127355	1.018311	1.001034	1.035886
Lag 45	1.060026	0.998034	1.125868	1.017293	0.999421	1.035484

Table S29- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.000648	0.994024	1.007316	1.000304	0.99719	1.003428
Lag 1	1.002373	0.990103	1.014796	1.001114	0.995341	1.006919
Lag 2	1.005061	0.987972	1.022445	1.002373	0.994335	1.010476
Lag 3	1.008601	0.987389	1.030268	1.004029	0.994059	1.014098
Lag 4	1.012889	0.988131	1.038266	1.00603	0.99441	1.017787
Lag 5	1.017826	0.989994	1.046441	1.00833	0.99529	1.021541
Lag 6	1.023319	0.99279	1.054788	1.010881	0.996608	1.025358
Lag 7	1.029277	0.996345	1.063298	1.01364	0.998282	1.029234
Lag 8	1.035613	1.000501	1.071956	1.016564	1.000235	1.03316
Lag 9	1.042242	1.005116	1.080739	1.019614	1.002399	1.037126
Lag 10	1.049085	1.010061	1.089616	1.022752	1.004711	1.041117
Lag 11	1.056064	1.01522	1.09855	1.02594	1.007117	1.045115
Lag 12	1.063105	1.020494	1.107494	1.029146	1.00957	1.049101
Lag 13	1.070136	1.025796	1.116394	1.032336	1.012029	1.053051
Lag 14	1.077092	1.031048	1.125192	1.035481	1.014458	1.056939
Lag 15	1.083907	1.036185	1.133826	1.038552	1.016828	1.060739
Lag 16	1.090522	1.041152	1.142232	1.041523	1.019114	1.064424
Lag 17	1.096881	1.045899	1.150347	1.044369	1.021292	1.067968
Lag 18	1.102932	1.050382	1.158111	1.047071	1.023345	1.071346
Lag 19	1.108629	1.054563	1.165468	1.049606	1.025255	1.074536
Lag 20	1.11393	1.058405	1.172368	1.05196	1.027008	1.077518
Lag 21	1.118799	1.061878	1.178771	1.054116	1.028588	1.080277
Lag 22	1.123204	1.064951	1.184644	1.056062	1.029985	1.0828
Lag 23	1.12712	1.067596	1.189963	1.057789	1.031185	1.08508
Lag 24	1.130528	1.06979	1.194716	1.05929	1.032179	1.087112
Lag 25	1.133415	1.071509	1.198897	1.060559	1.032958	1.088897
Lag 26	1.135773	1.072737	1.202513	1.061594	1.033513	1.090438
Lag 27	1.137601	1.073459	1.205577	1.062396	1.03384	1.091741
Lag 28	1.138906	1.073668	1.208109	1.062968	1.033934	1.092817
Lag 29	1.1397	1.073362	1.210137	1.063316	1.033796	1.093678
Lag 30	1.14	1.072548	1.211693	1.063447	1.033428	1.094338
Lag 31	1.139832	1.071243	1.212812	1.063373	1.032837	1.094812
Lag 32	1.139226	1.06947	1.213531	1.063108	1.032035	1.095117
Lag 33	1.138219	1.067265	1.213891	1.062667	1.031035	1.095269
Lag 34	1.136856	1.064672	1.213933	1.062069	1.029858	1.095287
Lag 35	1.135183	1.061743	1.213702	1.061335	1.028527	1.09519
Lag 36	1.133256	1.058538	1.213247	1.060489	1.027068	1.094997
Lag 37	1.131134	1.055122	1.212621	1.059556	1.025511	1.094731
Lag 38	1.128882	1.051561	1.211888	1.058565	1.023885	1.094421
Lag 39	1.12657	1.047921	1.211123	1.057547	1.022219	1.094096
Lag 40	1.124274	1.044259	1.210421	1.056535	1.02054	1.093798
Lag 41	1.122074	1.040625	1.209897	1.055563	1.018871	1.093576
Lag 42	1.120054	1.037049	1.209702	1.054671	1.017226	1.093493
Lag 43	1.118304	1.033538	1.210022	1.053897	1.015608	1.093629
Lag 44	1.116919	1.03007	1.211092	1.053284	1.014006	1.094083
Lag 45	1.116001	1.026586	1.213203	1.052877	1.012395	1.094978

Table S30- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	0.999743	0.991941	1.007607	0.999822	0.994396	1.005277
Lag 1	1.000878	0.98656	1.015404	1.00061	0.990647	1.010672
Lag 2	1.003249	0.983505	1.02339	1.002255	0.988516	1.016186
Lag 3	1.006713	0.982461	1.031565	1.004657	0.987787	1.021816
Lag 4	1.011134	0.983139	1.039927	1.007719	0.988261	1.027561
Lag 5	1.016383	0.985275	1.048473	1.011349	0.989751	1.033418
Lag 6	1.022339	0.988627	1.0572	1.01546	0.992088	1.039383
Lag 7	1.028884	0.99297	1.066096	1.019971	0.995113	1.045449
Lag 8	1.035906	0.998098	1.075147	1.0248	0.998679	1.051605
Lag 9	1.0433	1.00382	1.084332	1.029874	1.002651	1.057836
Lag 10	1.050962	1.009967	1.09362	1.03512	1.006911	1.06412
Lag 11	1.058792	1.016384	1.10297	1.04047	1.011349	1.07043
Lag 12	1.066698	1.022936	1.112332	1.045859	1.015873	1.076731
Lag 13	1.074589	1.029507	1.121644	1.051226	1.0204	1.082983
Lag 14	1.082379	1.035996	1.130838	1.056512	1.024862	1.08914
Lag 15	1.089988	1.042318	1.139839	1.061665	1.029201	1.095153
Lag 16	1.097342	1.048401	1.148567	1.066634	1.033369	1.100969
Lag 17	1.104371	1.054187	1.156943	1.071374	1.037326	1.106539
Lag 18	1.111012	1.059624	1.164892	1.075843	1.041038	1.111813
Lag 19	1.117208	1.064667	1.172342	1.080006	1.044476	1.116746
Lag 20	1.12291	1.069277	1.179232	1.083831	1.047615	1.1213
Lag 21	1.128076	1.07342	1.185514	1.087291	1.050432	1.125444
Lag 22	1.132671	1.077064	1.191149	1.090365	1.052907	1.129157
Lag 23	1.13667	1.080177	1.196117	1.093037	1.055019	1.132425
Lag 24	1.140054	1.082734	1.200408	1.095296	1.056753	1.135245
Lag 25	1.142814	1.08471	1.20403	1.097137	1.058092	1.137622
Lag 26	1.14495	1.086088	1.207002	1.09856	1.059025	1.139571
Lag 27	1.146469	1.086852	1.209356	1.099572	1.059542	1.141115
Lag 28	1.14739	1.086999	1.211135	1.100185	1.059642	1.14228
Lag 29	1.147737	1.086534	1.212387	1.100417	1.059327	1.1431
Lag 30	1.147546	1.085474	1.213167	1.10029	1.05861	1.143611
Lag 31	1.146859	1.083852	1.213529	1.099832	1.05751	1.143848
Lag 32	1.145729	1.081714	1.213532	1.099079	1.056062	1.143849
Lag 33	1.144214	1.079125	1.213228	1.09807	1.054306	1.143651
Lag 34	1.142382	1.076163	1.212674	1.096849	1.052295	1.143288
Lag 35	1.140308	1.072923	1.211924	1.095465	1.050094	1.142797
Lag 36	1.138074	1.06951	1.211033	1.093975	1.047773	1.142214
Lag 37	1.13577	1.066036	1.210066	1.092436	1.045408	1.14158
Lag 38	1.133492	1.062618	1.209094	1.090914	1.04308	1.140943
Lag 39	1.131344	1.05937	1.208209	1.089478	1.040864	1.140363
Lag 40	1.129436	1.056396	1.207527	1.088202	1.038834	1.139916
Lag 41	1.127886	1.05378	1.207203	1.087164	1.037047	1.139704
Lag 42	1.126817	1.051576	1.20744	1.086449	1.035541	1.139859
Lag 43	1.126362	1.049798	1.208509	1.086144	1.034324	1.14056
Lag 44	1.126661	1.048399	1.210764	1.086344	1.033367	1.142037
Lag 45	1.127864	1.047267	1.214663	1.08715	1.032592	1.14459

Table S31- The cumulative effect between AQI and non-accidental mortality in cooler months (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002626	0.996159	1.009136	1.000772	0.998869	1.002678
Lag 1	1.006093	0.994075	1.018255	1.001788	0.998254	1.005335
Lag 2	1.0103	0.993512	1.02737	1.003018	0.998088	1.007974
Lag 3	1.015154	0.994254	1.036492	1.004433	0.998307	1.010598
Lag 4	1.020564	0.9961	1.04563	1.006005	0.998851	1.01321
Lag 5	1.026446	0.998866	1.054787	1.007707	0.999666	1.015812
Lag 6	1.032716	1.002383	1.063967	1.009513	1.0007	1.018404
Lag 7	1.039295	1.006494	1.073165	1.011401	1.001906	1.020985
Lag 8	1.046107	1.011059	1.08237	1.013346	1.00324	1.023553
Lag 9	1.053078	1.015948	1.091565	1.015327	1.004664	1.026103
Lag 10	1.060138	1.02105	1.100724	1.017325	1.006146	1.028628
Lag 11	1.067221	1.026263	1.109814	1.019319	1.007654	1.031119
Lag 12	1.074263	1.031503	1.118796	1.021293	1.009164	1.033567
Lag 13	1.081203	1.036695	1.127622	1.023229	1.010656	1.035958
Lag 14	1.087985	1.041778	1.136243	1.025112	1.012111	1.038281
Lag 15	1.094557	1.046697	1.144604	1.02693	1.013514	1.040523
Lag 16	1.100869	1.05141	1.152653	1.028668	1.014854	1.04267
Lag 17	1.106877	1.05588	1.160337	1.030316	1.016121	1.044709
Lag 18	1.112542	1.060073	1.167609	1.031864	1.017306	1.04663
Lag 19	1.11783	1.063963	1.174424	1.033304	1.018403	1.048423
Lag 20	1.12271	1.067527	1.180746	1.034629	1.019405	1.05008
Lag 21	1.12716	1.070742	1.18655	1.035833	1.020307	1.051596
Lag 22	1.131159	1.07359	1.191814	1.036913	1.021104	1.052966
Lag 23	1.134695	1.076054	1.196531	1.037865	1.021793	1.05419
Lag 24	1.137762	1.07812	1.200703	1.038689	1.02237	1.05527
Lag 25	1.140357	1.079774	1.204339	1.039386	1.022831	1.056208
Lag 26	1.142486	1.081009	1.20746	1.039956	1.023175	1.057013
Lag 27	1.144161	1.081819	1.210095	1.040404	1.0234	1.057691
Lag 28	1.145397	1.082205	1.212279	1.040735	1.023507	1.058252
Lag 29	1.146218	1.082172	1.214055	1.040954	1.023498	1.058707
Lag 30	1.146654	1.081735	1.215468	1.04107	1.023377	1.05907
Lag 31	1.146738	1.080915	1.216569	1.041093	1.023148	1.059352
Lag 32	1.146512	1.079742	1.21741	1.041032	1.022822	1.059567
Lag 33	1.146022	1.078257	1.218045	1.040902	1.022408	1.05973
Lag 34	1.145319	1.076509	1.218528	1.040714	1.02192	1.059853
Lag 35	1.144462	1.074556	1.218917	1.040485	1.021375	1.059953
Lag 36	1.143513	1.072462	1.219273	1.040231	1.020789	1.060044
Lag 37	1.14254	1.070296	1.219662	1.039971	1.020182	1.060143
Lag 38	1.141616	1.068129	1.220159	1.039723	1.019574	1.06027
Lag 39	1.140819	1.066032	1.220853	1.03951	1.018985	1.060448
Lag 40	1.140233	1.064066	1.221852	1.039352	1.018432	1.060703
Lag 41	1.139946	1.062282	1.223287	1.039275	1.017929	1.061069
Lag 42	1.140053	1.060714	1.225325	1.039304	1.017487	1.061589
Lag 43	1.140653	1.059369	1.228174	1.039465	1.017108	1.062314
Lag 44	1.141854	1.058224	1.232092	1.039787	1.016784	1.06331
Lag 45	1.143768	1.05722	1.2374	1.040299	1.0165	1.064655

Table S32- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002631	0.99675	1.008548	1.001235	0.998473	1.004004
Lag 1	1.005444	0.994517	1.016491	1.002552	0.997422	1.007709
Lag 2	1.008414	0.993158	1.023904	1.003941	0.996782	1.011152
Lag 3	1.011517	0.992536	1.030862	1.005391	0.996489	1.014372
Lag 4	1.014732	0.992525	1.037436	1.00689	0.996484	1.017404
Lag 5	1.018035	0.993009	1.043693	1.008427	0.996712	1.02028
Lag 6	1.021406	0.993881	1.049693	1.009993	0.997122	1.02303
Lag 7	1.024822	0.995045	1.05549	1.011578	0.997671	1.025679
Lag 8	1.028264	0.996417	1.061129	1.013171	0.998316	1.028248
Lag 9	1.031712	0.997924	1.066644	1.014765	0.999025	1.030753
Lag 10	1.035146	0.999504	1.07206	1.01635	0.999767	1.033207
Lag 11	1.038549	1.001107	1.07739	1.017916	1.00052	1.035616
Lag 12	1.041901	1.002696	1.082638	1.019458	1.001265	1.037981
Lag 13	1.045185	1.00424	1.087799	1.020965	1.001988	1.040301
Lag 14	1.048385	1.005718	1.092862	1.022432	1.002681	1.042571
Lag 15	1.051485	1.007116	1.09781	1.02385	1.003334	1.044785
Lag 16	1.05447	1.008422	1.102621	1.025213	1.003945	1.046932
Lag 17	1.057324	1.009629	1.107273	1.026515	1.004509	1.049003
Lag 18	1.060035	1.010731	1.111745	1.02775	1.005024	1.05099
Lag 19	1.06259	1.011722	1.116015	1.028912	1.005486	1.052883
Lag 20	1.064976	1.012596	1.120065	1.029996	1.005894	1.054675
Lag 21	1.067182	1.013346	1.123879	1.030997	1.006244	1.05636
Lag 22	1.069198	1.01396	1.127446	1.031911	1.00653	1.057933
Lag 23	1.071015	1.014429	1.130758	1.032734	1.006749	1.059391
Lag 24	1.072625	1.01474	1.133812	1.033463	1.006893	1.060733
Lag 25	1.074019	1.014876	1.136609	1.034093	1.006957	1.061961
Lag 26	1.075192	1.014823	1.139153	1.034623	1.006932	1.063076
Lag 27	1.076138	1.014564	1.141449	1.03505	1.006811	1.064082
Lag 28	1.076853	1.014084	1.143508	1.035373	1.006588	1.064982
Lag 29	1.077333	1.013367	1.145338	1.03559	1.006253	1.065782
Lag 30	1.077577	1.012401	1.146949	1.0357	1.005803	1.066486
Lag 31	1.077583	1.011175	1.148352	1.035702	1.005231	1.067098
Lag 32	1.07735	1.009682	1.149553	1.035598	1.004534	1.067622
Lag 33	1.07688	1.007919	1.15056	1.035386	1.00371	1.068061
Lag 34	1.076175	1.005885	1.151378	1.035067	1.002759	1.068417
Lag 35	1.075238	1.003584	1.152008	1.034644	1.001681	1.068692
Lag 36	1.074073	1.001022	1.152455	1.034117	1.00048	1.068886
Lag 37	1.072685	0.998203	1.152723	1.03349	0.999156	1.069003
Lag 38	1.071079	0.995135	1.15282	1.032763	0.997713	1.069045
Lag 39	1.069264	0.991818	1.152758	1.031941	0.99615	1.069018
Lag 40	1.067247	0.988248	1.152562	1.031027	0.994465	1.068933
Lag 41	1.065038	0.984411	1.152268	1.030024	0.992651	1.068805
Lag 42	1.062646	0.98028	1.151933	1.028938	0.990693	1.068659
Lag 43	1.060082	0.975807	1.151636	1.027771	0.988568	1.068529
Lag 44	1.057358	0.970925	1.151485	1.026531	0.986243	1.068464
Lag 45	1.054487	0.965543	1.151625	1.025221	0.983672	1.068524

Table S33- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.001285	0.9938	1.008826	1.000892	0.995691	1.006121
Lag 1	1.003565	0.989697	1.017627	1.002474	0.992834	1.012209
Lag 2	1.006747	0.987431	1.02644	1.00468	0.991255	1.018288
Lag 3	1.01074	0.986765	1.035298	1.007446	0.99079	1.024382
Lag 4	1.015461	0.987483	1.044231	1.010711	0.991291	1.030512
Lag 5	1.020828	0.989387	1.053267	1.014418	0.992618	1.036697
Lag 6	1.026763	0.992295	1.062428	1.01851	0.994643	1.04295
Lag 7	1.033192	0.996038	1.071731	1.022935	0.997247	1.049284
Lag 8	1.040042	1.000464	1.081185	1.02764	1.000322	1.055703
Lag 9	1.047243	1.005434	1.090791	1.032576	1.003771	1.062207
Lag 10	1.054728	1.010823	1.100539	1.037695	1.007504	1.068791
Lag 11	1.06243	1.016521	1.110413	1.042952	1.011444	1.07544
Lag 12	1.070286	1.02243	1.120383	1.048301	1.015523	1.082137
Lag 13	1.078235	1.028464	1.130415	1.053702	1.019682	1.088857
Lag 14	1.086217	1.034551	1.140463	1.059113	1.023869	1.095569
Lag 15	1.094175	1.040627	1.150479	1.064495	1.028041	1.102242
Lag 16	1.102055	1.046635	1.16041	1.069813	1.032159	1.10884
Lag 17	1.109804	1.052526	1.170199	1.075031	1.03619	1.115328
Lag 18	1.117373	1.058255	1.179794	1.080117	1.040104	1.121671
Lag 19	1.124716	1.063781	1.189142	1.085042	1.043873	1.127835
Lag 20	1.131791	1.069065	1.198197	1.089777	1.047471	1.133792
Lag 21	1.138557	1.074069	1.206917	1.094297	1.050873	1.139516
Lag 22	1.144979	1.078756	1.215267	1.09858	1.054055	1.144985
Lag 23	1.151025	1.083089	1.223222	1.102605	1.056994	1.150184
Lag 24	1.156667	1.087033	1.230761	1.106355	1.059665	1.155103
Lag 25	1.161881	1.090555	1.237873	1.109817	1.062048	1.159734
Lag 26	1.16665	1.093622	1.244553	1.112978	1.064121	1.164077
Lag 27	1.170957	1.096208	1.250803	1.11583	1.065868	1.168133
Lag 28	1.174794	1.098288	1.256629	1.118368	1.067272	1.171909
Lag 29	1.178156	1.099848	1.262041	1.120589	1.068324	1.175411
Lag 30	1.181044	1.100876	1.267049	1.122496	1.069018	1.178649
Lag 31	1.183462	1.101375	1.271667	1.124091	1.069354	1.18163
Lag 32	1.185421	1.101352	1.275907	1.125383	1.069339	1.184365
Lag 33	1.186936	1.100826	1.279782	1.126382	1.068984	1.186861
Lag 34	1.188028	1.099827	1.283302	1.127101	1.068311	1.189128
Lag 35	1.188722	1.098391	1.286482	1.127559	1.067342	1.191173
Lag 36	1.189049	1.096563	1.289335	1.127774	1.066108	1.193007
Lag 37	1.189043	1.094391	1.291881	1.12777	1.064641	1.194642
Lag 38	1.188744	1.091925	1.294147	1.127573	1.062975	1.196097
Lag 39	1.188197	1.089216	1.296173	1.127213	1.061142	1.197397
Lag 40	1.18745	1.086304	1.298015	1.126721	1.059171	1.198578
Lag 41	1.186558	1.08322	1.299754	1.126133	1.057082	1.199694
Lag 42	1.185577	1.079976	1.301504	1.125486	1.054883	1.200815
Lag 43	1.18457	1.07656	1.303416	1.124822	1.052564	1.20204
Lag 44	1.183602	1.072926	1.305695	1.124184	1.050096	1.203499
Lag 45	1.182744	1.068991	1.308602	1.123618	1.04742	1.205359

Table S34- The cumulative effect between AQI and non-accidental mortality in cooler months (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004236	0.998415	1.010092	1.001244	0.999534	1.002958
Lag 1	1.008706	0.997833	1.019698	1.002553	0.999362	1.005754
Lag 2	1.013384	0.998119	1.028883	1.003918	0.999446	1.00841
Lag 3	1.018243	0.999143	1.037707	1.005331	0.999748	1.010946
Lag 4	1.023257	1.000789	1.04623	1.006785	1.000232	1.013381
Lag 5	1.028402	1.002946	1.054505	1.008271	1.000866	1.015732
Lag 6	1.033654	1.005516	1.062579	1.009783	1.001619	1.018013
Lag 7	1.038987	1.008409	1.070493	1.011312	1.002466	1.020237
Lag 8	1.044379	1.011545	1.078279	1.012853	1.003382	1.022414
Lag 9	1.049806	1.014856	1.085959	1.014398	1.004347	1.02455
Lag 10	1.055245	1.018284	1.093548	1.015941	1.005343	1.026651
Lag 11	1.060674	1.021779	1.10105	1.017476	1.006357	1.028718
Lag 12	1.066072	1.025303	1.108462	1.018996	1.007376	1.03075
Lag 13	1.071417	1.028823	1.115774	1.020496	1.008393	1.032745
Lag 14	1.076689	1.032315	1.12297	1.02197	1.009398	1.034699
Lag 15	1.081867	1.035759	1.130028	1.023413	1.010387	1.036608
Lag 16	1.086933	1.039138	1.136926	1.024821	1.011356	1.038465
Lag 17	1.091867	1.04244	1.143639	1.026187	1.0123	1.040264
Lag 18	1.096653	1.045651	1.150143	1.027508	1.013216	1.042001
Lag 19	1.101273	1.048759	1.156415	1.028779	1.014101	1.043669
Lag 20	1.10571	1.051752	1.162436	1.029996	1.014951	1.045264
Lag 21	1.109949	1.054614	1.168188	1.031156	1.015763	1.046783
Lag 22	1.113977	1.05733	1.173659	1.032255	1.016531	1.048222
Lag 23	1.117779	1.059882	1.178839	1.03329	1.017252	1.049581
Lag 24	1.121344	1.062251	1.183723	1.034258	1.01792	1.050858
Lag 25	1.124659	1.064415	1.188312	1.035157	1.01853	1.052055
Lag 26	1.127714	1.066352	1.192606	1.035983	1.019075	1.053172
Lag 27	1.1305	1.068041	1.196612	1.036735	1.019549	1.054211
Lag 28	1.13301	1.06946	1.200337	1.037412	1.019948	1.055175
Lag 29	1.135237	1.070589	1.203788	1.038011	1.020264	1.056066
Lag 30	1.137174	1.07141	1.206974	1.038531	1.020494	1.056888
Lag 31	1.138817	1.071909	1.209902	1.038973	1.020634	1.057641
Lag 32	1.140164	1.072074	1.212578	1.039334	1.02068	1.058329
Lag 33	1.141212	1.071901	1.215005	1.039615	1.020632	1.058951
Lag 34	1.141962	1.071387	1.217185	1.039816	1.020488	1.059509
Lag 35	1.142412	1.070535	1.219116	1.039936	1.020249	1.060004
Lag 36	1.142567	1.06935	1.220797	1.039978	1.019917	1.060433
Lag 37	1.142428	1.067838	1.222229	1.039941	1.019492	1.060799
Lag 38	1.142001	1.066007	1.223413	1.039826	1.018978	1.061101
Lag 39	1.141292	1.063858	1.224361	1.039636	1.018373	1.061343
Lag 40	1.140306	1.061389	1.22509	1.039372	1.017678	1.061529
Lag 41	1.139053	1.058585	1.225638	1.039036	1.016886	1.061668
Lag 42	1.137543	1.055416	1.22606	1.038631	1.01599	1.061776
Lag 43	1.135785	1.051833	1.226438	1.038158	1.014974	1.061872
Lag 44	1.133792	1.04776	1.226888	1.037622	1.013816	1.061987
Lag 45	1.131576	1.043094	1.227564	1.037025	1.012487	1.062159

Table S35- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004583	0.996802	1.012424	1.002149	0.998497	1.005814
Lag 1	1.008483	0.994069	1.023106	1.003974	0.997211	1.010782
Lag 2	1.011762	0.99172	1.03221	1.005505	0.996104	1.014995
Lag 3	1.014481	0.98968	1.039904	1.006773	0.995142	1.01854
Lag 4	1.016699	0.98788	1.046359	1.007806	0.994292	1.021503
Lag 5	1.018474	0.986257	1.051742	1.008631	0.993524	1.023967
Lag 6	1.01986	0.984756	1.056215	1.009275	0.992814	1.026009
Lag 7	1.020911	0.983328	1.059931	1.009763	0.992138	1.027702
Lag 8	1.021678	0.981936	1.063029	1.01012	0.991478	1.029112
Lag 9	1.022209	0.980552	1.065636	1.010366	0.990822	1.030296
Lag 10	1.022549	0.979157	1.067864	1.010524	0.99016	1.031307
Lag 11	1.022741	0.977745	1.069808	1.010613	0.989489	1.032187
Lag 12	1.022824	0.976317	1.071546	1.010651	0.988811	1.032974
Lag 13	1.022834	0.974884	1.073143	1.010656	0.988129	1.033697
Lag 14	1.022806	0.973462	1.07465	1.010643	0.987452	1.034378
Lag 15	1.022768	0.972073	1.076107	1.010625	0.98679	1.035036
Lag 16	1.022749	0.970742	1.077542	1.010617	0.986155	1.035684
Lag 17	1.022772	0.969491	1.078981	1.010627	0.985559	1.036333
Lag 18	1.022859	0.968346	1.080441	1.010668	0.985012	1.036991
Lag 19	1.023027	0.967324	1.081938	1.010746	0.984524	1.037666
Lag 20	1.023292	0.966443	1.083486	1.010869	0.984103	1.038362
Lag 21	1.023666	0.965711	1.085098	1.011042	0.983753	1.039088
Lag 22	1.024156	0.965133	1.086789	1.011269	0.983476	1.039848
Lag 23	1.02477	0.964706	1.088574	1.011554	0.983272	1.040649
Lag 24	1.02551	0.964422	1.090466	1.011896	0.983136	1.041498
Lag 25	1.026375	0.964267	1.092483	1.012297	0.983062	1.042402
Lag 26	1.027363	0.964222	1.094639	1.012755	0.983041	1.043367
Lag 27	1.028467	0.964264	1.096945	1.013265	0.98306	1.044398
Lag 28	1.029678	0.964366	1.099414	1.013825	0.983109	1.045501
Lag 29	1.030983	0.9645	1.102048	1.014428	0.983174	1.046677
Lag 30	1.032366	0.96464	1.104848	1.015067	0.98324	1.047924
Lag 31	1.03381	0.964757	1.107805	1.015733	0.983296	1.04924
Lag 32	1.03529	0.964826	1.110901	1.016416	0.98333	1.050615
Lag 33	1.036783	0.964824	1.11411	1.017104	0.983329	1.052039
Lag 34	1.03826	0.964729	1.117396	1.017784	0.983283	1.053495
Lag 35	1.039689	0.96452	1.120716	1.018441	0.983183	1.054963
Lag 36	1.041034	0.964177	1.124018	1.01906	0.983019	1.056422
Lag 37	1.042258	0.963675	1.127249	1.019622	0.982779	1.057846
Lag 38	1.043318	0.962985	1.130353	1.020108	0.982448	1.059212
Lag 39	1.04417	0.962067	1.133279	1.020499	0.982008	1.060499
Lag 40	1.044765	0.960867	1.135988	1.020772	0.981433	1.061688
Lag 41	1.045052	0.959309	1.138458	1.020904	0.980686	1.062772
Lag 42	1.044976	0.957291	1.140694	1.020869	0.979716	1.063751
Lag 43	1.044482	0.954675	1.142737	1.020643	0.978459	1.064645
Lag 44	1.043509	0.951285	1.144674	1.020196	0.976826	1.065492
Lag 45	1.041995	0.946896	1.146645	1.019501	0.974708	1.066353

Table S36- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.00649	0.996735	1.01634	1.004502	0.997731	1.011319
Lag 1	1.012452	0.99441	1.03082	1.008631	0.996115	1.021304
Lag 2	1.017914	0.992869	1.04359	1.012406	0.995042	1.030073
Lag 3	1.022905	0.991965	1.054811	1.015851	0.994413	1.037752
Lag 4	1.027456	0.991561	1.064651	1.018988	0.994132	1.044465
Lag 5	1.031596	0.991532	1.073278	1.021837	0.994112	1.050335
Lag 6	1.035353	0.991762	1.08086	1.02442	0.994272	1.055483
Lag 7	1.038757	0.992145	1.087558	1.026758	0.994539	1.060021
Lag 8	1.041836	0.992594	1.093522	1.028871	0.994851	1.064053
Lag 9	1.044619	0.993032	1.098886	1.030778	0.995156	1.067676
Lag 10	1.047132	0.9934	1.103771	1.0325	0.995412	1.07097
Lag 11	1.049403	0.993656	1.108277	1.034054	0.99559	1.074004
Lag 12	1.051457	0.993775	1.112487	1.035459	0.995673	1.076835
Lag 13	1.053319	0.993745	1.116465	1.036732	0.995652	1.079508
Lag 14	1.055013	0.993569	1.120257	1.03789	0.995529	1.082053
Lag 15	1.056562	0.99326	1.123898	1.038948	0.995314	1.084494
Lag 16	1.057988	0.992838	1.127412	1.039921	0.995021	1.086847
Lag 17	1.059311	0.99233	1.130814	1.040824	0.994667	1.089123
Lag 18	1.060552	0.99176	1.134115	1.041671	0.99427	1.091331
Lag 19	1.061728	0.991154	1.137327	1.042473	0.993849	1.093476
Lag 20	1.062857	0.990536	1.140459	1.043243	0.993418	1.095567
Lag 21	1.063956	0.989922	1.143527	1.043992	0.992991	1.097612
Lag 22	1.065039	0.989326	1.146546	1.044729	0.992575	1.099624
Lag 23	1.06612	0.988754	1.149539	1.045466	0.992177	1.101616
Lag 24	1.067211	0.988207	1.152531	1.046209	0.991796	1.103606
Lag 25	1.068324	0.987682	1.15555	1.046966	0.99143	1.105613
Lag 26	1.069469	0.987171	1.158627	1.047745	0.991073	1.107657
Lag 27	1.070654	0.986662	1.161796	1.048551	0.990719	1.10976
Lag 28	1.071888	0.986144	1.165086	1.04939	0.990358	1.111942
Lag 29	1.073176	0.985606	1.168526	1.050266	0.989982	1.11422
Lag 30	1.074524	0.985037	1.172139	1.051182	0.989585	1.116612
Lag 31	1.075935	0.984433	1.175942	1.05214	0.989164	1.119126
Lag 32	1.077412	0.983792	1.179941	1.053143	0.988717	1.121768
Lag 33	1.078957	0.983119	1.184138	1.054192	0.988247	1.124537
Lag 34	1.08057	0.982424	1.188521	1.055285	0.987761	1.127426
Lag 35	1.082248	0.98172	1.193071	1.056424	0.98727	1.130422
Lag 36	1.083991	0.981024	1.197764	1.057605	0.986784	1.133508
Lag 37	1.085793	0.980355	1.202572	1.058825	0.986316	1.136665
Lag 38	1.087651	0.979725	1.207464	1.060083	0.985876	1.139875
Lag 39	1.089556	0.979143	1.212421	1.061372	0.985469	1.143122
Lag 40	1.091502	0.978599	1.217431	1.062689	0.985089	1.146401
Lag 41	1.09348	0.978068	1.222511	1.064025	0.984718	1.14972
Lag 42	1.095479	0.977493	1.227706	1.065376	0.984316	1.153111
Lag 43	1.097486	0.976777	1.233112	1.066731	0.983815	1.156635
Lag 44	1.09949	0.975778	1.238886	1.068083	0.983116	1.160393
Lag 45	1.101474	0.97429	1.24526	1.069421	0.982075	1.164536

Table S37- The cumulative effect between AQI and non-accidental mortality in cooler months (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.001858	0.994361	1.009411	1.000546	0.998338	1.002759
Lag 1	1.003317	0.989469	1.01736	1.000975	0.996891	1.005075
Lag 2	1.004425	0.985224	1.024001	1.0013	0.995631	1.007
Lag 3	1.005227	0.981533	1.029493	1.001534	0.994533	1.008586
Lag 4	1.005764	0.978311	1.033988	1.001692	0.993571	1.009879
Lag 5	1.006078	0.975481	1.037635	1.001784	0.992725	1.010925
Lag 6	1.006208	0.972975	1.040575	1.001822	0.991975	1.011767
Lag 7	1.006189	0.970732	1.042941	1.001816	0.991301	1.012443
Lag 8	1.006056	0.968701	1.04485	1.001777	0.990691	1.012988
Lag 9	1.00584	0.966842	1.04641	1.001714	0.990131	1.013432
Lag 10	1.00557	0.965123	1.047713	1.001635	0.989613	1.013803
Lag 11	1.005275	0.963525	1.048834	1.001548	0.989131	1.014122
Lag 12	1.004977	0.962034	1.049837	1.001461	0.98868	1.014407
Lag 13	1.004699	0.960647	1.050771	1.00138	0.988261	1.014673
Lag 14	1.004461	0.959368	1.051673	1.00131	0.987874	1.014929
Lag 15	1.004279	0.958204	1.05257	1.001257	0.987521	1.015183
Lag 16	1.00417	0.957167	1.053481	1.001225	0.987207	1.015442
Lag 17	1.004144	0.956267	1.054418	1.001217	0.986934	1.015707
Lag 18	1.004213	0.955517	1.055391	1.001237	0.986706	1.015983
Lag 19	1.004384	0.954926	1.056404	1.001287	0.986526	1.016269
Lag 20	1.004662	0.954498	1.057463	1.001369	0.986396	1.016569
Lag 21	1.005051	0.954233	1.058575	1.001483	0.986316	1.016883
Lag 22	1.005551	0.954127	1.059746	1.00163	0.986284	1.017214
Lag 23	1.006161	0.95417	1.060985	1.001808	0.986297	1.017564
Lag 24	1.006876	0.954343	1.062301	1.002018	0.986349	1.017935
Lag 25	1.007691	0.954625	1.063706	1.002256	0.986435	1.01833
Lag 26	1.008596	0.954989	1.065212	1.002521	0.986546	1.018754
Lag 27	1.00958	0.955403	1.066829	1.002808	0.986671	1.019209
Lag 28	1.01063	0.955835	1.068567	1.003115	0.986802	1.019697
Lag 29	1.01173	0.956249	1.070431	1.003436	0.986928	1.02022
Lag 30	1.012861	0.95661	1.07242	1.003766	0.987038	1.020777
Lag 31	1.014003	0.956888	1.074527	1.004098	0.987122	1.021366
Lag 32	1.015131	0.957051	1.076736	1.004427	0.987172	1.021984
Lag 33	1.016221	0.957075	1.079022	1.004744	0.987179	1.022621
Lag 34	1.017242	0.956936	1.08135	1.005041	0.987137	1.02327
Lag 35	1.018165	0.956614	1.083677	1.005309	0.987039	1.023917
Lag 36	1.018956	0.956091	1.085955	1.005538	0.98688	1.024549
Lag 37	1.019579	0.955346	1.088131	1.005719	0.986654	1.025153
Lag 38	1.019995	0.954352	1.090153	1.00584	0.986352	1.025713
Lag 39	1.020164	0.953073	1.091978	1.005889	0.985963	1.026217
Lag 40	1.020042	0.951457	1.093572	1.005854	0.985471	1.026658
Lag 41	1.019585	0.949429	1.094925	1.005721	0.984853	1.027031
Lag 42	1.018744	0.946886	1.096056	1.005477	0.984076	1.027343
Lag 43	1.017471	0.943689	1.097023	1.005107	0.983098	1.02761
Lag 44	1.015716	0.939656	1.097931	1.004597	0.98186	1.02786
Lag 45	1.013424	0.934563	1.098941	1.00393	0.980292	1.028138

Table S38- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in cooler months (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	0.990554	0.968831	1.012764	0.995554	0.985244	1.005972
Lag 1	0.984399	0.944902	1.025548	0.992645	0.973743	1.011914
Lag 2	0.981119	0.926979	1.038422	0.991091	0.965028	1.017858
Lag 3	0.980347	0.914047	1.051457	0.990725	0.958684	1.023837
Lag 4	0.981752	0.905247	1.064722	0.991391	0.95434	1.029881
Lag 5	0.985034	0.89985	1.078282	0.992945	0.951664	1.036018
Lag 6	0.989914	0.897218	1.092188	0.995252	0.950356	1.042269
Lag 7	0.996136	0.896796	1.106481	0.998184	0.950146	1.048651
Lag 8	1.003455	0.898093	1.121179	1.001621	0.950791	1.055168
Lag 9	1.01164	0.900676	1.136275	1.005448	0.952074	1.061814
Lag 10	1.02047	0.904168	1.151733	1.009559	0.953805	1.068572
Lag 11	1.029734	0.908239	1.167482	1.013851	0.955819	1.075407
Lag 12	1.03923	0.912609	1.183418	1.01823	0.957976	1.082274
Lag 13	1.048763	0.917043	1.199404	1.022605	0.960158	1.089113
Lag 14	1.058151	0.921342	1.215273	1.026892	0.962268	1.095855
Lag 15	1.067218	0.925348	1.230839	1.031014	0.96423	1.102422
Lag 16	1.075803	0.928928	1.245901	1.034899	0.96598	1.108735
Lag 17	1.083757	0.931978	1.260253	1.038484	0.967468	1.114713
Lag 18	1.090942	0.934411	1.273695	1.041711	0.968653	1.12028
Lag 19	1.09724	0.936156	1.286042	1.04453	0.969502	1.125365
Lag 20	1.102547	0.937153	1.297131	1.046899	0.969986	1.12991
Lag 21	1.106778	0.937352	1.306828	1.048783	0.970083	1.133868
Lag 22	1.109868	0.936709	1.315037	1.050157	0.96977	1.137207
Lag 23	1.11177	0.935187	1.321696	1.051001	0.96903	1.139907
Lag 24	1.112462	0.932758	1.326787	1.051308	0.967848	1.141966
Lag 25	1.111939	0.929399	1.33033	1.051076	0.96621	1.143396
Lag 26	1.110219	0.925101	1.332381	1.050313	0.964109	1.144224
Lag 27	1.107344	0.919865	1.333033	1.049035	0.961544	1.144487
Lag 28	1.103372	0.91371	1.332404	1.047267	0.958518	1.144233
Lag 29	1.098384	0.90667	1.330635	1.045041	0.955044	1.14352
Lag 30	1.092478	0.898805	1.327884	1.042399	0.951145	1.142409
Lag 31	1.085772	0.890194	1.324319	1.03939	0.946856	1.140968
Lag 32	1.078397	0.880942	1.320111	1.03607	0.942223	1.139265
Lag 33	1.070503	0.871175	1.315437	1.032502	0.937304	1.137369
Lag 34	1.06225	0.861044	1.310472	1.028757	0.932171	1.135351
Lag 35	1.053812	0.850716	1.305394	1.024913	0.926904	1.133284
Lag 36	1.045374	0.840368	1.30039	1.021052	0.921594	1.131242
Lag 37	1.037132	0.830188	1.295662	1.017264	0.916336	1.129309
Lag 38	1.029292	0.820359	1.291438	1.013647	0.911226	1.127579
Lag 39	1.02207	0.811053	1.287987	1.010301	0.906359	1.126164
Lag 40	1.015691	0.802421	1.285643	1.007336	0.901817	1.125201
Lag 41	1.010393	0.794579	1.284824	1.004866	0.897669	1.124865
Lag 42	1.006428	0.787593	1.286066	1.003013	0.893955	1.125375
Lag 43	1.004063	0.781466	1.290066	1.001906	0.890683	1.127017
Lag 44	1.003586	0.776116	1.297723	1.001682	0.887815	1.130153
Lag 45	1.005308	0.771369	1.310195	1.002488	0.885261	1.135239

Table S39- The cumulative effect between NO_2 and non-accidental mortality in cooler months (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	0.999821	0.971442	1.029029	0.999875	0.98008	1.020071
Lag 1	1.002393	0.95036	1.057274	1.001661	0.965261	1.039434
Lag 2	1.007328	0.935424	1.084759	1.005083	0.9547	1.058125
Lag 3	1.014269	0.92553	1.111516	1.009887	0.947676	1.076182
Lag 4	1.022881	0.919746	1.137581	1.015835	0.94356	1.093646
Lag 5	1.03285	0.917269	1.162995	1.0227	0.941794	1.110555
Lag 6	1.043873	0.917395	1.187788	1.030267	0.941884	1.126943
Lag 7	1.055659	0.919499	1.211982	1.038331	0.943384	1.142835
Lag 8	1.067928	0.923023	1.23558	1.046696	0.945893	1.158242
Lag 9	1.080405	0.927469	1.258559	1.055174	0.949055	1.173158
Lag 10	1.092827	0.932397	1.280862	1.063584	0.952554	1.187557
Lag 11	1.104942	0.93742	1.302402	1.071759	0.956115	1.20139
Lag 12	1.116508	0.942209	1.323051	1.079537	0.959504	1.214586
Lag 13	1.127297	0.946485	1.342651	1.08677	0.962525	1.227053
Lag 14	1.137099	0.950021	1.361016	1.093324	0.965021	1.238684
Lag 15	1.145721	0.952636	1.377941	1.099074	0.966865	1.249361
Lag 16	1.152993	0.954193	1.393212	1.103914	0.967962	1.25896
Lag 17	1.15877	0.95459	1.406624	1.107752	0.968242	1.267364
Lag 18	1.162933	0.953756	1.417987	1.110514	0.967654	1.274465
Lag 19	1.16539	0.951645	1.427143	1.112143	0.966167	1.280175
Lag 20	1.166083	0.948235	1.433978	1.112602	0.963762	1.284429
Lag 21	1.164982	0.943519	1.438426	1.111872	0.96043	1.287194
Lag 22	1.162089	0.937503	1.440477	1.109955	0.956173	1.288469
Lag 23	1.157441	0.93021	1.440181	1.10687	0.951001	1.288285
Lag 24	1.151103	0.921672	1.437647	1.102657	0.944931	1.28671
Lag 25	1.14317	0.911936	1.433036	1.097374	0.937989	1.283843
Lag 26	1.133766	0.901065	1.426561	1.091097	0.930209	1.279812
Lag 27	1.123039	0.889135	1.418474	1.083918	0.921639	1.274769
Lag 28	1.111162	0.876245	1.409057	1.075944	0.91234	1.268886
Lag 29	1.098327	0.862512	1.398614	1.067298	0.902387	1.262348
Lag 30	1.084744	0.848077	1.387457	1.058115	0.891872	1.255346
Lag 31	1.070639	0.833104	1.375901	1.048541	0.880907	1.248076
Lag 32	1.056248	0.817778	1.364257	1.038733	0.869622	1.240732
Lag 33	1.041818	0.802308	1.352827	1.028858	0.858164	1.233504
Lag 34	1.027603	0.786918	1.341905	1.019089	0.846698	1.226579
Lag 35	1.013866	0.771843	1.331779	1.009609	0.835401	1.220144
Lag 36	1.000874	0.757328	1.322742	1.000607	0.82446	1.214389
Lag 37	0.988902	0.743615	1.315099	0.99228	0.814064	1.209512
Lag 38	0.978233	0.730942	1.309186	0.984833	0.804404	1.205733
Lag 39	0.969158	0.71953	1.30539	0.97848	0.795662	1.203304
Lag 40	0.961985	0.709579	1.304176	0.973445	0.788004	1.202526
Lag 41	0.957039	0.701256	1.306119	0.969967	0.781574	1.20377
Lag 42	0.954671	0.694687	1.311955	0.968299	0.776482	1.207503
Lag 43	0.955267	0.689938	1.322634	0.968719	0.772792	1.21432
Lag 44	0.959257	0.687006	1.339397	0.971527	0.77051	1.224987
Lag 45	0.967133	0.6858	1.363876	0.977059	0.76957	1.240491

Table S40- The cumulative effect between AQI and non-accidental mortality in cooler months (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	0.987795	0.966644	1.009408	0.996395	0.990072	1.002758
Lag 1	0.979238	0.940789	1.019259	0.993848	0.982208	1.005626
Lag 2	0.973849	0.921127	1.029588	0.992236	0.976126	1.008613
Lag 3	0.971204	0.906585	1.040428	0.991443	0.971568	1.011725
Lag 4	0.970927	0.896263	1.051811	0.99136	0.968301	1.014968
Lag 5	0.97268	0.889399	1.06376	0.991886	0.966114	1.018346
Lag 6	0.976154	0.885337	1.076286	0.992927	0.964814	1.021858
Lag 7	0.98106	0.883508	1.089384	0.994392	0.964228	1.0255
Lag 8	0.987132	0.883415	1.103026	0.996198	0.964198	1.02926
Lag 9	0.994117	0.884625	1.117159	0.998266	0.964586	1.033122
Lag 10	1.001774	0.886764	1.131702	1.000522	0.965271	1.037059
Lag 11	1.009878	0.889507	1.146537	1.002895	0.966149	1.041039
Lag 12	1.01821	0.892582	1.161521	1.005322	0.96713	1.045022
Lag 13	1.026567	0.895756	1.176479	1.007742	0.96814	1.048963
Lag 14	1.034752	0.89884	1.191215	1.010098	0.969119	1.05281
Lag 15	1.042586	0.901676	1.205516	1.012341	0.970018	1.056512
Lag 16	1.0499	0.904135	1.219164	1.014425	0.970795	1.060016
Lag 17	1.05654	0.906112	1.231941	1.016308	0.971419	1.063271
Lag 18	1.062371	0.907522	1.243642	1.017954	0.971863	1.066232
Lag 19	1.067274	0.908293	1.254081	1.019334	0.972106	1.068856
Lag 20	1.071148	0.908367	1.263099	1.020421	0.972129	1.071111
Lag 21	1.073915	0.907695	1.270574	1.021195	0.971917	1.072972
Lag 22	1.075518	0.906237	1.276421	1.021643	0.971458	1.074421
Lag 23	1.075922	0.90396	1.280597	1.021756	0.970739	1.075454
Lag 24	1.075115	0.90084	1.283105	1.021531	0.969753	1.076073
Lag 25	1.073108	0.896864	1.283987	1.02097	0.968492	1.076291
Lag 26	1.069936	0.892026	1.28333	1.020081	0.966953	1.076129
Lag 27	1.065655	0.886336	1.281253	1.018879	0.965134	1.075616
Lag 28	1.060343	0.879819	1.277907	1.017382	0.963042	1.074789
Lag 29	1.054098	0.872518	1.273468	1.015617	0.960684	1.07369
Lag 30	1.04704	0.864495	1.268129	1.013611	0.958078	1.072364
Lag 31	1.039302	0.855838	1.262095	1.011403	0.955246	1.070861
Lag 32	1.031037	0.846653	1.255577	1.00903	0.952219	1.069231
Lag 33	1.022412	0.837073	1.248787	1.00654	0.949037	1.067527
Lag 34	1.013606	0.82725	1.241941	1.003983	0.945748	1.065803
Lag 35	1.00481	0.817356	1.235256	1.001412	0.942407	1.064112
Lag 36	0.996229	0.807574	1.228956	0.998889	0.939076	1.062513
Lag 37	0.988076	0.798095	1.22328	0.996478	0.93582	1.061067
Lag 38	0.980574	0.789108	1.218496	0.994247	0.932709	1.059845
Lag 39	0.973959	0.780796	1.21491	0.992269	0.929808	1.058927
Lag 40	0.968479	0.773317	1.212895	0.990624	0.92718	1.05841
Lag 41	0.964397	0.7668	1.212911	0.989394	0.924875	1.058414
Lag 42	0.961991	0.761328	1.215542	0.988668	0.922929	1.059089
Lag 43	0.961563	0.756921	1.221534	0.988538	0.921354	1.060622
Lag 44	0.963444	0.753522	1.231847	0.989106	0.920135	1.063247
Lag 45	0.967996	0.750987	1.247712	0.990479	0.919224	1.067257

Table S41- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002861	0.998003	1.007743	1.001712	0.998804	1.00463
Lag 1	1.005165	0.996102	1.014311	1.00309	0.997664	1.008545
Lag 2	1.006961	0.994263	1.01982	1.004162	0.996561	1.011822
Lag 3	1.008295	0.992456	1.024387	1.004959	0.995476	1.014532
Lag 4	1.009216	0.990654	1.028125	1.005508	0.994393	1.016748
Lag 5	1.009767	0.988832	1.031145	1.005837	0.993298	1.018535
Lag 6	1.009992	0.98697	1.033551	1.005971	0.992177	1.019957
Lag 7	1.009931	0.985051	1.03544	1.005935	0.991021	1.021073
Lag 8	1.009623	0.983064	1.0369	1.005751	0.989824	1.021935
Lag 9	1.009105	0.981004	1.038012	1.005442	0.988581	1.022591
Lag 10	1.008411	0.978869	1.038843	1.005028	0.987293	1.023082
Lag 11	1.007572	0.976665	1.039456	1.004527	0.985961	1.023443
Lag 12	1.006617	0.9744	1.0399	1.003957	0.984591	1.023704
Lag 13	1.005575	0.972087	1.040217	1.003335	0.983191	1.023891
Lag 14	1.004468	0.96974	1.04044	1.002673	0.981769	1.024023
Lag 15	1.00332	0.967377	1.040599	1.001987	0.980335	1.024116
Lag 16	1.002149	0.965014	1.040713	1.001286	0.978901	1.024184
Lag 17	1.000972	0.962668	1.040801	1.000582	0.977475	1.024235
Lag 18	0.999804	0.960353	1.040876	0.999883	0.976067	1.02428
Lag 19	0.998658	0.958084	1.04095	0.999196	0.974685	1.024323
Lag 20	0.997541	0.955868	1.041031	0.998527	0.973335	1.024371
Lag 21	0.996463	0.953714	1.041128	0.99788	0.972021	1.024428
Lag 22	0.995427	0.951623	1.041247	0.997259	0.970744	1.024498
Lag 23	0.994436	0.949595	1.041394	0.996664	0.969505	1.024585
Lag 24	0.99349	0.947626	1.041574	0.996097	0.968301	1.024691
Lag 25	0.992587	0.945708	1.041789	0.995554	0.967127	1.024818
Lag 26	0.991722	0.943832	1.042042	0.995035	0.965977	1.024967
Lag 27	0.990888	0.941983	1.042332	0.994534	0.964844	1.025137
Lag 28	0.990076	0.940147	1.042657	0.994045	0.963717	1.025329
Lag 29	0.989274	0.938306	1.04301	0.993563	0.962587	1.025537
Lag 30	0.988468	0.936443	1.043384	0.993079	0.961441	1.025757
Lag 31	0.987642	0.934538	1.043764	0.992582	0.96027	1.02598
Lag 32	0.986777	0.932572	1.044133	0.992061	0.95906	1.026198
Lag 33	0.985853	0.930526	1.044469	0.991505	0.9578	1.026396
Lag 34	0.984846	0.92838	1.044747	0.990898	0.956476	1.026559
Lag 35	0.983731	0.926113	1.044934	0.990226	0.955077	1.026669
Lag 36	0.982481	0.923705	1.044997	0.989472	0.953589	1.026706
Lag 37	0.981065	0.921131	1.0449	0.988618	0.951997	1.026649
Lag 38	0.979453	0.918367	1.044602	0.987645	0.950285	1.026474
Lag 39	0.97761	0.915382	1.044067	0.986532	0.948435	1.026159
Lag 40	0.9755	0.912142	1.043258	0.985256	0.946423	1.025683
Lag 41	0.973086	0.908604	1.042145	0.983796	0.944223	1.025027
Lag 42	0.97033	0.904713	1.040705	0.982126	0.9418	1.024179
Lag 43	0.967189	0.900406	1.038926	0.980221	0.939112	1.02313
Lag 44	0.963623	0.8956	1.036812	0.978056	0.936108	1.021883
Lag 45	0.959588	0.890199	1.034386	0.975601	0.932723	1.020451

Table S42- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.004742	0.99812	1.011409	1.00431	0.998291	1.010366
Lag 1	1.008661	0.99645	1.021022	1.007871	0.996772	1.019093
Lag 2	1.011818	0.99493	1.028993	1.010738	0.99539	1.026323
Lag 3	1.014274	0.993501	1.035482	1.012968	0.99409	1.032205
Lag 4	1.016089	0.992105	1.040653	1.014616	0.99282	1.03689
Lag 5	1.017322	0.990692	1.044669	1.015735	0.991534	1.040527
Lag 6	1.018032	0.989212	1.047691	1.016379	0.990188	1.043263
Lag 7	1.018272	0.987623	1.049873	1.016597	0.988741	1.045238
Lag 8	1.018098	0.985889	1.051359	1.016439	0.987163	1.046583
Lag 9	1.017559	0.983983	1.05228	1.01595	0.985429	1.047417
Lag 10	1.016704	0.981888	1.052755	1.015174	0.983521	1.047846
Lag 11	1.015579	0.979596	1.052884	1.014153	0.981434	1.047963
Lag 12	1.014226	0.97711	1.052752	1.012925	0.979169	1.047843
Lag 13	1.012685	0.974443	1.052427	1.011525	0.976739	1.04755
Lag 14	1.010992	0.971616	1.051964	1.009988	0.974163	1.047131
Lag 15	1.009182	0.968656	1.051402	1.008343	0.971465	1.046622
Lag 16	1.007283	0.965595	1.05077	1.006619	0.968674	1.04605
Lag 17	1.005324	0.962466	1.05009	1.004839	0.965819	1.045434
Lag 18	1.003328	0.959302	1.049375	1.003025	0.962932	1.044787
Lag 19	1.001317	0.956132	1.048637	1.001197	0.96004	1.04412
Lag 20	0.999309	0.952984	1.047885	0.999372	0.957165	1.043439
Lag 21	0.997318	0.949878	1.047126	0.997561	0.954329	1.042752
Lag 22	0.995356	0.946831	1.046368	0.995777	0.951545	1.042065
Lag 23	0.993433	0.943852	1.045618	0.994028	0.948823	1.041386
Lag 24	0.991553	0.940946	1.044882	0.992318	0.946167	1.04072
Lag 25	0.989721	0.938112	1.04417	0.990651	0.943576	1.040075
Lag 26	0.987937	0.935344	1.043487	0.989027	0.941045	1.039456
Lag 27	0.986197	0.932633	1.042838	0.987444	0.938565	1.038869
Lag 28	0.984496	0.929964	1.042226	0.985896	0.936123	1.038314
Lag 29	0.982826	0.927324	1.04165	0.984375	0.933707	1.037793
Lag 30	0.981175	0.924696	1.041105	0.982872	0.931301	1.037299
Lag 31	0.979531	0.922062	1.04058	0.981374	0.928889	1.036824
Lag 32	0.977875	0.919407	1.04006	0.979866	0.926457	1.036353
Lag 33	0.976188	0.916715	1.03952	0.978329	0.92399	1.035863
Lag 34	0.974449	0.913969	1.03893	0.976744	0.921474	1.035329
Lag 35	0.972632	0.911156	1.038256	0.975089	0.918896	1.034718
Lag 36	0.970711	0.90826	1.037456	0.973338	0.91624	1.033993
Lag 37	0.968654	0.905263	1.036485	0.971463	0.913491	1.033114
Lag 38	0.966431	0.902143	1.0353	0.969435	0.910629	1.03204
Lag 39	0.964005	0.898872	1.033858	0.967223	0.907627	1.030733
Lag 40	0.96134	0.895411	1.032123	0.964792	0.904449	1.029161
Lag 41	0.958396	0.891705	1.030074	0.962105	0.901046	1.027303
Lag 42	0.955131	0.887681	1.027707	0.959126	0.897347	1.025157
Lag 43	0.951503	0.883235	1.025048	0.955813	0.893261	1.022745
Lag 44	0.947466	0.878235	1.022156	0.952126	0.888663	1.020121
Lag 45	0.942975	0.872507	1.019134	0.948021	0.883392	1.017379

Table S43- The cumulative effect between AQI and non-accidental mortality in warmer months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003429	0.998807	1.008073	1.001269	0.999558	1.002983
Lag 1	1.006037	0.997449	1.014698	1.002232	0.999054	1.005419
Lag 2	1.007897	0.995923	1.020016	1.002918	0.998488	1.007367
Lag 3	1.009086	0.994225	1.024169	1.003355	0.997857	1.008884
Lag 4	1.009674	0.992352	1.027298	1.003572	0.997161	1.010025
Lag 5	1.009732	0.990304	1.029541	1.003594	0.996398	1.010841
Lag 6	1.009328	0.988081	1.031031	1.003445	0.995569	1.011382
Lag 7	1.008525	0.985686	1.031892	1.003149	0.994675	1.011695
Lag 8	1.007384	0.983126	1.03224	1.002728	0.993717	1.011822
Lag 9	1.005962	0.98041	1.03218	1.002204	0.992699	1.0118
Lag 10	1.004313	0.977554	1.031806	1.001595	0.991627	1.011664
Lag 11	1.002487	0.974575	1.031199	1.000921	0.990507	1.011443
Lag 12	1.00053	0.971498	1.030429	1.000196	0.989347	1.011164
Lag 13	0.998482	0.968346	1.029556	0.999438	0.988157	1.010846
Lag 14	0.996382	0.965149	1.028627	0.998659	0.986948	1.010509
Lag 15	0.994265	0.961933	1.027683	0.997872	0.985729	1.010165
Lag 16	0.992159	0.958729	1.026755	0.997089	0.984511	1.009827
Lag 17	0.990092	0.955563	1.025868	0.996319	0.983306	1.009504
Lag 18	0.988084	0.952458	1.025043	0.99557	0.982121	1.009203
Lag 19	0.986156	0.949436	1.024297	0.99485	0.980966	1.008931
Lag 20	0.984322	0.946514	1.02364	0.994164	0.979847	1.008691
Lag 21	0.982593	0.943704	1.023084	0.993517	0.978768	1.008488
Lag 22	0.980976	0.941013	1.022635	0.992911	0.977734	1.008324
Lag 23	0.979475	0.938444	1.022299	0.992348	0.976744	1.008202
Lag 24	0.97809	0.935996	1.022078	0.991829	0.9758	1.008121
Lag 25	0.976819	0.933661	1.021973	0.991351	0.974897	1.008082
Lag 26	0.975655	0.931429	1.021981	0.990913	0.974034	1.008085
Lag 27	0.974587	0.929286	1.022096	0.990511	0.973203	1.008127
Lag 28	0.973601	0.927215	1.022309	0.99014	0.972399	1.008205
Lag 29	0.972681	0.925194	1.022606	0.989794	0.971614	1.008314
Lag 30	0.971806	0.923202	1.022969	0.989464	0.970838	1.008446
Lag 31	0.970951	0.921213	1.023374	0.989141	0.970063	1.008594
Lag 32	0.970089	0.919202	1.023793	0.988816	0.969278	1.008747
Lag 33	0.969188	0.91714	1.024191	0.988476	0.968473	1.008892
Lag 34	0.968216	0.915	1.024526	0.988108	0.967635	1.009015
Lag 35	0.967132	0.91275	1.024754	0.987698	0.966753	1.009098
Lag 36	0.965897	0.910358	1.024824	0.987231	0.965814	1.009123
Lag 37	0.964465	0.90779	1.02468	0.986689	0.964804	1.009071
Lag 38	0.96279	0.905006	1.024264	0.986054	0.963707	1.008919
Lag 39	0.96082	0.901963	1.023517	0.985306	0.962506	1.008646
Lag 40	0.958502	0.898614	1.022382	0.984425	0.96118	1.008232
Lag 41	0.95578	0.8949	1.020802	0.983389	0.959707	1.007655
Lag 42	0.952596	0.890755	1.018729	0.982174	0.958058	1.006896
Lag 43	0.948888	0.8861	1.016126	0.980756	0.956201	1.005942
Lag 44	0.944595	0.880839	1.012966	0.979111	0.954094	1.004783
Lag 45	0.939654	0.874862	1.009244	0.97721	0.951691	1.003414

Table S44- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran, adjusted for NO_2.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003878	0.998993	1.008787	1.00232	0.999397	1.005252
Lag 1	1.007041	0.99793	1.016235	1.00421	0.99876	1.00969
Lag 2	1.009547	0.996795	1.022463	1.005706	0.998079	1.013391
Lag 3	1.011454	0.995572	1.027591	1.006843	0.997346	1.016431
Lag 4	1.01282	0.994248	1.031739	1.007657	0.996552	1.018886
Lag 5	1.013698	0.992812	1.035023	1.00818	0.99569	1.020827
Lag 6	1.014142	0.991257	1.037555	1.008444	0.994756	1.022321
Lag 7	1.014203	0.989578	1.03944	1.00848	0.993746	1.023433
Lag 8	1.013929	0.987774	1.040776	1.008317	0.992661	1.024221
Lag 9	1.013367	0.985848	1.041654	1.007983	0.991502	1.024738
Lag 10	1.01256	0.983808	1.042152	1.007502	0.990272	1.025031
Lag 11	1.011548	0.981664	1.042342	1.006899	0.988979	1.025144
Lag 12	1.01037	0.979431	1.042287	1.006197	0.987632	1.025111
Lag 13	1.00906	0.977126	1.042039	1.005416	0.986239	1.024965
Lag 14	1.007651	0.974768	1.041643	1.004574	0.984814	1.024732
Lag 15	1.006171	0.972378	1.041138	1.003691	0.983367	1.024434
Lag 16	1.004646	0.969977	1.040554	1.002779	0.981912	1.02409
Lag 17	1.003099	0.967583	1.03992	1.001855	0.98046	1.023716
Lag 18	1.001551	0.965214	1.039256	1.000929	0.979022	1.023325
Lag 19	1.000019	0.962886	1.038583	1.000011	0.977608	1.022928
Lag 20	0.998516	0.960612	1.037916	0.999111	0.976224	1.022535
Lag 21	0.997055	0.958399	1.03727	0.998235	0.974877	1.022153
Lag 22	0.995643	0.956254	1.036656	0.997389	0.97357	1.021791
Lag 23	0.994288	0.954176	1.036085	0.996575	0.972303	1.021454
Lag 24	0.99299	0.952165	1.035566	0.995797	0.971075	1.021147
Lag 25	0.991751	0.950213	1.035105	0.995052	0.969883	1.020875
Lag 26	0.990568	0.948313	1.034707	0.994342	0.968721	1.02064
Lag 27	0.989436	0.946452	1.034373	0.993661	0.967582	1.020443
Lag 28	0.988346	0.944616	1.0341	0.993005	0.966458	1.020282
Lag 29	0.987288	0.942792	1.033883	0.992368	0.96534	1.020154
Lag 30	0.986247	0.940963	1.033711	0.991742	0.964218	1.020052
Lag 31	0.985208	0.939112	1.033567	0.991116	0.963081	1.019967
Lag 32	0.984152	0.937223	1.03343	0.99048	0.961921	1.019886
Lag 33	0.983057	0.935281	1.033273	0.98982	0.960727	1.019793
Lag 34	0.981898	0.933269	1.033061	0.989121	0.959489	1.019668
Lag 35	0.980649	0.931172	1.032756	0.988367	0.958197	1.019487
Lag 36	0.979281	0.928972	1.032314	0.987541	0.956841	1.019226
Lag 37	0.97776	0.926652	1.031688	0.986623	0.95541	1.018856
Lag 38	0.976053	0.924191	1.030827	0.985591	0.953889	1.018346
Lag 39	0.974123	0.921564	1.029681	0.984424	0.952265	1.017668
Lag 40	0.971931	0.91874	1.028201	0.983096	0.950516	1.016793
Lag 41	0.969434	0.915679	1.026346	0.981583	0.948619	1.015694
Lag 42	0.966591	0.912328	1.02408	0.979858	0.946539	1.01435
Lag 43	0.963354	0.908621	1.021384	0.977892	0.944234	1.012751
Lag 44	0.959679	0.904469	1.018259	0.975657	0.941648	1.010894
Lag 45	0.955516	0.899759	1.014728	0.97312	0.938708	1.008794

Table S45- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for both sexes and all ages) from March 2011 through March 2014 in Tehran megacity, Iran, adjusted for $PM_{2.5}$.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003863	0.997298	1.010472	1.003511	0.997543	1.009515
Lag 1	1.007097	0.99502	1.01932	1.006449	0.995472	1.017548
Lag 2	1.009748	0.993087	1.026688	1.008858	0.993714	1.024233
Lag 3	1.011865	0.991423	1.032728	1.01078	0.9922	1.029709
Lag 4	1.013493	0.989956	1.037589	1.012259	0.990865	1.034114
Lag 5	1.014678	0.988618	1.041424	1.013334	0.989648	1.037588
Lag 6	1.015462	0.987347	1.044378	1.014047	0.98849	1.040263
Lag 7	1.015888	0.986085	1.046592	1.014433	0.987342	1.042269
Lag 8	1.015996	0.984783	1.048199	1.014532	0.986156	1.043723
Lag 9	1.015824	0.9834	1.049318	1.014375	0.984897	1.044736
Lag 10	1.015408	0.981904	1.050055	1.013998	0.983536	1.045403
Lag 11	1.014782	0.980276	1.050502	1.013429	0.982053	1.045807
Lag 12	1.013976	0.978506	1.050733	1.012698	0.98044	1.046017
Lag 13	1.013022	0.976594	1.050809	1.011831	0.978699	1.046085
Lag 14	1.011945	0.974551	1.050774	1.010853	0.976837	1.046054
Lag 15	1.01077	0.972394	1.050661	1.009786	0.974872	1.045951
Lag 16	1.00952	0.970147	1.050491	1.008651	0.972824	1.045798
Lag 17	1.008214	0.967835	1.050278	1.007465	0.970716	1.045605
Lag 18	1.006871	0.965485	1.05003	1.006244	0.968573	1.04538
Lag 19	1.005504	0.96312	1.049753	1.005002	0.966416	1.045129
Lag 20	1.004127	0.960763	1.049448	1.003751	0.964266	1.044854
Lag 21	1.00275	0.95843	1.04912	1.0025	0.962137	1.044557
Lag 22	1.001382	0.956133	1.048772	1.001256	0.96004	1.044242
Lag 23	1.000028	0.95388	1.04841	1.000026	0.957983	1.043914
Lag 24	0.998692	0.95167	1.048038	0.998811	0.955965	1.043577
Lag 25	0.997375	0.949501	1.047663	0.997613	0.953984	1.043238
Lag 26	0.996076	0.947363	1.047293	0.996432	0.952032	1.042903
Lag 27	0.994791	0.945246	1.046933	0.995264	0.950098	1.042577
Lag 28	0.993516	0.943135	1.046587	0.994104	0.948169	1.042264
Lag 29	0.992242	0.941015	1.046258	0.992945	0.94623	1.041966
Lag 30	0.99096	0.938868	1.045941	0.991778	0.944268	1.041679
Lag 31	0.989656	0.93668	1.04563	0.990592	0.942267	1.041397
Lag 32	0.988319	0.934436	1.045308	0.989375	0.940214	1.041106
Lag 33	0.986929	0.932123	1.044957	0.98811	0.938099	1.040788
Lag 34	0.98547	0.929732	1.044549	0.986782	0.935911	1.040418
Lag 35	0.98392	0.927253	1.044049	0.985371	0.933642	1.039966
Lag 36	0.982256	0.924677	1.04342	0.983856	0.931284	1.039396
Lag 37	0.980454	0.921994	1.042621	0.982215	0.928826	1.038673
Lag 38	0.978487	0.919189	1.041611	0.980424	0.926257	1.037757
Lag 39	0.976326	0.916241	1.040352	0.978455	0.923556	1.036617
Lag 40	0.973941	0.913117	1.038817	0.976282	0.920693	1.035227
Lag 41	0.971299	0.909767	1.036994	0.973874	0.917622	1.033575
Lag 42	0.968367	0.906118	1.034892	0.971201	0.914275	1.03167
Lag 43	0.965108	0.902067	1.032555	0.968229	0.910559	1.029553
Lag 44	0.961487	0.897472	1.030068	0.964926	0.906341	1.027297
Lag 45	0.957465	0.892148	1.027563	0.961256	0.901452	1.025026

Table S46- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.001522	0.995701	1.007377	1.000911	0.997424	1.004411
Lag 1	1.00272	0.991915	1.013643	1.001628	0.995151	1.008147
Lag 2	1.003614	0.988557	1.0189	1.002162	0.993132	1.011275
Lag 3	1.004221	0.985547	1.023249	1.002526	0.99132	1.013857
Lag 4	1.004562	0.982814	1.026791	1.002729	0.989673	1.015957
Lag 5	1.004652	0.980289	1.029621	1.002783	0.98815	1.017633
Lag 6	1.004511	0.977914	1.031831	1.002699	0.986715	1.018941
Lag 7	1.004153	0.975635	1.033505	1.002485	0.985338	1.01993
Lag 8	1.003597	0.973408	1.034722	1.002152	0.983991	1.020649
Lag 9	1.002856	0.971196	1.035548	1.001709	0.982651	1.021137
Lag 10	1.001946	0.968968	1.036046	1.001165	0.981301	1.021431
Lag 11	1.00088	0.966704	1.036264	1.000527	0.979927	1.02156
Lag 12	0.999672	0.964388	1.036247	0.999804	0.978521	1.021549
Lag 13	0.998335	0.962014	1.036026	0.999002	0.977077	1.021419
Lag 14	0.996879	0.959579	1.035629	0.99813	0.975596	1.021185
Lag 15	0.995317	0.957084	1.035076	0.997193	0.974076	1.020858
Lag 16	0.993657	0.954536	1.034382	0.996197	0.972522	1.020448
Lag 17	0.991911	0.95194	1.033559	0.995148	0.970938	1.019962
Lag 18	0.990085	0.949306	1.032616	0.994051	0.969328	1.019405
Lag 19	0.988189	0.94664	1.031561	0.99291	0.967697	1.018781
Lag 20	0.986228	0.943948	1.030403	0.991731	0.966048	1.018096
Lag 21	0.98421	0.941235	1.029148	0.990515	0.964385	1.017353
Lag 22	0.98214	0.938502	1.027807	0.989267	0.962707	1.016559
Lag 23	0.980022	0.935751	1.026388	0.987989	0.961016	1.015719
Lag 24	0.977861	0.932978	1.024904	0.986684	0.95931	1.014839
Lag 25	0.97566	0.930179	1.023364	0.985353	0.957586	1.013925
Lag 26	0.97342	0.927349	1.02178	0.983998	0.95584	1.012986
Lag 27	0.971144	0.92448	1.020164	0.98262	0.954068	1.012026
Lag 28	0.968833	0.921566	1.018525	0.981219	0.952266	1.011052
Lag 29	0.966487	0.918601	1.016869	0.979795	0.95043	1.010068
Lag 30	0.964105	0.91558	1.015203	0.978349	0.948557	1.009076
Lag 31	0.961686	0.9125	1.013524	0.976878	0.946645	1.008077
Lag 32	0.959229	0.909361	1.011831	0.975383	0.944694	1.007068
Lag 33	0.95673	0.906167	1.010113	0.97386	0.942706	1.006044
Lag 34	0.954186	0.902923	1.008359	0.972309	0.940684	1.004997
Lag 35	0.951593	0.899638	1.006548	0.970726	0.938633	1.003916
Lag 36	0.948947	0.896322	1.004661	0.969108	0.93656	1.002789
Lag 37	0.946242	0.892986	1.002674	0.967453	0.934471	1.0016
Lag 38	0.943472	0.889641	1.000561	0.965757	0.932373	1.000336
Lag 39	0.940631	0.886292	0.998302	0.964014	0.93027	0.998983
Lag 40	0.937712	0.882942	0.995879	0.962221	0.928163	0.99753
Lag 41	0.934706	0.879582	0.993284	0.960373	0.926046	0.995973
Lag 42	0.931606	0.87619	0.990527	0.958465	0.923906	0.994316
Lag 43	0.928402	0.872723	0.987634	0.95649	0.921715	0.992577
Lag 44	0.925086	0.869112	0.984664	0.954442	0.91943	0.990788
Lag 45	0.921646	0.865255	0.981712	0.952316	0.916984	0.989009

Table S47- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.008586	1.000163	1.01708	1.007802	1.000148	1.015515
Lag 1	1.015623	1.000067	1.031421	1.014193	1.000061	1.028525
Lag 2	1.021221	0.999685	1.04322	1.019273	0.999714	1.039215
Lag 3	1.02549	0.998989	1.052694	1.023146	0.999081	1.047791
Lag 4	1.028546	0.997954	1.060075	1.025917	0.99814	1.054467
Lag 5	1.030501	0.996556	1.065602	1.02769	0.996869	1.059465
Lag 6	1.03147	0.994776	1.069518	1.028569	0.99525	1.063003
Lag 7	1.031563	0.992599	1.072057	1.028653	0.99327	1.065297
Lag 8	1.030887	0.990018	1.073444	1.02804	0.990921	1.06655
Lag 9	1.029544	0.987032	1.073888	1.026823	0.988204	1.066951
Lag 10	1.027633	0.983655	1.073577	1.02509	0.98513	1.06667
Lag 11	1.025245	0.979908	1.07268	1.022924	0.981718	1.06586
Lag 12	1.022466	0.975824	1.071337	1.020403	0.977998	1.064647
Lag 13	1.019376	0.971448	1.069669	1.017599	0.97401	1.06314
Lag 14	1.016049	0.966832	1.067771	1.014579	0.969801	1.061425
Lag 15	1.01255	0.962033	1.065721	1.011403	0.965424	1.059572
Lag 16	1.008941	0.957111	1.063577	1.008125	0.960933	1.057634
Lag 17	1.005274	0.952127	1.061387	1.004793	0.956383	1.055654
Lag 18	1.001596	0.947138	1.059185	1.001451	0.951826	1.053663
Lag 19	0.997948	0.942194	1.057001	0.998134	0.947308	1.051688
Lag 20	0.994364	0.937339	1.054858	0.994875	0.942869	1.049749
Lag 21	0.990871	0.932608	1.052774	0.991697	0.938542	1.047863
Lag 22	0.987492	0.928026	1.050767	0.988622	0.93435	1.046047
Lag 23	0.984241	0.923611	1.048852	0.985664	0.930307	1.044314
Lag 24	0.98113	0.919368	1.047042	0.982831	0.926421	1.042675
Lag 25	0.978162	0.915295	1.045346	0.980127	0.92269	1.04114
Lag 26	0.975335	0.911384	1.043774	0.977552	0.919104	1.039717
Lag 27	0.972643	0.907616	1.042329	0.975099	0.91565	1.038408
Lag 28	0.970073	0.903971	1.041008	0.972756	0.912306	1.037212
Lag 29	0.967606	0.90042	1.039804	0.970507	0.909048	1.036121
Lag 30	0.965219	0.896935	1.038702	0.968331	0.905848	1.035123
Lag 31	0.962884	0.893484	1.037676	0.966201	0.902679	1.034193
Lag 32	0.960567	0.890033	1.036691	0.964087	0.899509	1.033301
Lag 33	0.958228	0.886549	1.035702	0.961952	0.896307	1.032405
Lag 34	0.955822	0.882997	1.034653	0.959756	0.893043	1.031454
Lag 35	0.953301	0.879344	1.033477	0.957454	0.889683	1.030388
Lag 36	0.950609	0.875551	1.032101	0.954996	0.886194	1.029141
Lag 37	0.947687	0.871578	1.030443	0.952328	0.882537	1.027638
Lag 38	0.944473	0.867378	1.02842	0.949391	0.87867	1.025804
Lag 39	0.940896	0.862893	1.025951	0.946122	0.874539	1.023564
Lag 40	0.936886	0.858053	1.022962	0.942455	0.870078	1.020853
Lag 41	0.932367	0.852767	1.019396	0.938321	0.865204	1.017617
Lag 42	0.927259	0.84692	1.015219	0.933647	0.859809	1.013826
Lag 43	0.921481	0.840362	1.010431	0.928357	0.853754	1.009479
Lag 44	0.914951	0.832905	1.00508	0.922375	0.846864	1.004618
Lag 45	0.907585	0.824316	0.999266	0.915621	0.838922	0.999333

Table S48- The cumulative effect between AQI and non-accidental mortality in warmer months (for males and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.000923	0.995142	1.006738	1.000342	0.998198	1.00249
Lag 1	1.001481	0.990772	1.012306	1.000548	0.996572	1.00454
Lag 2	1.001707	0.986809	1.016829	1.000632	0.995094	1.0062
Lag 3	1.001631	0.983178	1.020431	1.000604	0.993736	1.007519
Lag 4	1.001286	0.979811	1.023232	1.000476	0.992474	1.008542
Lag 5	1.0007	0.976643	1.02535	1.000259	0.991285	1.009315
Lag 6	0.999902	0.973618	1.026895	0.999964	0.990147	1.009878
Lag 7	0.998916	0.970686	1.027967	0.999598	0.989041	1.010268
Lag 8	0.997769	0.967806	1.02866	0.999173	0.987953	1.010521
Lag 9	0.996484	0.964945	1.029054	0.998696	0.986871	1.010664
Lag 10	0.995082	0.962078	1.029218	0.998176	0.985784	1.010723
Lag 11	0.993583	0.95919	1.029209	0.997619	0.984687	1.01072
Lag 12	0.992006	0.956273	1.029074	0.997032	0.983576	1.010671
Lag 13	0.990367	0.953325	1.028848	0.996421	0.982452	1.010589
Lag 14	0.988682	0.950351	1.028558	0.995793	0.981316	1.010483
Lag 15	0.986963	0.947361	1.028222	0.995152	0.980171	1.010361
Lag 16	0.985224	0.944364	1.027853	0.994502	0.979022	1.010227
Lag 17	0.983474	0.941372	1.027459	0.993847	0.977872	1.010083
Lag 18	0.981722	0.938398	1.027046	0.993191	0.976727	1.009933
Lag 19	0.979975	0.935451	1.026617	0.992536	0.975589	1.009777
Lag 20	0.978238	0.93254	1.026176	0.991884	0.974464	1.009616
Lag 21	0.976516	0.929667	1.025725	0.991237	0.973351	1.009452
Lag 22	0.97481	0.926837	1.025267	0.990596	0.972252	1.009285
Lag 23	0.973123	0.924046	1.024806	0.98996	0.971167	1.009117
Lag 24	0.971453	0.92129	1.024346	0.98933	0.970093	1.008949
Lag 25	0.969797	0.918562	1.023891	0.988706	0.969028	1.008783
Lag 26	0.968153	0.915851	1.023443	0.988085	0.967968	1.008619
Lag 27	0.966516	0.913145	1.023006	0.987465	0.966908	1.00846
Lag 28	0.964878	0.910432	1.02258	0.986845	0.965843	1.008304
Lag 29	0.963232	0.907699	1.022163	0.986221	0.964768	1.008152
Lag 30	0.961569	0.904933	1.021749	0.98559	0.963678	1.008001
Lag 31	0.959877	0.902122	1.021329	0.984948	0.962568	1.007847
Lag 32	0.958144	0.899255	1.020889	0.984289	0.961434	1.007686
Lag 33	0.956356	0.896323	1.02041	0.983608	0.960272	1.007511
Lag 34	0.954499	0.89332	1.019869	0.9829	0.959079	1.007313
Lag 35	0.952556	0.890237	1.019238	0.982159	0.957852	1.007082
Lag 36	0.95051	0.887071	1.018486	0.981377	0.956589	1.006807
Lag 37	0.948341	0.883813	1.017579	0.980547	0.955286	1.006475
Lag 38	0.946028	0.880458	1.016482	0.979661	0.953941	1.006073
Lag 39	0.943552	0.876991	1.015164	0.97871	0.952549	1.00559
Lag 40	0.940888	0.873396	1.013596	0.977686	0.951101	1.005014
Lag 41	0.938014	0.869646	1.011757	0.976579	0.949586	1.004339
Lag 42	0.934904	0.865699	1.009642	0.975378	0.947988	1.00356
Lag 43	0.931534	0.8615	1.007261	0.974074	0.946282	1.002683
Lag 44	0.927876	0.85697	1.004649	0.972656	0.944436	1.001719
Lag 45	0.923903	0.852002	1.001872	0.971111	0.942404	1.000693

Table S49- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.00673	1.000166	1.013337	1.004024	1.000099	1.007965
Lag 1	1.012414	1.000166	1.024813	1.007415	1.000099	1.014785
Lag 2	1.01713	0.99998	1.034574	1.010223	0.999988	1.020562
Lag 3	1.020956	0.999595	1.042773	1.012496	0.999758	1.025397
Lag 4	1.023969	0.998997	1.049565	1.014284	0.999399	1.029391
Lag 5	1.026246	0.998175	1.055106	1.015634	0.998907	1.032642
Lag 6	1.027863	0.997125	1.059549	1.016592	0.998277	1.035244
Lag 7	1.028895	0.995845	1.063041	1.017203	0.99751	1.037285
Lag 8	1.029411	0.994338	1.065721	1.017509	0.996606	1.038851
Lag 9	1.029482	0.992616	1.067717	1.017551	0.995572	1.040015
Lag 10	1.029172	0.990692	1.069146	1.017367	0.994416	1.040848
Lag 11	1.028543	0.988588	1.070112	1.016995	0.993151	1.041411
Lag 12	1.027653	0.98633	1.070708	1.016468	0.991792	1.041759
Lag 13	1.026558	0.983948	1.071014	1.015819	0.990357	1.041937
Lag 14	1.025307	0.981474	1.071098	1.015078	0.988865	1.041986
Lag 15	1.023947	0.978943	1.07102	1.014271	0.987337	1.04194
Lag 16	1.02252	0.976391	1.070829	1.013425	0.985795	1.041829
Lag 17	1.021066	0.973852	1.07057	1.012562	0.984259	1.041678
Lag 18	1.019619	0.971356	1.070279	1.011702	0.982748	1.041509
Lag 19	1.018208	0.968934	1.069989	1.010864	0.98128	1.041339
Lag 20	1.016862	0.966609	1.069728	1.010063	0.979869	1.041187
Lag 21	1.015602	0.964399	1.069523	1.009313	0.978527	1.041068
Lag 22	1.014447	0.96232	1.069396	1.008626	0.977264	1.040994
Lag 23	1.013412	0.96038	1.069371	1.008009	0.976084	1.04098
Lag 24	1.012508	0.958583	1.069466	1.007471	0.974989	1.041035
Lag 25	1.011743	0.956927	1.069698	1.007015	0.97398	1.04117
Lag 26	1.01112	0.955406	1.070082	1.006644	0.973053	1.041394
Lag 27	1.010639	0.954011	1.070628	1.006357	0.972202	1.041712
Lag 28	1.010296	0.952727	1.071342	1.006152	0.971419	1.042128
Lag 29	1.010083	0.951542	1.072227	1.006026	0.970695	1.042643
Lag 30	1.009991	0.950437	1.073276	1.00597	0.97002	1.043254
Lag 31	1.010002	0.949396	1.074477	1.005977	0.969383	1.043953
Lag 32	1.010099	0.948401	1.075811	1.006035	0.968775	1.044729
Lag 33	1.01026	0.947435	1.077251	1.006131	0.968184	1.045566
Lag 34	1.010457	0.946481	1.078758	1.006249	0.9676	1.046442
Lag 35	1.010662	0.945521	1.080291	1.006371	0.967012	1.047332
Lag 36	1.010839	0.944537	1.081797	1.006477	0.966409	1.048206
Lag 37	1.010953	0.943508	1.083218	1.006544	0.965779	1.04903
Lag 38	1.01096	0.942411	1.084495	1.006549	0.965106	1.049771
Lag 39	1.010816	0.941214	1.085566	1.006463	0.964372	1.050391
Lag 40	1.010473	0.939878	1.08637	1.006258	0.963552	1.050857
Lag 41	1.009877	0.938351	1.086855	1.005903	0.962614	1.051138
Lag 42	1.008973	0.936562	1.086984	1.005364	0.961515	1.051212
Lag 43	1.007702	0.934416	1.086736	1.004605	0.960195	1.051069
Lag 44	1.006001	0.931792	1.08612	1.003589	0.958579	1.050712
Lag 45	1.003805	0.92853	1.085184	1.002277	0.956568	1.05017

Table S50- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	0.999105	0.990107	1.008185	0.999186	0.991002	1.007438
Lag 1	0.998401	0.981938	1.015139	0.998546	0.983567	1.013753
Lag 2	0.997867	0.97526	1.020999	0.998061	0.977483	1.019072
Lag 3	0.997487	0.969857	1.025904	0.997715	0.972559	1.023522
Lag 4	0.997243	0.965534	1.029993	0.997493	0.968618	1.027229
Lag 5	0.997118	0.962111	1.033399	0.99738	0.965495	1.030317
Lag 6	0.997097	0.959422	1.036252	0.997361	0.963041	1.032903
Lag 7	0.997165	0.957315	1.038674	0.997423	0.961119	1.035097
Lag 8	0.997309	0.955657	1.040776	0.997553	0.959605	1.037001
Lag 9	0.997513	0.954326	1.042655	0.997739	0.958391	1.038704
Lag 10	0.997768	0.953221	1.044396	0.99797	0.957382	1.04028
Lag 11	0.998059	0.952258	1.046063	0.998236	0.956503	1.041789
Lag 12	0.998377	0.951371	1.047707	0.998525	0.955692	1.043277
Lag 13	0.998712	0.95051	1.049358	0.998829	0.954906	1.044772
Lag 14	0.999053	0.949644	1.051031	0.999139	0.954115	1.046287
Lag 15	0.999391	0.948755	1.05273	0.999447	0.953303	1.047824
Lag 16	0.99972	0.947835	1.054445	0.999745	0.952463	1.049375
Lag 17	1.000031	0.946885	1.056159	1.000028	0.951595	1.050926
Lag 18	1.000318	0.945912	1.057853	1.000289	0.950705	1.052459
Lag 19	1.000575	0.944921	1.059507	1.000523	0.9498	1.053954
Lag 20	1.000797	0.943922	1.0611	1.000725	0.948887	1.055394
Lag 21	1.00098	0.942919	1.062617	1.000891	0.947971	1.056766
Lag 22	1.001121	0.941916	1.064047	1.001019	0.947054	1.058059
Lag 23	1.001216	0.940911	1.065386	1.001105	0.946135	1.059269
Lag 24	1.001263	0.939899	1.066634	1.001148	0.94521	1.060397
Lag 25	1.001262	0.938872	1.067798	1.001147	0.944271	1.061449
Lag 26	1.001211	0.93782	1.068888	1.001101	0.943309	1.062434
Lag 27	1.001112	0.936729	1.06992	1.001011	0.942312	1.063367
Lag 28	1.000965	0.935589	1.070909	1.000877	0.941269	1.06426
Lag 29	1.000772	0.934387	1.071873	1.000701	0.94017	1.065131
Lag 30	1.000535	0.933117	1.072824	1.000486	0.939007	1.06599
Lag 31	1.000258	0.931774	1.073776	1.000235	0.937779	1.06685
Lag 32	0.999945	0.930362	1.074733	0.99995	0.936487	1.067714
Lag 33	0.999601	0.928888	1.075697	0.999637	0.935139	1.068585
Lag 34	0.999231	0.92737	1.076662	0.999301	0.933749	1.069456
Lag 35	0.998843	0.925827	1.077617	0.998948	0.932336	1.070319
Lag 36	0.998442	0.924284	1.078549	0.998583	0.930924	1.07116
Lag 37	0.998036	0.922769	1.079443	0.998215	0.929536	1.071967
Lag 38	0.997635	0.921305	1.080289	0.99785	0.928196	1.072731
Lag 39	0.997248	0.919911	1.081086	0.997498	0.926919	1.073451
Lag 40	0.996884	0.91859	1.081852	0.997167	0.925709	1.074142
Lag 41	0.996555	0.917323	1.082631	0.996868	0.924548	1.074845
Lag 42	0.996272	0.916059	1.083509	0.996611	0.92339	1.075637
Lag 43	0.996048	0.914702	1.084627	0.996406	0.922146	1.076646
Lag 44	0.995894	0.913098	1.086198	0.996267	0.920676	1.078064
Lag 45	0.995826	0.911023	1.088523	0.996205	0.918774	1.080161

Table S51- The cumulative effect between AQI and non-accidental mortality in warmer months (for females and all ages) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.008983	1.002972	1.015031	1.003318	1.0011	1.005541
Lag 1	1.016373	1.005217	1.027654	1.006033	1.001929	1.010154
Lag 2	1.022293	1.006773	1.038052	1.008199	1.002503	1.013928
Lag 3	1.026866	1.007677	1.04642	1.009867	1.002837	1.016948
Lag 4	1.030222	1.00797	1.052965	1.011089	1.002945	1.019299
Lag 5	1.032488	1.007691	1.057895	1.011911	1.002842	1.021063
Lag 6	1.033789	1.006879	1.061417	1.012384	1.002542	1.022321
Lag 7	1.034248	1.005579	1.063736	1.01255	1.002063	1.023148
Lag 8	1.033985	1.003834	1.065042	1.012455	1.001418	1.023613
Lag 9	1.033113	1.001693	1.065518	1.012138	1.000627	1.023783
Lag 10	1.031739	0.999208	1.06533	1.01164	0.999707	1.023715
Lag 11	1.029966	0.996434	1.064626	1.010996	0.998678	1.023465
Lag 12	1.027888	0.99343	1.063541	1.010239	0.997561	1.023079
Lag 13	1.025592	0.990255	1.062189	1.009403	0.99638	1.022597
Lag 14	1.023159	0.986974	1.060671	1.008516	0.995156	1.022055
Lag 15	1.020663	0.983648	1.059072	1.007604	0.993912	1.021484
Lag 16	1.01817	0.980338	1.057462	1.006692	0.992672	1.020909
Lag 17	1.015738	0.977101	1.055904	1.0058	0.991457	1.020351
Lag 18	1.01342	0.973989	1.054448	1.00495	0.990286	1.01983
Lag 19	1.01126	0.971048	1.053137	1.004156	0.989178	1.01936
Lag 20	1.009297	0.968317	1.05201	1.003433	0.988147	1.018956
Lag 21	1.007561	0.965827	1.051098	1.002794	0.987205	1.018629
Lag 22	1.006078	0.963599	1.050428	1.002247	0.986361	1.018389
Lag 23	1.004865	0.961648	1.050025	1.001799	0.985621	1.018244
Lag 24	1.003936	0.959979	1.049906	1.001456	0.984986	1.018201
Lag 25	1.003296	0.958589	1.050088	1.001219	0.984458	1.018266
Lag 26	1.002944	0.957468	1.05058	1.001089	0.984031	1.018443
Lag 27	1.002874	0.956599	1.051386	1.001063	0.983701	1.018732
Lag 28	1.003072	0.955961	1.052505	1.001137	0.983458	1.019134
Lag 29	1.00352	0.955526	1.053925	1.001302	0.983292	1.019643
Lag 30	1.004193	0.955264	1.055627	1.001551	0.983192	1.020252
Lag 31	1.005058	0.955142	1.057582	1.00187	0.983145	1.020952
Lag 32	1.006077	0.955123	1.05975	1.002246	0.983138	1.021726
Lag 33	1.007206	0.95517	1.062076	1.002663	0.983156	1.022556
Lag 34	1.008393	0.955245	1.064497	1.0031	0.983185	1.023419
Lag 35	1.009579	0.955305	1.066937	1.003537	0.983208	1.024287
Lag 36	1.010701	0.955307	1.069307	1.00395	0.983208	1.025129
Lag 37	1.011686	0.9552	1.071511	1.004312	0.983168	1.025912
Lag 38	1.012455	0.954931	1.073445	1.004595	0.983065	1.026597
Lag 39	1.012924	0.954434	1.074999	1.004767	0.982876	1.027147
Lag 40	1.013002	0.953634	1.076065	1.004796	0.98257	1.027524
Lag 41	1.012589	0.952437	1.076541	1.004644	0.982113	1.027692
Lag 42	1.011584	0.950727	1.076336	1.004275	0.98146	1.02762
Lag 43	1.009876	0.948363	1.07538	1.003647	0.980555	1.027282
Lag 44	1.007354	0.945165	1.073636	1.002718	0.979329	1.026665
Lag 45	1.003901	0.940912	1.071107	1.001443	0.977695	1.025768

Table S52- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.002005	0.996135	1.00791	1.0012	0.997684	1.004729
Lag 1	1.003693	0.992744	1.014761	1.002209	0.995649	1.008813
Lag 2	1.00508	0.989745	1.020654	1.003039	0.993846	1.012317
Lag 3	1.006186	0.987057	1.025687	1.0037	0.992229	1.015303
Lag 4	1.007028	0.984607	1.02996	1.004203	0.990754	1.017834
Lag 5	1.007623	0.982331	1.033566	1.004557	0.989382	1.019966
Lag 6	1.007986	0.980168	1.036594	1.004775	0.988077	1.021755
Lag 7	1.008135	0.978068	1.039127	1.004864	0.986809	1.023249
Lag 8	1.008085	0.975988	1.041238	1.004834	0.985552	1.024493
Lag 9	1.007852	0.973893	1.042994	1.004694	0.984284	1.025527
Lag 10	1.007448	0.971757	1.04445	1.004453	0.982991	1.026384
Lag 11	1.006889	0.969562	1.045653	1.004119	0.981661	1.027092
Lag 12	1.006187	0.967295	1.046642	1.0037	0.980286	1.027674
Lag 13	1.005355	0.964954	1.047448	1.003203	0.978865	1.028147
Lag 14	1.004406	0.962539	1.048093	1.002636	0.977397	1.028527
Lag 15	1.003349	0.960055	1.048596	1.002004	0.975886	1.028822
Lag 16	1.002196	0.95751	1.048969	1.001315	0.974336	1.029041
Lag 17	1.000957	0.954913	1.049222	1.000573	0.972752	1.02919
Lag 18	0.999641	0.952273	1.049365	0.999785	0.971141	1.029273
Lag 19	0.998256	0.949601	1.049403	0.998955	0.969509	1.029296
Lag 20	0.996809	0.946904	1.049344	0.998088	0.967859	1.029261
Lag 21	0.995309	0.94419	1.049196	0.997188	0.966196	1.029174
Lag 22	0.993761	0.941461	1.048966	0.996259	0.964524	1.02904
Lag 23	0.992171	0.938721	1.048665	0.995305	0.962842	1.028862
Lag 24	0.990545	0.93597	1.048302	0.994327	0.961151	1.028649
Lag 25	0.988885	0.933205	1.047888	0.99333	0.959449	1.028406
Lag 26	0.987197	0.930423	1.047435	0.992314	0.957736	1.02814
Lag 27	0.985482	0.927619	1.046955	0.991281	0.956006	1.027858
Lag 28	0.983744	0.924788	1.046458	0.990234	0.954258	1.027565
Lag 29	0.981983	0.921924	1.045954	0.989172	0.952487	1.027269
Lag 30	0.9802	0.919022	1.045451	0.988096	0.950691	1.026973
Lag 31	0.978397	0.916077	1.044955	0.987007	0.948866	1.026682
Lag 32	0.976571	0.913087	1.044469	0.985904	0.94701	1.026396
Lag 33	0.974723	0.91005	1.043993	0.984787	0.945123	1.026115
Lag 34	0.972851	0.906965	1.043523	0.983653	0.943203	1.025839
Lag 35	0.970952	0.903832	1.043056	0.982503	0.941251	1.025564
Lag 36	0.969023	0.900654	1.042582	0.981334	0.939267	1.025285
Lag 37	0.967061	0.89743	1.042094	0.980143	0.937252	1.024997
Lag 38	0.965061	0.894159	1.041584	0.978929	0.935206	1.024697
Lag 39	0.963019	0.890839	1.041047	0.977688	0.933124	1.02438
Lag 40	0.960929	0.887458	1.040481	0.976417	0.931003	1.024047
Lag 41	0.958785	0.884002	1.039895	0.975112	0.928829	1.023701
Lag 42	0.956581	0.880441	1.039305	0.973769	0.926588	1.023354
Lag 43	0.954309	0.876737	1.038745	0.972384	0.924251	1.023024
Lag 44	0.951962	0.87283	1.038268	0.970951	0.921783	1.022742
Lag 45	0.949532	0.868645	1.037951	0.969466	0.919133	1.022555

Table S53- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003808	0.995822	1.011857	1.003461	0.996201	1.010773
Lag 1	1.007014	0.99231	1.021936	1.006374	0.993007	1.019922
Lag 2	1.009659	0.989346	1.03039	1.008778	0.99031	1.02759
Lag 3	1.011784	0.986817	1.037383	1.010707	0.988008	1.033927
Lag 4	1.013427	0.984619	1.043078	1.012199	0.986007	1.039087
Lag 5	1.014628	0.982653	1.047643	1.013289	0.984217	1.043219
Lag 6	1.015423	0.980828	1.051238	1.014011	0.982556	1.046473
Lag 7	1.01585	0.979064	1.054018	1.014399	0.980949	1.048989
Lag 8	1.015944	0.977288	1.056129	1.014484	0.979331	1.050899
Lag 9	1.015739	0.975441	1.057701	1.014298	0.977649	1.052321
Lag 10	1.015267	0.973479	1.058849	1.01387	0.97586	1.053359
Lag 11	1.01456	0.971368	1.059672	1.013228	0.973937	1.054103
Lag 12	1.013647	0.969093	1.060248	1.012398	0.971863	1.054625
Lag 13	1.012554	0.966649	1.06064	1.011407	0.969634	1.054979
Lag 14	1.011309	0.964044	1.060892	1.010276	0.967258	1.055207
Lag 15	1.009935	0.961296	1.061036	1.009028	0.964751	1.055336
Lag 16	1.008454	0.958429	1.061091	1.007683	0.962136	1.055386
Lag 17	1.006887	0.955472	1.06107	1.006259	0.959436	1.055367
Lag 18	1.005253	0.952453	1.060979	1.004774	0.95668	1.055285
Lag 19	1.003567	0.949402	1.060822	1.003242	0.953894	1.055143
Lag 20	1.001845	0.946343	1.060602	1.001677	0.9511	1.054944
Lag 21	1.0001	0.943298	1.060322	1.000091	0.948317	1.054691
Lag 22	0.998343	0.940283	1.059988	0.998494	0.945561	1.054389
Lag 23	0.996584	0.93731	1.059607	0.996894	0.942842	1.054044
Lag 24	0.99483	0.934382	1.059189	0.995299	0.940165	1.053666
Lag 25	0.993088	0.931503	1.058745	0.993714	0.937531	1.053265
Lag 26	0.991361	0.928667	1.058287	0.992143	0.934936	1.052851
Lag 27	0.989652	0.925869	1.057829	0.990588	0.932375	1.052437
Lag 28	0.987962	0.923099	1.057382	0.98905	0.929839	1.052032
Lag 29	0.986289	0.920348	1.056955	0.987528	0.927319	1.051645
Lag 30	0.984632	0.917606	1.056553	0.986019	0.924807	1.051282
Lag 31	0.982985	0.914863	1.056178	0.984519	0.922294	1.050943
Lag 32	0.981342	0.912113	1.055826	0.983024	0.919773	1.050625
Lag 33	0.979697	0.909352	1.055485	0.981526	0.917241	1.050316
Lag 34	0.97804	0.906576	1.055137	0.980016	0.914695	1.050001
Lag 35	0.976359	0.903785	1.05476	0.978485	0.912135	1.049661
Lag 36	0.974643	0.900981	1.054327	0.976921	0.909562	1.049269
Lag 37	0.972876	0.898161	1.053807	0.975311	0.906974	1.048798
Lag 38	0.971045	0.895323	1.053171	0.973642	0.904368	1.048223
Lag 39	0.96913	0.892453	1.052395	0.971897	0.901733	1.047521
Lag 40	0.967115	0.88953	1.051466	0.970059	0.899047	1.04668
Lag 41	0.964977	0.886512	1.050388	0.96811	0.896273	1.045705
Lag 42	0.962697	0.883332	1.049193	0.96603	0.89335	1.044622
Lag 43	0.96025	0.879893	1.047946	0.963798	0.890188	1.043494
Lag 44	0.957613	0.876054	1.046765	0.961391	0.886657	1.042425
Lag 45	0.95476	0.871627	1.045822	0.958787	0.882582	1.041571

Table S54- The cumulative effect between AQI and non-accidental mortality in warmer months (for both sexes and age group >65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003276	0.997664	1.008919	1.001212	0.999134	1.003294
Lag 1	1.005808	0.995382	1.016342	1.002147	0.998287	1.006022
Lag 2	1.007657	0.993117	1.02241	1.002829	0.997445	1.008242
Lag 3	1.008883	0.990833	1.027262	1.003281	0.996595	1.010012
Lag 4	1.009546	0.988499	1.031041	1.003525	0.995725	1.011386
Lag 5	1.009702	0.986086	1.033885	1.003583	0.994824	1.012419
Lag 6	1.009408	0.983568	1.035927	1.003474	0.993882	1.013159
Lag 7	1.008716	0.980926	1.037292	1.003219	0.992893	1.013653
Lag 8	1.007676	0.978147	1.038097	1.002836	0.99185	1.013944
Lag 9	1.006338	0.975223	1.038447	1.002343	0.990751	1.014071
Lag 10	1.004747	0.972153	1.038434	1.001756	0.989595	1.014066
Lag 11	1.002945	0.968945	1.038139	1.00109	0.988384	1.013959
Lag 12	1.000972	0.965609	1.03763	1.00036	0.987122	1.013775
Lag 13	0.998865	0.962165	1.036965	0.99958	0.985817	1.013535
Lag 14	0.996658	0.958634	1.036189	0.998761	0.984475	1.013254
Lag 15	0.994381	0.955042	1.03534	0.997915	0.983107	1.012946
Lag 16	0.992062	0.951413	1.034447	0.997053	0.981722	1.012622
Lag 17	0.989726	0.947774	1.033535	0.996182	0.98033	1.012292
Lag 18	0.987395	0.944149	1.032622	0.995313	0.978939	1.01196
Lag 19	0.985088	0.940559	1.031724	0.994451	0.977559	1.011634
Lag 20	0.98282	0.937024	1.030855	0.993602	0.976197	1.011319
Lag 21	0.980606	0.933556	1.030027	0.992773	0.974857	1.011018
Lag 22	0.978455	0.930167	1.02925	0.991966	0.973545	1.010735
Lag 23	0.976375	0.926862	1.028533	0.991184	0.972262	1.010474
Lag 24	0.974371	0.923643	1.027884	0.99043	0.97101	1.010238
Lag 25	0.972444	0.920509	1.02731	0.989704	0.969788	1.010029
Lag 26	0.970595	0.917452	1.026817	0.989007	0.968595	1.009849
Lag 27	0.968821	0.914466	1.026406	0.988337	0.967426	1.0097
Lag 28	0.967114	0.911538	1.026079	0.987692	0.966277	1.009581
Lag 29	0.965468	0.908656	1.025831	0.987069	0.965145	1.00949
Lag 30	0.96387	0.905806	1.025656	0.986463	0.964022	1.009427
Lag 31	0.962308	0.902973	1.025541	0.985871	0.962905	1.009385
Lag 32	0.960764	0.900142	1.025469	0.985285	0.961785	1.009358
Lag 33	0.959221	0.897297	1.025419	0.984698	0.960658	1.00934
Lag 34	0.957657	0.894423	1.025362	0.984104	0.959518	1.009319
Lag 35	0.956049	0.891503	1.025267	0.983491	0.958356	1.009285
Lag 36	0.954369	0.888521	1.025098	0.982851	0.957168	1.009223
Lag 37	0.95259	0.885457	1.024814	0.982172	0.955944	1.009119
Lag 38	0.950681	0.88229	1.024373	0.981442	0.954676	1.008959
Lag 39	0.948608	0.878995	1.023733	0.980649	0.953354	1.008725
Lag 40	0.946335	0.875538	1.022856	0.979778	0.951964	1.008405
Lag 41	0.943825	0.871879	1.021707	0.978815	0.950488	1.007985
Lag 42	0.941038	0.867967	1.02026	0.977743	0.948907	1.007456
Lag 43	0.937932	0.863735	1.018503	0.976547	0.94719	1.006813
Lag 44	0.934465	0.859099	1.016442	0.975208	0.945304	1.006058
Lag 45	0.93059	0.853953	1.014105	0.973709	0.943203	1.005201

Table S55- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 μg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003575	0.995785	1.011426	1.002139	0.997474	1.006827
Lag 1	1.006481	0.991994	1.02118	1.003876	0.995198	1.01263
Lag 2	1.008781	0.988558	1.029419	1.005249	0.993133	1.017513
Lag 3	1.010537	0.985414	1.036301	1.006296	0.99124	1.021581
Lag 4	1.011808	0.982503	1.041987	1.007054	0.989485	1.024934
Lag 5	1.012651	0.979772	1.046633	1.007556	0.987838	1.027668
Lag 6	1.013121	0.977174	1.050391	1.007836	0.986269	1.029876
Lag 7	1.013271	0.97467	1.053401	1.007926	0.984754	1.031642
Lag 8	1.01315	0.972228	1.055795	1.007854	0.983276	1.033046
Lag 9	1.012804	0.969822	1.057691	1.007647	0.981818	1.034156
Lag 10	1.012276	0.967436	1.059194	1.007333	0.980371	1.035036
Lag 11	1.011606	0.965062	1.060394	1.006933	0.97893	1.035738
Lag 12	1.01083	0.962698	1.061368	1.006471	0.977493	1.036308
Lag 13	1.009982	0.960348	1.06218	1.005965	0.976064	1.036782
Lag 14	1.009091	0.958023	1.062881	1.005434	0.974648	1.037192
Lag 15	1.008184	0.955736	1.063511	1.004893	0.973254	1.03756
Lag 16	1.007284	0.953501	1.064102	1.004356	0.971891	1.037905
Lag 17	1.006411	0.951333	1.064678	1.003834	0.970567	1.038242
Lag 18	1.005581	0.949248	1.065258	1.003338	0.969293	1.03858
Lag 19	1.004808	0.947256	1.065857	1.002876	0.968074	1.03893
Lag 20	1.004101	0.945366	1.066485	1.002454	0.966917	1.039296
Lag 21	1.003466	0.943581	1.067153	1.002074	0.965823	1.039686
Lag 22	1.002908	0.941901	1.067867	1.00174	0.964793	1.040103
Lag 23	1.002426	0.94032	1.068635	1.001452	0.963823	1.04055
Lag 24	1.002018	0.938827	1.069462	1.001208	0.962907	1.041032
Lag 25	1.001676	0.937408	1.070351	1.001003	0.962035	1.041551
Lag 26	1.001392	0.936043	1.071304	1.000833	0.961196	1.042106
Lag 27	1.001152	0.934709	1.072318	1.00069	0.960376	1.042697
Lag 28	1.000942	0.933384	1.073389	1.000564	0.95956	1.04332
Lag 29	1.00074	0.932039	1.074505	1.000443	0.958732	1.043969
Lag 30	1.000526	0.930649	1.075649	1.000315	0.957875	1.044635
Lag 31	1.000273	0.929189	1.076795	1.000163	0.956975	1.045301
Lag 32	0.999953	0.927632	1.077911	0.999972	0.956015	1.04595
Lag 33	0.999533	0.925957	1.078956	0.99972	0.95498	1.046556
Lag 34	0.998979	0.92414	1.079878	0.999388	0.953858	1.047092
Lag 35	0.998252	0.922163	1.080619	0.998953	0.952635	1.047522
Lag 36	0.997311	0.920003	1.081114	0.998389	0.951299	1.047809
Lag 37	0.996111	0.917642	1.08129	0.997669	0.949836	1.047912
Lag 38	0.994606	0.915054	1.081074	0.996766	0.948231	1.047786
Lag 39	0.992745	0.91221	1.080391	0.99565	0.946465	1.04739
Lag 40	0.990478	0.909072	1.079173	0.994287	0.944514	1.046683
Lag 41	0.987748	0.905588	1.077362	0.992645	0.942345	1.04563
Lag 42	0.9845	0.901689	1.074916	0.990689	0.939913	1.044208
Lag 43	0.980675	0.897279	1.071822	0.988383	0.937158	1.042408
Lag 44	0.976215	0.892233	1.068102	0.985689	0.933999	1.040239
Lag 45	0.971059	0.886384	1.063823	0.982568	0.930328	1.037742

Table S56- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.007639	0.996984	1.018408	1.006942	0.997257	1.016721
Lag 1	1.014155	0.994567	1.034128	1.01286	0.99506	1.030978
Lag 2	1.019635	0.99264	1.047364	1.017834	0.993307	1.042967
Lag 3	1.024169	0.991098	1.058345	1.021948	0.991904	1.052903
Lag 4	1.027846	0.989839	1.067313	1.025283	0.990758	1.061011
Lag 5	1.030753	0.988769	1.074519	1.027918	0.989785	1.067521
Lag 6	1.032974	0.987799	1.080215	1.029932	0.988902	1.072664
Lag 7	1.034593	0.986848	1.084647	1.031399	0.988036	1.076665
Lag 8	1.035688	0.985845	1.08805	1.032391	0.987124	1.079735
Lag 9	1.036334	0.984733	1.090639	1.032977	0.986111	1.08207
Lag 10	1.036602	0.983466	1.092609	1.03322	0.984958	1.083847
Lag 11	1.036559	0.982018	1.094129	1.033181	0.98364	1.085218
Lag 12	1.036266	0.980379	1.095338	1.032915	0.982147	1.086308
Lag 13	1.035779	0.978556	1.096348	1.032474	0.980487	1.087218
Lag 14	1.03515	0.976571	1.097243	1.031904	0.978678	1.088025
Lag 15	1.034425	0.974457	1.098083	1.031247	0.976752	1.088782
Lag 16	1.033645	0.972258	1.098908	1.03054	0.974748	1.089526
Lag 17	1.032846	0.97002	1.099742	1.029816	0.972708	1.090277
Lag 18	1.032059	0.967789	1.100597	1.029103	0.970674	1.091048
Lag 19	1.031309	0.965609	1.101481	1.028423	0.968686	1.091845
Lag 20	1.030617	0.963514	1.102393	1.027795	0.966775	1.092667
Lag 21	1.029998	0.961534	1.103336	1.027234	0.964969	1.093516
Lag 22	1.029461	0.959686	1.10431	1.026747	0.963282	1.094394
Lag 23	1.029013	0.957976	1.105316	1.026341	0.961722	1.0953
Lag 24	1.028652	0.956402	1.106359	1.026014	0.960286	1.09624
Lag 25	1.028374	0.954951	1.107443	1.025762	0.958961	1.097216
Lag 26	1.028169	0.953599	1.10857	1.025576	0.957727	1.098231
Lag 27	1.028022	0.952317	1.109745	1.025442	0.956556	1.099289
Lag 28	1.027912	0.951068	1.110964	1.025342	0.955416	1.100387
Lag 29	1.027814	0.949814	1.112219	1.025254	0.95427	1.101517
Lag 30	1.027698	0.948512	1.113494	1.025148	0.953081	1.102665
Lag 31	1.027528	0.947122	1.11476	1.024995	0.951811	1.103805
Lag 32	1.027265	0.945603	1.115978	1.024756	0.950424	1.104901
Lag 33	1.026862	0.943919	1.117093	1.02439	0.948885	1.105904
Lag 34	1.026269	0.942035	1.118036	1.023853	0.947163	1.106753
Lag 35	1.025432	0.939919	1.118725	1.023094	0.945228	1.107373
Lag 36	1.02429	0.937538	1.119069	1.022058	0.943051	1.107683
Lag 37	1.022778	0.934857	1.118968	1.020686	0.9406	1.107592
Lag 38	1.020829	0.931834	1.118324	1.018918	0.937834	1.107012
Lag 39	1.018369	0.92841	1.117044	1.016685	0.934701	1.10586
Lag 40	1.015322	0.924507	1.115057	1.013919	0.931128	1.104072
Lag 41	1.011608	0.920014	1.112321	1.010547	0.927013	1.101609
Lag 42	1.007146	0.914775	1.108844	1.006494	0.922213	1.098478
Lag 43	1.001852	0.908579	1.104701	1.001684	0.916532	1.094746
Lag 44	0.995641	0.901142	1.100049	0.996037	0.90971	1.090555
Lag 45	0.988428	0.89211	1.095146	0.989475	0.901417	1.086134

Table S57- The cumulative effect between AQI and non-accidental mortality in warmer months (for both sexes and age group 18–65) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.003847	0.996837	1.010906	1.001423	0.998827	1.004025
Lag 1	1.006827	0.99389	1.019932	1.002523	0.997733	1.007337
Lag 2	1.00903	0.991122	1.027263	1.003335	0.996702	1.010012
Lag 3	1.010543	0.988494	1.033083	1.003892	0.995723	1.012128
Lag 4	1.011448	0.985972	1.037583	1.004225	0.994781	1.013758
Lag 5	1.011829	0.983525	1.040947	1.004365	0.993866	1.014974
Lag 6	1.011762	0.981125	1.043355	1.00434	0.992967	1.015843
Lag 7	1.011321	0.978749	1.044978	1.004178	0.992076	1.016428
Lag 8	1.010576	0.976378	1.045972	1.003904	0.991185	1.016786
Lag 9	1.009592	0.974001	1.046483	1.003542	0.990291	1.01697
Lag 10	1.008428	0.971614	1.046638	1.003113	0.989391	1.017026
Lag 11	1.007142	0.96922	1.046548	1.002639	0.988488	1.016993
Lag 12	1.005783	0.966829	1.046307	1.002138	0.987584	1.016907
Lag 13	1.004398	0.964457	1.045993	1.001627	0.986686	1.016794
Lag 14	1.003029	0.962128	1.045668	1.001121	0.985803	1.016677
Lag 15	1.001711	0.959866	1.04538	1.000633	0.984944	1.016573
Lag 16	1.000477	0.957699	1.045165	1.000177	0.984119	1.016496
Lag 17	0.999353	0.955654	1.045051	0.99976	0.98334	1.016455
Lag 18	0.998363	0.953754	1.045059	0.999394	0.982616	1.016457
Lag 19	0.997525	0.952022	1.045202	0.999083	0.981955	1.016509
Lag 20	0.996851	0.950473	1.045492	0.998833	0.981363	1.016614
Lag 21	0.996351	0.949115	1.045938	0.998647	0.980843	1.016774
Lag 22	0.99603	0.947952	1.046546	0.998528	0.980398	1.016993
Lag 23	0.995887	0.946978	1.047321	0.998475	0.980025	1.017272
Lag 24	0.995918	0.946183	1.048267	0.998486	0.97972	1.017612
Lag 25	0.996115	0.945548	1.049387	0.998559	0.979476	1.018014
Lag 26	0.996464	0.945047	1.050678	0.998689	0.979284	1.018478
Lag 27	0.996948	0.944654	1.052138	0.998869	0.979133	1.019002
Lag 28	0.997545	0.944332	1.053756	0.99909	0.97901	1.019582
Lag 29	0.998228	0.944048	1.055517	0.999343	0.9789	1.020213
Lag 30	0.998965	0.943763	1.057397	0.999617	0.978791	1.020886
Lag 31	0.999722	0.94344	1.059362	0.999897	0.978667	1.021588
Lag 32	1.000457	0.943041	1.06137	1.000169	0.978514	1.022304
Lag 33	1.001126	0.942531	1.063364	1.000417	0.978318	1.023015
Lag 34	1.001678	0.941876	1.065278	1.000621	0.978066	1.023697
Lag 35	1.00206	0.941041	1.067036	1.000762	0.977745	1.024322
Lag 36	1.002212	0.939993	1.068549	1.000819	0.977341	1.02486
Lag 37	1.002071	0.938696	1.069724	1.000766	0.976841	1.025278
Lag 38	1.001569	0.93711	1.070462	1.000581	0.97623	1.025539
Lag 39	1.000635	0.935188	1.070662	1.000235	0.975488	1.02561
Lag 40	0.999193	0.932871	1.07023	0.999701	0.974592	1.025457
Lag 41	0.997164	0.930083	1.069082	0.998949	0.973512	1.02505
Lag 42	0.994466	0.926727	1.067157	0.997947	0.97221	1.024365
Lag 43	0.991016	0.922674	1.064421	0.996663	0.970633	1.023392
Lag 44	0.986728	0.917754	1.060885	0.995064	0.968713	1.022132
Lag 45	0.981515	0.911754	1.056613	0.993113	0.966362	1.020605

Table S58- The cumulative effect between $PM_{2.5}$ and non-accidental mortality in warmer months (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 µg/m^3		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.016558	0.996805	1.036703	1.009882	0.998086	1.021819
Lag 1	1.029707	0.992842	1.067942	1.017684	0.995708	1.040146
Lag 2	1.039691	0.988149	1.09392	1.023581	0.992887	1.055224
Lag 3	1.046779	0.982765	1.114964	1.027754	0.989644	1.067333
Lag 4	1.051265	0.976731	1.131486	1.030389	0.986001	1.076775
Lag 5	1.053447	0.970095	1.14396	1.031669	0.981984	1.083868
Lag 6	1.053628	0.962909	1.152894	1.031775	0.977621	1.088929
Lag 7	1.052106	0.955232	1.158804	1.030883	0.972947	1.092268
Lag 8	1.049169	0.947134	1.162196	1.029158	0.967999	1.094182
Lag 9	1.045091	0.938692	1.163551	1.026762	0.962824	1.094945
Lag 10	1.04013	0.929994	1.16331	1.02384	0.957472	1.094809
Lag 11	1.034525	0.921137	1.161869	1.020532	0.952001	1.093997
Lag 12	1.028491	0.912223	1.159578	1.016964	0.946474	1.092705
Lag 13	1.022227	0.903359	1.156737	1.013251	0.940956	1.091101
Lag 14	1.015909	0.894654	1.153598	1.009496	0.935515	1.089327
Lag 15	1.00969	0.886212	1.150373	1.005791	0.93022	1.087502
Lag 16	1.003706	0.878134	1.147235	1.002217	0.925133	1.085725
Lag 17	0.99807	0.870508	1.144325	0.998844	0.920314	1.084076
Lag 18	0.99288	0.863414	1.141759	0.99573	0.915815	1.082619
Lag 19	0.988212	0.856913	1.13963	0.992925	0.91168	1.08141
Lag 20	0.984129	0.851054	1.138011	0.990466	0.907942	1.08049
Lag 21	0.980673	0.845865	1.136965	0.988382	0.904623	1.079895
Lag 22	0.977874	0.841359	1.136539	0.986692	0.901735	1.079653
Lag 23	0.975746	0.83753	1.13677	0.985405	0.899275	1.079784
Lag 24	0.974286	0.834355	1.137685	0.984522	0.897232	1.080304
Lag 25	0.973478	0.831793	1.139296	0.984033	0.895581	1.08122
Lag 26	0.973291	0.829792	1.141607	0.98392	0.89429	1.082533
Lag 27	0.97368	0.828282	1.144603	0.984156	0.893316	1.084233
Lag 28	0.974584	0.827183	1.148251	0.984702	0.892606	1.086301
Lag 29	0.975925	0.826406	1.152496	0.985513	0.892104	1.088704
Lag 30	0.977612	0.825853	1.157257	0.986533	0.891746	1.091395
Lag 31	0.979535	0.825421	1.162424	0.987695	0.891466	1.09431
Lag 32	0.981569	0.825001	1.16785	0.988922	0.891195	1.097366
Lag 33	0.98357	0.824483	1.173354	0.990129	0.89086	1.10046
Lag 34	0.985379	0.823753	1.178717	0.991219	0.890388	1.103469
Lag 35	0.986818	0.822694	1.183683	0.992085	0.889702	1.106251
Lag 36	0.987691	0.821182	1.187961	0.992611	0.888723	1.108643
Lag 37	0.987787	0.819087	1.191232	0.992669	0.887364	1.11047
Lag 38	0.98688	0.816265	1.193157	0.992123	0.885532	1.111544
Lag 39	0.984732	0.812555	1.193394	0.990829	0.88312	1.111676
Lag 40	0.981094	0.807768	1.191611	0.988636	0.880001	1.110682
Lag 41	0.97571	0.801683	1.187513	0.985383	0.876025	1.108393
Lag 42	0.968323	0.794035	1.180867	0.98091	0.871011	1.104674
Lag 43	0.958682	0.784501	1.171536	0.975049	0.864734	1.099439
Lag 44	0.946543	0.772694	1.159506	0.967638	0.856917	1.092665
Lag 45	0.931684	0.758159	1.144925	0.958513	0.847227	1.084416

Table S59- The cumulative effect between NO_2 and non-accidental mortality in warmer months (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 ppb		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.011264	0.983943	1.039343	1.010234	0.985392	1.035703
Lag 1	1.019506	0.969859	1.071696	1.017717	0.972561	1.064971
Lag 2	1.024967	0.957419	1.097281	1.022672	0.961214	1.08806
Lag 3	1.027902	0.946325	1.116511	1.025334	0.951083	1.105381
Lag 4	1.028578	0.936306	1.129942	1.025946	0.941925	1.117463
Lag 5	1.027264	0.927113	1.138234	1.024755	0.933514	1.124914
Lag 6	1.024229	0.91852	1.142104	1.022002	0.925645	1.128391
Lag 7	1.019734	0.910324	1.142294	1.017924	0.918133	1.128562
Lag 8	1.014029	0.902346	1.139534	1.012746	0.910815	1.126083
Lag 9	1.007351	0.894439	1.134517	1.006681	0.903556	1.121575
Lag 10	0.999922	0.886487	1.127873	0.999929	0.89625	1.115602
Lag 11	0.991946	0.878412	1.120154	0.992676	0.888826	1.108659
Lag 12	0.98361	0.870181	1.111825	0.985089	0.881251	1.101162
Lag 13	0.975083	0.8618	1.103256	0.977322	0.873532	1.093445
Lag 14	0.966515	0.853318	1.094727	0.969512	0.865712	1.085757
Lag 15	0.958039	0.844818	1.086434	0.96178	0.857869	1.078277
Lag 16	0.949771	0.836407	1.078501	0.954231	0.850101	1.071117
Lag 17	0.941812	0.828207	1.070999	0.946959	0.842522	1.064341
Lag 18	0.934244	0.820344	1.063959	0.940039	0.835246	1.057979
Lag 19	0.927139	0.812932	1.057389	0.933537	0.828383	1.052039
Lag 20	0.92055	0.806073	1.051285	0.927504	0.822026	1.046516
Lag 21	0.914522	0.799843	1.045642	0.921981	0.816249	1.041408
Lag 22	0.909084	0.794295	1.040461	0.916995	0.8111	1.036716
Lag 23	0.904254	0.789453	1.035751	0.912566	0.806603	1.032448
Lag 24	0.900041	0.785312	1.031532	0.9087	0.802756	1.028625
Lag 25	0.896441	0.781843	1.027837	0.905395	0.799532	1.025275
Lag 26	0.89344	0.778991	1.024704	0.902639	0.79688	1.022433
Lag 27	0.891013	0.776682	1.022174	0.90041	0.794733	1.020138
Lag 28	0.889126	0.774829	1.020284	0.898676	0.793008	1.018424
Lag 29	0.887734	0.773332	1.01906	0.897397	0.791616	1.017312
Lag 30	0.886782	0.772096	1.018503	0.896521	0.790466	1.016807
Lag 31	0.886203	0.771027	1.018583	0.895989	0.789471	1.016879
Lag 32	0.88592	0.770048	1.019227	0.895729	0.78856	1.017464
Lag 33	0.885846	0.769098	1.020315	0.895661	0.787675	1.018451
Lag 34	0.88588	0.768136	1.021673	0.895693	0.786779	1.019683
Lag 35	0.885912	0.767138	1.023077	0.895722	0.785849	1.020957
Lag 36	0.88582	0.766091	1.02426	0.895637	0.784874	1.022031
Lag 37	0.885468	0.764982	1.02493	0.895314	0.783842	1.022638
Lag 38	0.884712	0.763783	1.024787	0.894619	0.782725	1.022508
Lag 39	0.883396	0.762424	1.023562	0.893409	0.781458	1.021397
Lag 40	0.881354	0.760762	1.02106	0.891531	0.77991	1.019127
Lag 41	0.878411	0.75854	1.017226	0.888825	0.777838	1.015648
Lag 42	0.874389	0.75532	1.012227	0.885124	0.774837	1.011109
Lag 43	0.869101	0.750423	1.006547	0.880256	0.770268	1.00595
Lag 44	0.86236	0.742869	1.001072	0.874048	0.763216	1.000974
Lag 45	0.853983	0.731407	0.997102	0.866326	0.752503	0.997365

Table S60- The cumulative effect between AQI and non-accidental mortality in warmer months (for both sexes and age group <18) from March 2011 through March 2014 in Tehran megacity, Iran.

	Per IQR			Per 10 units		
Lag	RR	Lower CI	Upper CI	RR	Lower CI	Upper CI
Lag 0	1.016252	0.997839	1.035004	1.005989	0.999199	1.012824
Lag 1	1.029669	0.995527	1.064981	1.010887	0.998341	1.023591
Lag 2	1.040452	0.993026	1.090142	1.014795	0.997411	1.032482
Lag 3	1.048821	0.990299	1.110801	1.017811	0.996396	1.039686
Lag 4	1.05501	0.987311	1.127351	1.020031	0.995282	1.045397
Lag 5	1.05926	0.984033	1.140238	1.021551	0.994056	1.049807
Lag 6	1.061813	0.980441	1.149938	1.022463	0.992711	1.053106
Lag 7	1.062907	0.976521	1.156936	1.022853	0.991239	1.055475
Lag 8	1.062775	0.972269	1.161707	1.022806	0.989638	1.057085
Lag 9	1.061639	0.967697	1.164701	1.0224	0.987912	1.058093
Lag 10	1.059707	0.962831	1.16633	1.021711	0.986069	1.058641
Lag 11	1.057174	0.957714	1.166964	1.020806	0.984125	1.058854
Lag 12	1.054222	0.952407	1.16692	1.019749	0.982102	1.058839
Lag 13	1.051012	0.946985	1.166467	1.018598	0.980027	1.058687
Lag 14	1.047694	0.941532	1.165826	1.017406	0.977933	1.058471
Lag 15	1.044397	0.936141	1.165173	1.016219	0.975856	1.058252
Lag 16	1.041238	0.930906	1.164647	1.015079	0.973831	1.058075
Lag 17	1.038315	0.925919	1.164355	1.014023	0.971895	1.057977
Lag 18	1.035712	0.921262	1.16438	1.013081	0.970082	1.057985
Lag 19	1.033497	0.917006	1.164787	1.012278	0.96842	1.058122
Lag 20	1.031725	0.913208	1.165624	1.011635	0.966933	1.058404
Lag 21	1.030436	0.909905	1.166932	1.011166	0.965636	1.058843
Lag 22	1.029654	0.907117	1.168743	1.010882	0.964539	1.059452
Lag 23	1.029392	0.904844	1.171084	1.010787	0.963643	1.060237
Lag 24	1.029649	0.903066	1.173974	1.01088	0.962941	1.061205
Lag 25	1.030408	0.901747	1.177427	1.011156	0.96242	1.06236
Lag 26	1.031642	0.900832	1.181446	1.011604	0.962059	1.063702
Lag 27	1.033307	0.900254	1.186024	1.012209	0.96183	1.065227
Lag 28	1.035346	0.899932	1.191136	1.012948	0.961702	1.066925
Lag 29	1.037688	0.899777	1.196737	1.013796	0.961641	1.06878
Lag 30	1.040246	0.899694	1.202756	1.014721	0.961608	1.070768
Lag 31	1.042919	0.899585	1.209091	1.015686	0.961565	1.072853
Lag 32	1.045589	0.899349	1.215608	1.016648	0.961472	1.074991
Lag 33	1.048123	0.89889	1.222131	1.01756	0.96129	1.077124
Lag 34	1.050372	0.898109	1.228449	1.018368	0.96098	1.079183
Lag 35	1.052171	0.896911	1.234308	1.019014	0.960505	1.081087
Lag 36	1.05334	0.895196	1.239422	1.019433	0.959825	1.082743
Lag 37	1.053684	0.892862	1.243473	1.019556	0.958897	1.084053
Lag 38	1.052995	0.889796	1.246127	1.019309	0.957676	1.084909
Lag 39	1.051054	0.885867	1.247042	1.018613	0.956108	1.085204
Lag 40	1.047631	0.880919	1.245892	1.017383	0.954126	1.084833
Lag 41	1.042492	0.874759	1.242387	1.015532	0.95165	1.083702
Lag 42	1.035401	0.867144	1.236306	1.012968	0.948573	1.081735
Lag 43	1.026125	0.857764	1.227531	1.009597	0.94476	1.078885
Lag 44	1.014438	0.846229	1.216082	1.005323	0.940034	1.075147
Lag 45	1.00013	0.832056	1.202155	1.000048	0.934172	1.07057

PART II: Modeling the long-term spatial variability

Article 2: Annual and seasonal spatial models for nitrogen oxides in Tehran, Iran

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Annual and seasonal spatial models for nitrogen oxides in Tehran, Iran

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Very few land use regression (LUR) models have been developed for megacities in low- and middle-income countries, but such models are needed to facilitate epidemiologic research on air pollution. We developed annual and seasonal LUR models for ambient oxides of nitrogen (NO, NO_2, and NO_X) in the Middle Eastern city of Tehran, Iran, using 2010 data from 23 fixed monitoring stations. A novel systematic algorithm was developed for spatial modeling. The R^2 values for the LUR models ranged from 0.69 to 0.78 for NO, 0.64 to 0.75 for NO_2, and 0.61 to 0.79 for NOx. The most predictive variables were: distance to the traffic access control zone; distance to primary schools; green space; official areas; bridges; and slope. The annual average concentrations of all pollutants were high, approaching those reported for megacities in Asia. At 1000 randomly-selected locations the correlations between cooler and warmer season estimates were 0.64 for NO, 0.58 for NO_X, and 0.30 for NO_2. Seasonal differences in spatial patterns of pollution are likely driven by differences in source contributions and meteorology. These models provide a basis for understanding long-term exposures and chronic health effects of air pollution in Tehran, where such research has been limited.

Air pollution is a complex mixture of gases and particles, and it has been associated with a wide range of health outcomes[1,2]. The latest estimates from the Global Burden of Disease (GBD) Study indicated that approximately 87% of the global population is exposed to ambient concentrations of fine particulate matter ($PM_{2.5}$) that do not meet the guideline values set by the World Health Organization (WHO)[3,4]. This estimate is even higher when restricted to the populations of low- and middle-income countries (LMICs). In addition, air pollution was one of six modifiable risk factors associated with more than 5% of the GBD, as measured by disability-adjusted life years lost (DALYs)[5]. This burden is also reflected in Iran[6,7], where the latest estimates suggest that approximately 7% of total DALYs are attributable to air pollution, which is ten times greater than the DALYs attributable to HIV/AIDS and tuberculosis combined[8]. Even so, the burden of air pollution might be substantially underestimated because (1) most of the exposure-response estimates are from high-income countries, and (2) the burden might not be fully captured by $PM_{2.5}$ and ozone, which were the only indicators used in the GBD analyses. Furthermore, emerging evidence suggests that air pollution is associated with many chronic diseases not yet included in the GBD assessment, such as acceleration of atherosclerosis[2], high blood pressure[9,10], diabetes[11,12], metabolic syndrome[13], and possibly with neurodegenerative diseases such as multiple sclerosis[14], vascular dementia and Alzheimer's disease[15,16].

The scientific community has consistently stated that lack of epidemiologic evidence from LMICs limits the generalizability of current air pollution findings[4]. One pillar of air pollution epidemiology is high quality exposure estimates[17], but quantification of exposures at the individual level has been especially challenging in LMICs[18–20]. In light of the long-term health effects associated with reduced air quality, methods that estimate the spatial distribution of air pollutants are particularly useful. Land use regression (LUR) is a widely applied, state-of-the-science method used to map spatial variability in ambient air pollutants. Generally speaking, LUR uses local land use

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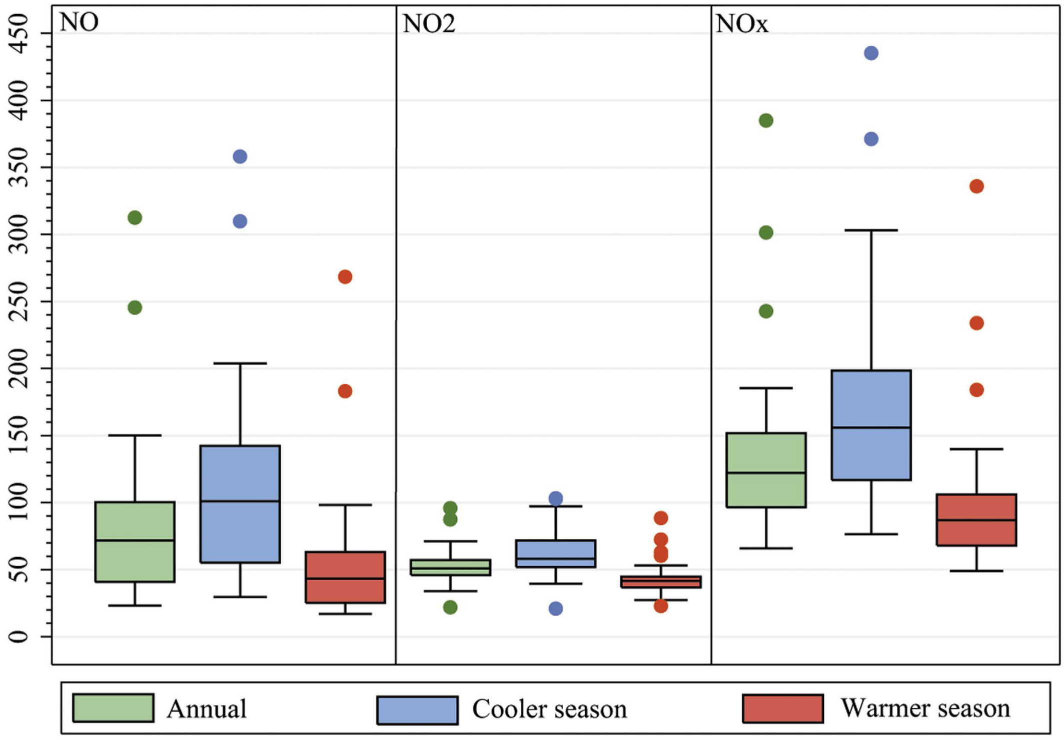

Figure 1. Distribution of pollutant concentrations (ppb) over the 23 monitoring stations in Tehran, Iran, 2010. The figure is generated using STATA 13 (STATA Corp., TX, USA, http://www.stata.com/).

information characterized in geographic information systems (GIS) to estimate concentrations of air pollutants at any location within a city[21]. The land use variables can represent a broad range of characteristics in the area surrounding the locations, such as the type of land use, elevation, population density, point sources, and vehicle traffic[22]. Valid LUR models offer the opportunity to estimate air pollution concentrations at locations where no measurement data are available.

Two important considerations in LUR modeling are (1) the number of monitoring sites and (2) the locations of those sites within the study area[23]. Some LUR models are based on data from a small number sites (for example, 17 sites in Houston metropolitan area)[24], whereas others use large numbers of local, national, or multi-national measurement locations (for example, 562 sites across 12 Spanish cities in Girona Province[25] or 2400 sites across Europe)[26]. Previous work suggests that LUR models should be constructed using measurements from at least 80 locations[27] identified by some algorithm to optimize their spatial variability[28]. However, several studies have used secondary data from existing regulatory monitoring networks, which typically have fewer locations[24,29–32] with less spatial variability. In addition to these considerations, Basagaña *et al.* (2012) suggested that LUR analyses should use a restricted set of predictor variables, especially when the number of monitoring sites is small[27]. However, no LUR study to date has introduced a systematic approach to restricting the variable set.

Nitrogen oxides (NOx) are a group of highly reactive gasses that contain different numbers of nitrogen and oxygen atoms, including nitrogen oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O). However, NOx is frequently considered to be the sum of NO and NO_2 in atmospheric sciences[33]. Fossil fuel combustion produces NO[34] as a primary pollutant. This free radical rapidly oxidizes in the atmosphere, scavenges tropospheric ozone, and converts to secondary NO_2[35]. Both mobile and point sources contribute to NO in Tehran. Iran benefits from large natural gas reserves[36] that are used for most commercial processes and residential heating.

To date, LUR has been applied to model NO_2[21,22,30,37–39] in many high-income countries and in some LMICs[40,41]. However, LUR models for NO and NOx are rare, especially in LMICs[42]. We previously reported LUR models for particulate matter (PM_{10}) and sulfur dioxide (SO_2) in Tehran, where the entire population was located in areas exceeding the WHO guidelines for both pollutants[40]. The results also suggested the potential for seasonal differences in the spatial patterns of more primary pollutants. Here we develop annual and seasonal models for NO, NO_2 and NOx using data from the regulatory monitoring network.

Results

Air quality data. None of the pollutants were normally distributed ($p < 0.001$). The annual median concentrations (interquartile range, or IQR) were 71.7 (59.3) ppb for NO, 50.9 (11.1) ppb for NO_2, and 122.3 (55.1) ppb for NO_X across the 23 monitoring stations. The cooler season medians (IQR) were 100.9 (87), 58.1 (19.7), and 155.9 (81.6) ppb, respectively, and the warmer season values were 43.4 (37.7), 41.7 (7.9), and 87.0 (38.0) ppb, respectively (Fig. 1). The correlation between the annual, cooler season, and warmer season concentrations ranged from 0.94 to 0.99 for NO, from 0.61 to 0.92 for NO_2, and from 0.90 to 0.99 for NO_X across the 23

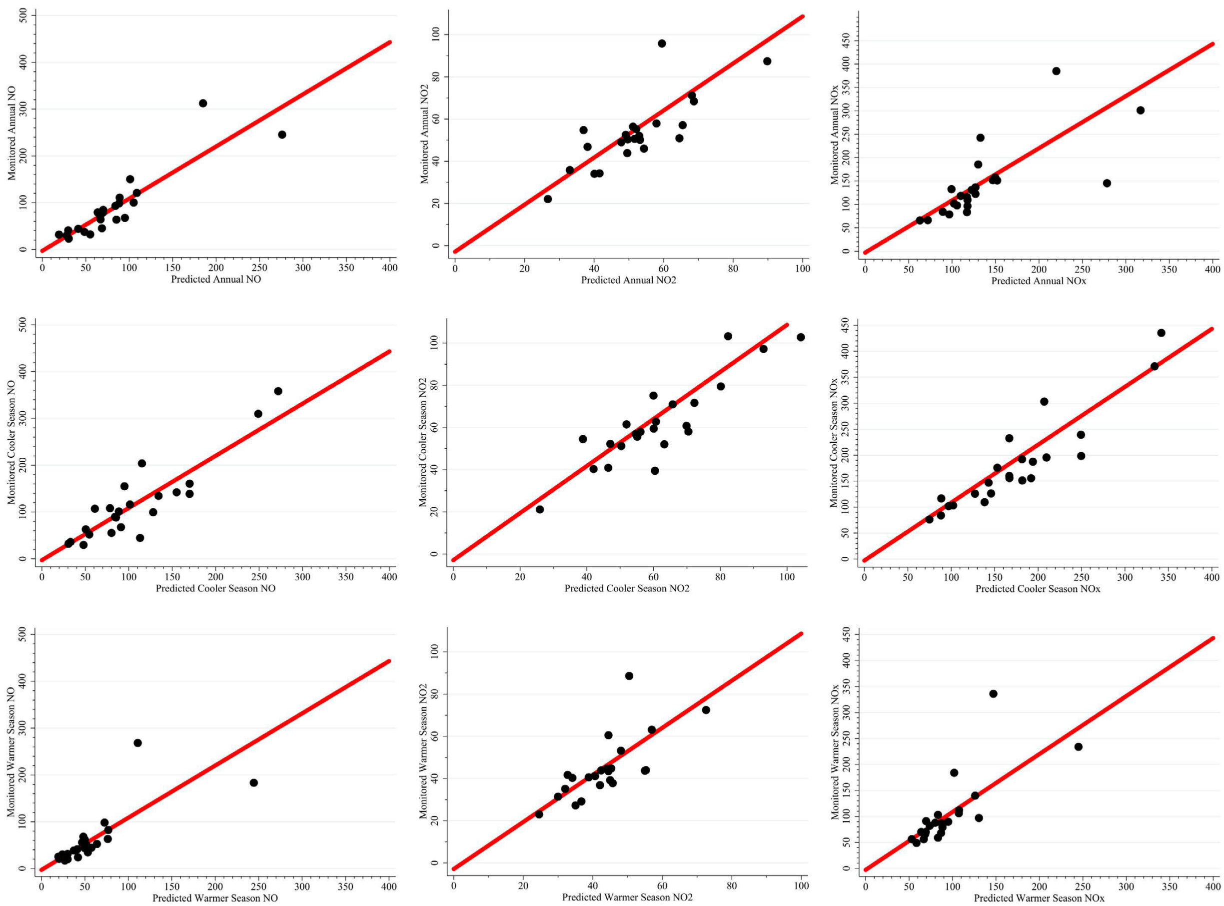

Figure 2. Observed versus predicted concentrations (ppb) for annual, cooler and warmer seasons of NO, NO_2, and NO_X in Tehran, Iran. The red line is the 1:1 linear prediction. The figures are generated using STATA 13 (STATA Corp., TX, USA, http://www.stata.com/).

monitoring stations. The between-pollutant correlations ranged from 0.25 to 0.46 for NO and NO_2, from 0.85 to 0.95 for NO and NO_X, and from 0.38 to 0.72 for NO_2 and NO_X (Table S2, supplemental information).

Final LUR models. Of the 210 potentially predictive variables (PPVs) we generated, 21 (10%) were significantly predictive in one or more of the LUR models. The R^2 values for the final annual mean models were 0.78, 0.69, and 0.71 for NO, NO_2 and NO_X, respectively. They ranged from 0.69 to 0.79 for the cooler season models and 0.61 to 0.72 for the warmer season models (Table 1). Some of the variables appeared in multiple models. These included: (1) distance to the traffic access control zone; (2) distance to sensitive land use areas; (3) the natural logarithm of distance to the nearest primary school; (4) the natural logarithm of distance to the nearest hazardous facility; (5) slope; (6) the presence of bridges, and (7) areas of green, official/commercial, and other land uses (Table 1, and Tables S3–S11, supplemental information). The Moran's I results were −0.07, −0.12, and −0.04 for residuals of the annual, cooler season, and warmer season NO models. All p-values were greater than 0.23. The values were similar for the NO_2 and NOx models (not shown), with a minimum p-value of 0.06.

Model stability. The R^2 values for the leave-one-out cross validations ranged from 0.53 to 0.66 for the NO models, 0.51 to 0.58 for NO_2 models, and from 0.42 to 0.63 for the NO_X models (Table 1, and Tables S3–S11, Supplemental information). A final leave-one-out cross-validation (LOOCV) check was done for the coefficient of each predictive variable in the final regression models. The minimum and maximum of the LOOCV coefficients had the same direction of effect for all variables in all models. All the coefficients of variation ranged from 7% to 11%.

Regression maps. The limits of prediction for the annual, cooler season, and warmer season NO models were 16.4, 21.0, and 12.0 ppb, respectively. For the NO_2 models they were 15.6, 14.9, and 16.3 ppb, respectively, and for the NOx models they were 46.6, 54.0, and 34.6 ppb, respectively. Overall, out of 24,505,474 grid cells in the modeling domain, a range of 0.2% to 16.0% of cells were increased to the limit of prediction and 0.0% to 5.3% of cells were truncated to 120% of the maximum observed concentrations (Table 2).

Agreement between the measured and predicted pollutant concentrations was relatively good (Fig. 2). The maps showed clear hotspots for the NO concentrations across the city. These were well-characterized by distance to the traffic access control zone, the natural logarithm of distance to the nearest primary school, surrounding

Response	Equation (variables are ordered by partial R^2)	R^2	Adjusted R^2	LOOCV[a] R^2	Highest Variance Inflation Factor (variable)	*p*-value	RMSE[b]	Measured Response[c]
Log Annual NO	1.53 − 1.4e-04 × **DIST to TACZ** + 6.9e-01 × **LNDIST to PRSC** − 3.1e-06 × **GRS.500** − 4.4e-02 × **SLP** − 3.0e-05 × URF.100	0.78	0.71	0.66	1.8 (LNDIST to PRSC)	<0.001	32.1	88 (23–312)
Log Cooler Season NO	1.92 + 5.1e-01 × **LNDIST to PRSC** + 4.7e-05 × TPDC.2500 − 1.1e-04 × DIST to BST − 3.2e-04 × DIST to PST − 2.1e-06 × **GRS.400**	0.69	0.60	0.53	1.5 (TPDC.2500)	<0.001	38.6	117 (30–358)
Log Warmer Season NO	0.68 − 1.5e-04 × **DIST to TACZ** + 7.4e-01 × **LNDIST to PRSC** − 6.3e-02 × **SLP** − 2.0e-06 × **GRS.500** + 9.4e-04 × DIST to GRS	0.72	0.64	0.59	2.2 (SLP)	<0.001	36.9	60 (17–268)
Log Annual NO_2	2.9 + 1.1e-05 × **OFIC.300** − 1.5e-04 × **DIST to SNS** + 1.7e-01 × **LNDIST to PRSC** + 2.2e-05 × **OTHR.300**	0.69	0.62	0.57	1.3 (LNDIST to PRSC)	<0.001	9.9	53 (22–96)
(Log Cooler Season NO_2)^3	−5.7e + 01 + 5.9e-04 × **OFIC.300** + 1.1e-01 × × ELEV − 4.1e-03 × DIST to AIR + 8.3e-04 × **OTHR.400** − 1.5e-03 × ARD.100	0.75	0.68	0.58	3.8 (DIST to AIR)	<0.001	9.2	62 (21–103)
(Log Warmer Season NO_2)$^{-1}$	3.3e-01 − 6.8e-07 × **OFIC.300** + 1.2e-05 × **DIST to SNS** − 1.0e-02 × **LNDIST to PRSC**	0.64	0.58	0.51	1.2 (LNDIST to PRSC)	<0.001	10.2	45 (23–89)
(Log Annual NO_X)$^{-2}$	9.2e-02 + 2.0e-06 × **DIST to TACZ** − 6.5e-03 × **LNDIST to PRSC** + 2.6e-05 × DIST to OFIC − 3.2e-03 × **LNDIST to HZRFAC** − 1.2e-03 × **BGD.400**	0.71	0.62	0.58	1.7 (DIST to OFIC)	<0.001	52.7	142 (66–385)
(Log Cooler Season NO_X)$^{-1}$	2.9e-01 + 5.8e-06 × × **DIST to TACZ** − 1.1e-02 × **LNDIST to HZRFAC** + 1.6e-06 × URF.100 + 8.8e-08 × GRS.400 − 9.2e-03 × **LNDIST to PRSC**	0.79	0.73	0.63	1.9 (DIST to TACZ)	<0.001	37.1	180 (76–435)
(Log Warmer Season NO_X)$^{-4}$	7.1e-03 − 8.1e-04 × **LNDIST to PRSC** + 1.3e-07 × **DIST to TACZ** − 4.0e-04 × (OFIC.100)$^{0.1}$ − 1.3e-04 × × **BGD.400** + 3.4e-05 × SLP	0.61	0.50	0.42	1.9 (LNDIST to PRSC)	0.004	44.8	105 (49–336)

Radius variable types included in the models were:	The log-linear distance variables included in the models were:
GRS = green space area	**LNDIST to HZRFAC** = log distance to hazardous facilities
OFIC = official/commercial land use area	**LNDIST to PRSC** = log distance to the nearest primary school
OTHR = other land use area	
URF = urban facilities area	Other variable included in the models were:
ARD = arid/undeveloped area	**BGD** = bridge length in a buffer radii divided by distance to the bridges
The linear distance variables included in the models were:	**ELEV** = elevation
DIST to AIR = distance to airport or air cargo facilities	**SLP** = slope
DIST to BST = distance to bus terminal	**TPDC** = population density excluding unemployed and children <5 years
DIST to GRS = distance to green space area	
DIST to SNS = distance to sensitive area	For variables of the form **XXX.YYY** the **XXX** indicates the variable type, and the **YYY** indicates the buffer size, in meters.
DIST to OFIC = distance to official/commercial area	
DIST to PST = distance to petrol stations	
DIST to TACZ = distance to the traffic access control zone	

Table 1. Final land use regression models for annual and seasonal concentrations of NO, NO_2 and NO_X in Tehran, Iran. Variables in bold highlight consistencies between models for the same pollutant—see SI, Tables S2–S7 for full description of each model. [a]Leave one out cross validation; [b]Root mean square error = $\sqrt{\frac{1}{N}\sum(Observed - Predicted)^2}$; [c]Mean (min–max); note that the units are ppb. The *p*-values of underlined variables are ≤0.001; The *p*-values of dotted-underlined variables are ≤0.01; The *p*-values of wave-underlined variables are ≤0.05.

Action	Pollutant	Annual	Cooler season	Warmer season
Enlarged	NO	8.9%	11.3%	11.4%
	NO_2	0.4%	2.1%	0.2%
	NOx	16.0%	12.1%	0.5%
Truncated	NO	0.1%	0.0%	1.5%
	NO_2	4.6%	5.3%	2.0%
	NOx	1.0%	1.3%	0.9%

Table 2. The percentage of predicted grid cells out of >24 million cells in the study area that either enlarged to the quantification limit or truncated to 120% of the maximum observed concentrations by 2010 LUR models in Tehran, Iran.

areas of green land use, and slope. The NO_2 concentrations were more dispersed and homogeneous throughout the city. The NO_X maps were similar to the NO maps, and the hotspots were driven by similar variables, though they also reflected distance to the nearest hazardous facility and the presence of bridges (Fig. 3).

The correlations between the predicted annual, cooler season, and warmer season concentrations at 1000 randomly-selected sites were weak to moderate. Values for the warmer and cooler season estimates were 0.64 for NO, 0.58 for NOx, and 0.30 for NO_2 (Fig. 4).

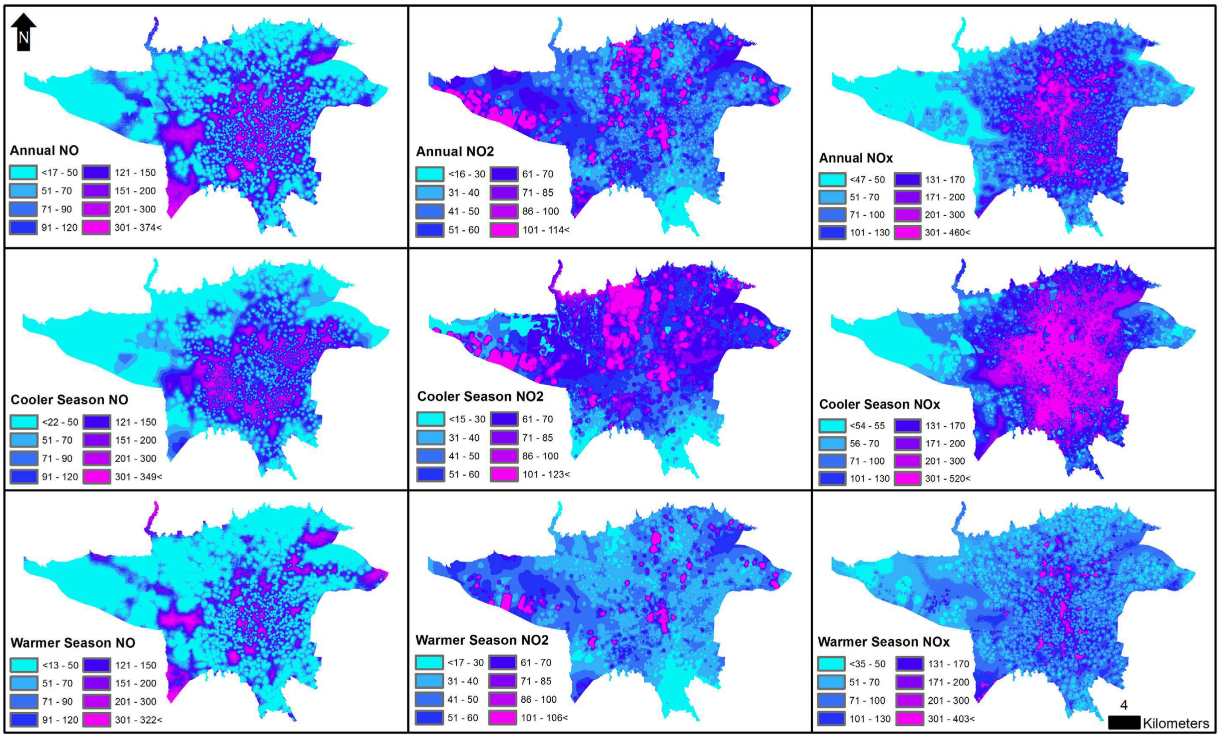

Figure 3. Estimated annual, cooler and warmer seasons NO, NO_2 and NO_X concentrations (ppb) from the final land use regression models in Tehran, Iran, 2010. The *prediction resolution* is 5 × 5 meters. The figure is generated using ESRI's ArcGIS 10.2.1 for Desktop (ESRI, Redlands, CA, USA, http://www.esri.com/).

	A_NO	C_NO	W_NO	A_NO₂	C_NO₂	W_NO₂	A_NOx	C_NOx	W_NOx
A_NO	1.00								
C_NO	0.72	1.00							
W_NO	0.91	**<u>0.64</u>**	1.00						
A_NO₂	0.20	-0.01	0.19	1.00					
C_NO₂	-0.02	-0.04	-0.04	0.47	1.00				
W_NO₂	0.22	0.05	0.23	0.89	**<u>0.30</u>**	1.00			
A_NOx	0.57	0.71	0.47	0.03	0.06	0.03	1.00		
C_NOx	0.69	0.72	0.55	-0.01	0.05	-0.01	0.84	1.00	
W_NOx	0.80	0.64	0.74	0.27	0.03	0.30	0.67	**<u>0.58</u>**	1.00

Legend
≤ 0.20
0.21 – 0.40
0.41 – 0.60
0.61 – 0.80
≥ 0.81

Figure 4. The Spearman correlation coefficients between the annual (**A**), cooler season (**C**), and warmer season (**W**) predicted concentrations across 1000 random locations for NO, NO_2, and NOx in 2010, Tehran, Iran. The seasonal comparisons (**C** vs **W**) are bold underlined.

Materials and Methods

Study area. The megacity of Tehran is the capital of Iran. It covers an area of 613 km^2, with the Alborz Mountains in north and desert in south. The populated areas within the city range from 1,000 to 1,800 meters above sea level (Fig. 5). The annual mean daily temperature is 18.5 °C, with highs of 43 °C in July and lows of −15 °C in January. The average annual precipitation is 220 millimeters (mm), with the maximum in March (39 mm) and the minimum in September (1 mm). The weather is typically sunny, with an annual average of 2800 h of bright sunshine and a mean cloud cover of 30%. The prevailing winds blow from west and north (Figure S1, Supplemental information). Tehran is the most populous city in Iran, and the third largest city in the Middle East. There are approximately 9 million urban residents, with a daytime population of more than 10 million due to diurnal migration from the surrounding areas[40,43].

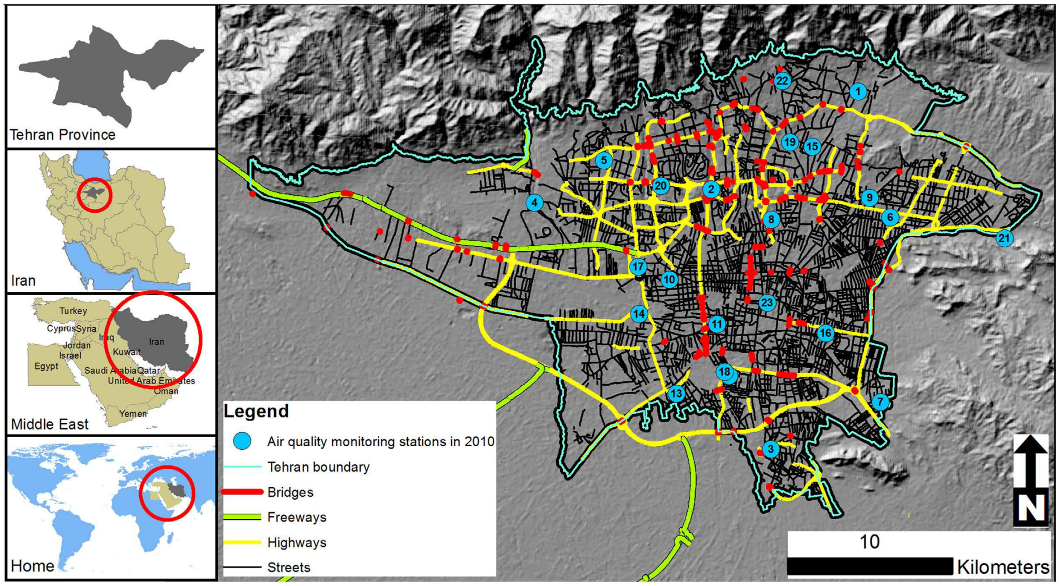

Figure 5. The study area of Tehran, Iran showing locations of 23 air quality monitoring stations in 2010. The figure is generated using ESRI's ArcGIS 10.2.1 for Desktop (ESRI, Redlands, CA, USA, http://www.esri.com/).

Air quality data. Hourly NO, NO_2 and NOx concentrations for the 2010 calendar year were obtained from 23 air quality monitoring stations administered by two government agencies (Fig. 5). Of the stations, 16 belonged to the Air Quality Control Company (AQCC), and 7 to the Department of Environment (DOE). Both the AQCC and DOE monitoring stations used chemiluminescence analyzers (Model AC 32 M of Environment SA, France; APNA-370 of Horiba, Japan; and EC 9841 of Ecotech, Australia) to measure nitrogen oxides. They follow quality assurance/quality control (QA/QC) procedures that, under ideal circumstances, ensure the instruments are checked and calibrated every two weeks. However, calibration gases can be challenging to obtain in Tehran.

A complete annual dataset would contain 8760 measurements (24 hours/day × 365 days in 2010) for each pollutant at each monitoring site. However, 28.1%, 27.7%, and 27.6% of the NO, NO_2 and NO_X values were missing, respectively (Figure S2, supplemental information). As in our previous work[40], the Amelia program was used for imputation of the missing data (Page S5, supplemental information)[44]. The program uses a new expectation-maximization algorithm with bootstrapping to impute missing values and return a complete dataset. We provided the program with all available hourly concentrations from the different stations, along with the month, day, and hours of measurement. In order to evaluate the consistency and reliability of the missing data estimates we ran the Amelia program 10 times for each pollutant to impute hourly missing values, and calculated the resulting 10 annual averages for each monitoring station. The mean of the 10 imputation-filled datasets was calculated for NO, NO_2 and NO_X from January 1st, 2010 through January 1st, 2011 for all monitors, and these values were used as the LUR response variables.

We also divided the year into warmer and cooler seasons based on our previous work[40] and because Chen *et al.* (2010) reported different LUR predictor variables and spatial patterns in Tianjin, China during the heating and non-heating seasons. The same study also found that the predictive variables and the R^2 values for the LUR models differed by season[41]. The warmer and cooler seasons were defined as April through September and October through March, respectively. These months were selected based on WHO guidelines for countries in the Northern hemisphere, and on the highest and lowest mean daily temperatures at Mehrabad International Airport in Tehran[40].

Spatial predictors. We generated 210 PPVs in six classes and 73 sub-classes (Table 3). The six classes were *Traffic Surrogates*, *Land Use*, *Distance Variables*, *Population Density*, *Product Variables, and Geographic Location*. The *Traffic Surrogates* class described the vehicular network in buffers around the pollution monitoring stations. The *Land Use* class described ten land use types within buffers around the stations. The *Distance Variables* class measured the Euclidian distance (and natural logarithm of the distance) from each station to all of the *Traffic Surrogate* and *Land Use* types, and to other features. The natural logarithms of the distances were used based on studies that have reported exponential decay in air pollutant concentrations with increasing distance from pollution sources[45–48]. The *Population Density* was calculated for the total population and for the population excluding unemployed people and children less than five years of age. The *Product Variables* class included the ratio of variables in the *Traffic Surrogates* class to the variables in the *Distance Variables* class. Finally, the *Geographic Location* class included the elevation of each monitoring site, obtained from a digital elevation model (DEM) of Tehran in meters above sea level, and a slope (gradient) variable that was created in GIS based on the DEM. The potential geospatial variables were selected based on previous studies and available information in Tehran. The raw GIS inputs were all in vector format, originating from the Japan International Cooperation Agency (JICA) and the Centre for Earthquake and Environmental Studies of Tehran (CEST)[49]. The final PPVs were all in raster format with a resolution of 5 × 5 meters, and their values in the grid cells underlying the monitoring stations were used

Variable class (N variables)	Description	Variable sub-class (N variables)	Buffer radii (m)	Assumed effect	Input file type & source, and procedure
Traffic Surrogates (26)	Total length of road types and bridges (m)	ST = streets (5) HW = highways (5) RDa = major roads (7) RDb = all roads (7) BG = bridges (2)	100–500 100–1000 400–500	+ + + + +	Polyline format, JICA and CEST[a] (a) Convert polyline files into raster files with 5 m pixel size (b) Use *Neighborhood, Focal Statistics*[b] to sum the number of road pixels within the search radii (c) Multiply the result by 5
Land Use (50)	Total area of 10 LU types (m^2)	RES = residential (5) GRS = green space (5) URF = urban facilities (5) IND = industrial/workshop (5) OFIC = official/commercial (5) TRS = transportation (5) SNS = sensitive areas (5) AGR = agriculture (5) ARD = arid/undeveloped (5) OTHR = other (5)	100–500	– – ?[c] + + + ?[c] – – ?[c]	Polygon format, JICA and CEST[a] (a) Convert land use polygons into 10 raster files for RES, GRS, URF, IND, OFIC, TRS, SNS, AGR, ARD, and OTHR with 5 m pixel size (b) Use *Neighborhood, Focal Statistics*[b] to sum the number of land use type pixels within the search radii (c) Multiply the result by 25
Distance Variables (60)	Distance (DIST) and log distance (LNDIST) to various features (m)	DIST and LNDIST to: All Traffic Surrogate and Land Use variables (30) FWY = freeways (2) TACZ = traffic access control zone (2) TACAP = TACZ in critical air pollution conditions (2) SPLND = sport land (2) PRSC = primary school (2) SCSC = high school (2) PST = petrol stations (2) PRK = park (2) MSQ = mosque (2) HZRFAC = hazardous facility (2) FV = various food shops (2) BST = bust terminal (2) AIR = airport or air cargo facilities (2) AMB = ambulance service (2)	N/A	Opposite of above – – – + + + – + + ?[c] ?[c] – ?[c] ?[c]	Raster format, calculated from raw files of JICA and CEST[a] Use *Spatial Analyst, Distance, Straight Line* to produce DIST variables; use *Spatial Analyst, Raster Calculator* to produce LNDIST variables
Population Density (22)	Density of population (persons per km^2)	PD = total (11) TPDC = PD excluding unemployed and children <5 years (11)	500–3000	+ +	Polygon format, JICA and CEST[a] a) Convert census polygons to centroids; assign each centroid the population count of the polygon from which it was derived (b) Use *Kernel Density* to estimate the values within each radius.
Product or Ratio Variables (52)	Integrated products of the traffic surrogates and distance variable classes	STD = ST/DISTST (5) HWD = HW/DISTHW (5) STSQD = ST/sq(DISTST) (5) HWSQD = HW/sq(DISTHW) (5) RDaD = RDa/DISTRDa (7) RDbD = RDb/DISTRDb (7) RDaSQD = RDa/sq(DISTRDa) (7) RDbSQD = RDb/sq(DISTRDb) (7) BGD = BG/DISTBG (2) BGSQD = BG/sq(DISTBG) (2)	100–500 100–1000 400–500	+ + + + + + + + + +	Raster format, calculated from raw files of JICA and CEST[a] Use *Spatial Analyst, Raster Calculator* to create Product Variables
Geographic Location (2)	Physical location	ELEV = elevation (m) SLP = slope (degree)	N/A	?[c] ?[c]	Digital Elevation Model (DEM), NCCI[d] Use *Spatial Analyst, Surface Analysis* to create slope from DEM

Table 3. The spatial predictor variables, assumed directions of their effects on pollutant concentrations, raw inputs, and the procedures for generating them. Modified from ref. 40 with permission from Elsevier. [a]Japan International Cooperation Agency and Center for Earthquake and Environmental Studies of Tehran. [b]Features of the Spatial Analyst Tools to ESRI's ArcMap 10.2.1 GIS (ESRI, Redlands, CA). [c]No *a priori* assigned because no effect could be assumed. [d]National Cartographic Center of Iran.

for the regression analyses. All spatial analyses and figures were generated using ESRI's ArcGIS 10.2.1 for Desktop (http://www.esri.com/).

Model development and diagnostics. The model building algorithm was based on one we developed for a previous study[40]. However, we further refined the algorithm to account for non-normality of the response variable, which can violate the assumptions of linear regression modeling. We also used transformation to normalize the relationships between the response variables and the PPVs, and we restricted the number of variables in the final model to the root of the number of observations. The key steps of the updated stepwise algorithm are:

(1) Take the log transformation of the response variable.
(2) Check for normality using the Shapiro-Wilk test[50].
(3) Apply a power transformation if not normally distributed.
(4) Linearize the relationships between the transformed variables and the PPVs using log and power transformations on the PPVs, and then proceed with the original algorithm[40] such that steps (5) through (8) are done for every iteration (i.e. the addition of each new PPV to the model):
(5) Check the direction of the effect of each PPV in the model for consistency with *a priori* assumptions (Table 3) to ensure that final models did not contradict knowledge about pollution emissions and dispersion.
(6) Ensure a p-value of < 0.1 for each PPV.

(7) Ensure that each new PPV increases the coefficient of determination (R^2) for a LOOCV[51].
(8) Calculate a multicollinearity index called the variance inflation factor (VIF)[52].
(9) Finally, restrict the number of predictor variables in LUR model to $\sqrt{N}$, where N denotes the number of monitoring stations.
(10) Check the normality of residuals using the Shapiro-Wilk test[50].

The algorithm was programmed as a function in the R statistical package. Its details are explained in pages S7–S11, the supplemental information, and in the original paper by Amini *et al.*[40]. Models were constructed for average annual, cooler season, and warmer season concentrations of NO, NO_2, and NOx.

To check the stability of the final LUR models, the regression coefficients for the LOOCV models were retained for all predictor variables in the final NO, NO_2, and NOx models. The minimum, maximum, and coefficient of variation were calculated for the set of LOOCV coefficients, and models with lower variability were considered to be more stable. The spatial autocorrelations for all annual and seasonal NO, NO_2, and NOx residuals were evaluated by calculating the global Moran's I statistic. Values of Moran's I range from −1.0 to 1.0, with −1.0 meaning perfect negative autocorrelation, 1.0 meaning perfect positive autocorrelation, and 0 meaning a random spatial pattern[53].

Regression mapping. When generating raster variables from vector data, raster cells outside of the buffer zones are returned as null (or "*NoData*" in ArcGIS). All null values for the *Traffic Surrogates*, *Land Use*, *Distance Variables*, *Population Density*, *Product Variables, and Geographic Location* variables were set to zero. The Raster Calculator in the ArcGIS Spatial Analyst Tools was used to render our final nine regression equations into maps that estimated annual and seasonal concentrations of NO, NO_2, and NO_X across the study area. We established a limit of prediction for low values, defined as the minimum observed concentration divided by the square root of two. All grid cells with estimates below this limit were set to this limit. Grid cells with very high estimates were set to 120% of the maximum observed concentrations, as per Henderson *et al.*[22] and Amini *et al.*[40].

Seasonality of the spatial variability. In order to evaluate the effect of season on the spatial variability in NO, NO_2, and NOx concentrations, we assessed the correlations between annual, cooler season, and warmer estimates at 1000 locations within the study area. These were randomly selected using the Feature Class Data Management Tools in ESRI ArcMap 10.2.1 GIS (ESRI, Redlands, CA). We checked the normality of the estimate distributions with a Shapiro-Wilk test, and we calculated the Pearson or Spearman correlation depending on the results.

Discussion

This study developed annual and seasonal LUR models for NO, NO_2 and NOx for the Middle Eastern megacity of Tehran, Iran, using data from 23 sites in the air quality monitoring network. The models performed reasonably well for all pollutants and time periods. Because there are few comparable studies published for LMICs, the discussion will focus on the observed patterns in concentrations, and the strengths and limitations of the models.

We found that the 2010 annual NO, NO_2, and NO_X concentrations were relatively high in Tehran. The mean NO concentrations (88 ppb) were more than five times higher than those reported for other large cities, such as New York (16 ppb)[54], and the mean NO_2 concentrations (53 ppb) were almost 2.5 times higher than the recommended WHO guideline value of 21 ppb[55]. They were also considerably higher than the 2008 concentrations reported for many comparable megacities, such as Delhi (18.8 ppb), São Paulo (24.6 ppb), Tokyo (28.7 ppb), Mexico City (29.3 ppb), Los Angeles (34.5 ppb), and Dhaka (43.3 ppb), and approaching the values in Beijing (63.8 ppb)[56].

Overall, the concentrations of nitrogen oxides were higher in the cooler season than in the warmer season (Fig. 1). This is consistent with the findings of Matte *et al.* (2013), where NO and NO_2 concentrations in New York were higher in winter than summer[54], and findings of Dons *et al.* (2014) in Antwerp (Belgium)[57]. The higher concentrations during the cooler season in Tehran could be due to residential heating, which is done primarily by natural gas[36]. There are also seasonal differences in meteorological factors given the specific topographical situation of the city, including inversions and low mixing heights. This may lead to more complex spatial variability in pollutants and different exposure patterns.

When considering the R^2, adjusted R^2, and LOOCV R^2 values, model performance was better in the cooler season than in the warmer season for NO_2 and NO_X, but the opposite was true for NO (Table 1). Regardless, several of the cooler and warmer season models shared the same predictor variables. The most predictive variables for all pollutants were surrogates of traffic impact, including distance to the traffic access control zone (DIST to TACZ) in the NO and NOx models (Table 1, and Figure S3, supplemental information). This is a high traffic zone in the middle of Tehran, with access restricted to authorized vehicles on working days. It supports the hypothesis that the major source of NO and NOx in Tehran is vehicles and traffic. The natural logarithm of distance to nearest primary school (LNDIST to PRSC) appeared in eight out of nine models. All models indicate that the primary schools tended to be located in less polluted areas (Figure S4, supplemental information).

Another important predictor was green space within buffers up to 500 meters. The negative coefficients suggest that concentrations of nitrogen oxides decreased as the green space increased, which supports the call for urban greening to improve air quality and overall health[58]. We also observed increasing nitrogen oxides with increasing elevation, but decreasing concentrations with increasing slopes. This may reflect different traffic flows through the city, where the northern and southern outskirts differ in elevation by almost 800 meters. In the cooler season, the NO concentrations were also increased in areas with higher total population density, which is consistent with the hypothesis that seasonal differences were driven by residential heating. Both the annual and warmer season mean NOx concentrations increased with higher bridge density. These are predominantly land bridges that allow one roadway to pass over another roadway, replacing roundabouts and traffic lights to control traffic flow. They are found at most intersections of major roads in Tehran, and also at many smaller intersections.

The correlations of cooler and warmer season measured concentrations across the 23 fixed sites were very high for NO and NOx, but they were reduced to 0.64 and 0.58, respectively, across the 1000 randomly-selected locations. The correlation for NO_2 was 0.61 across the fixed sites and 0.30 across the 1000 locations. Visual inspection of the pollution maps showed some interesting seasonal differences in the spatial distributions of NO_2. One region in the northern part of the city appeared highly polluted in the cooler season, but not in the warmer season. This region had some gaps in the monitoring data, so the validity of the model may have been compromised despite our use of Amelia (see S4 to S6, supplementary information). Overall, however, our findings suggest that epidemiologic studies based on long-term exposures should account for seasonal patterns in the spatial data.

To date, many LUR models have been developed for NO_2 in high-income countries, mainly because NO_2 is quite easy to measure with passive samplers[21]. However, some studies have also modeled NO and NOx[22,37,38,59]. In all of these studies, direct or surrogate measures of traffic have been the most predictive variables. For example, in Oslo (Norway) all oxides of nitrogen were modelled using elevation, length of large roads in a 100 m buffer, length of medium roads in a 250 m buffer, and length of small roads in a 1000 m buffer based on 80 measurement locations[37]. In Tehran, the models were mostly driven by distance to the traffic access control zone and the presence of bridges in a 400 m buffer. Su *et al.* (2009) conducted a study to estimate NO, NO_2, and NOx using 201 locations in Los Angeles (California) for two seasons. They found that traffic volume, truck routes, road networks, land use, greenness, and slope gradients were the most predictive variables[38]. We found similar explanatory variables in Tehran using data from 23 regulatory monitoring locations. However, the magnitude and ranking of the R^2 values in Los Angeles were more similar to those in Oslo, with 81% for NO, 85% for NOx, and 86% for NO_2[38]. Results from Vancouver (Canada) are also consistent with our findings in Tehran, with traffic variables, elevation, geographic coordinates, and total population within 2500 m buffer radius driving the models[22]. In Montreal (Canada) Gilbert *et al.* (2005) found that distance to highways, lengths of roads within buffers of 100–500 m, open space, and population density within a radius of 2000 m were the most predictive variables for NO_2, and the best-fitting model had an R^2 of 0.54[60].

The use of fixed site monitor locations to develop the LUR models can be both a strength and a limitation. Readily-available data from validated instruments allows academics and government agencies to regularly model the spatial variability in air pollutants with minimal additional costs. However, the locations for fixed monitoring networks are generally chosen by criteria that may not optimize their ability to capture the variability necessary for spatial modelling[28]. Although we did not evaluate whether 23 measurement sites are sufficient to reliably model spatial variability in a megacity such as Tehran[27], our future work will examine this question in more detail.

Another limitation is that some predictor variables could not be assigned a direction of effect *a priori* due to lack of previous knowledge or other studies. This, in turn, might have caused inconsistent effects of variables in the regression models. These variables include urban facilities, sensitive areas, such as military and protected government areas, other land use variables, distance to hazardous facilities areas, distance to food shops, distance to airports, distance to health and ambulance services, elevation, and slope gradients. Therefore, we suggest conducting further studies in Tehran to better specify the impact of these areas on air pollution concentrations.

Conclusions

We found significant seasonal differences in the spatial variation of nitrogen oxides in Tehran, especially NO_2. However, the small number of measurement sites in our study might affect these findings. Examples of LUR models are rare in LMICs, and these results are relevant for the next generation of exposure assessment, population-based health research, and policy-making in such contexts. In addition, this work establishes a benchmark for future air pollution modeling in Tehran. Overall, our models performed relatively well. Our next step is to evaluate whether a larger number of monitoring sites selected with a strict algorithm produces different results and/or different conclusions about the spatial patterns reported here.

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Author Contributions
H.A., C.S., M.Y., N.K., S.B.H., S.-M.T.S. and V.H. contributed in study design, technical consultation, and/or supervision of the work. H.A., S.B.H. and S.-M.T.S. conducted the GIS and/or statistical analyses. H.H., M.N. and S.A. contributed in air quality measurement and data collection. All authors reviewed the manuscript. The order of author initials is alphabetical.

Additional Information
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Supplemental Information

Annual and seasonal spatial models for nitrogen oxides in Tehran, Iran

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The Supplemental Information Contains:

25 Pages

4 Figures

11 Tables

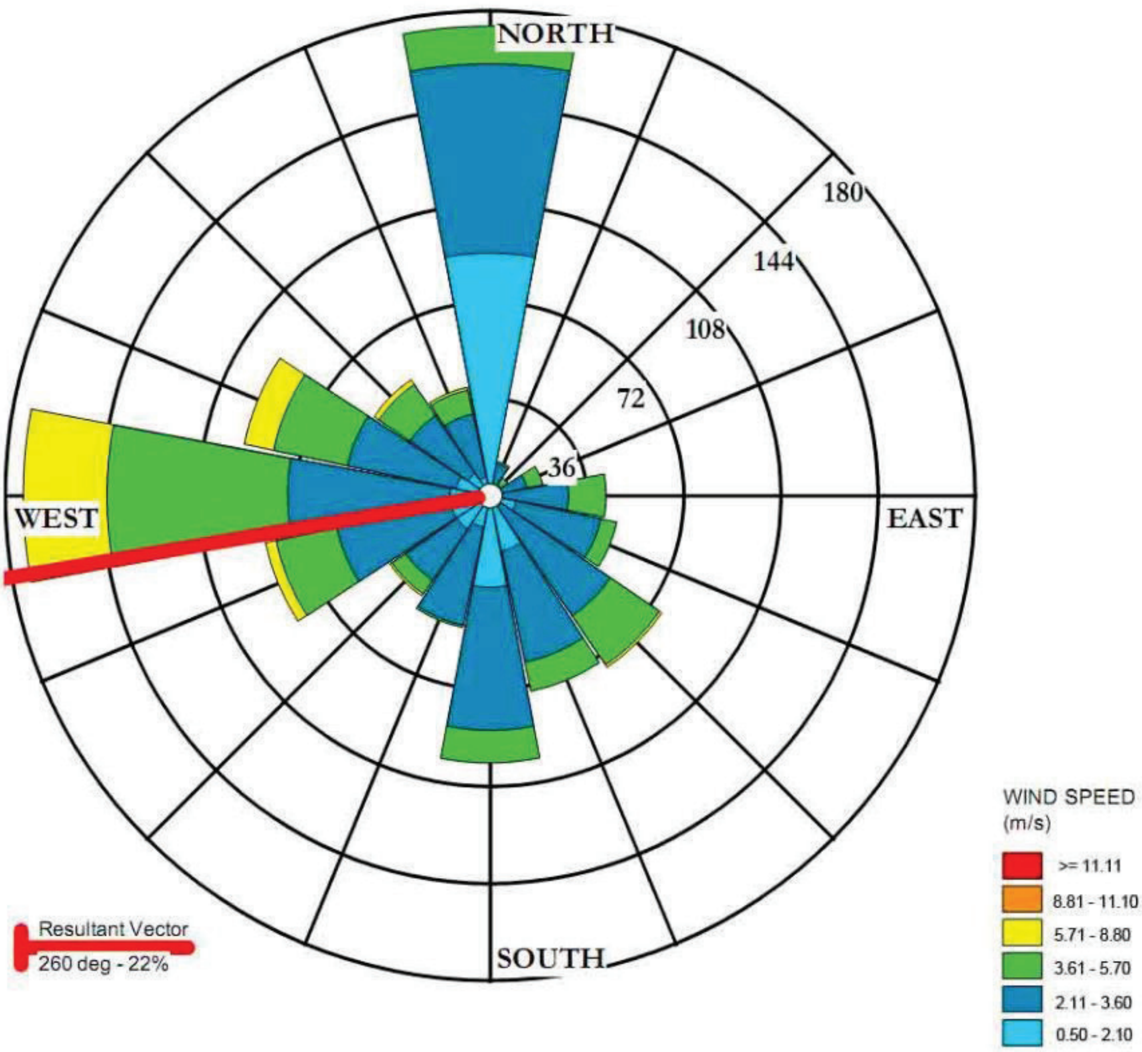

Figure S1. Wind-rose diagram for the Mehrabad International Airport meteorology station, indicating the wind is predominantly from the west and north.

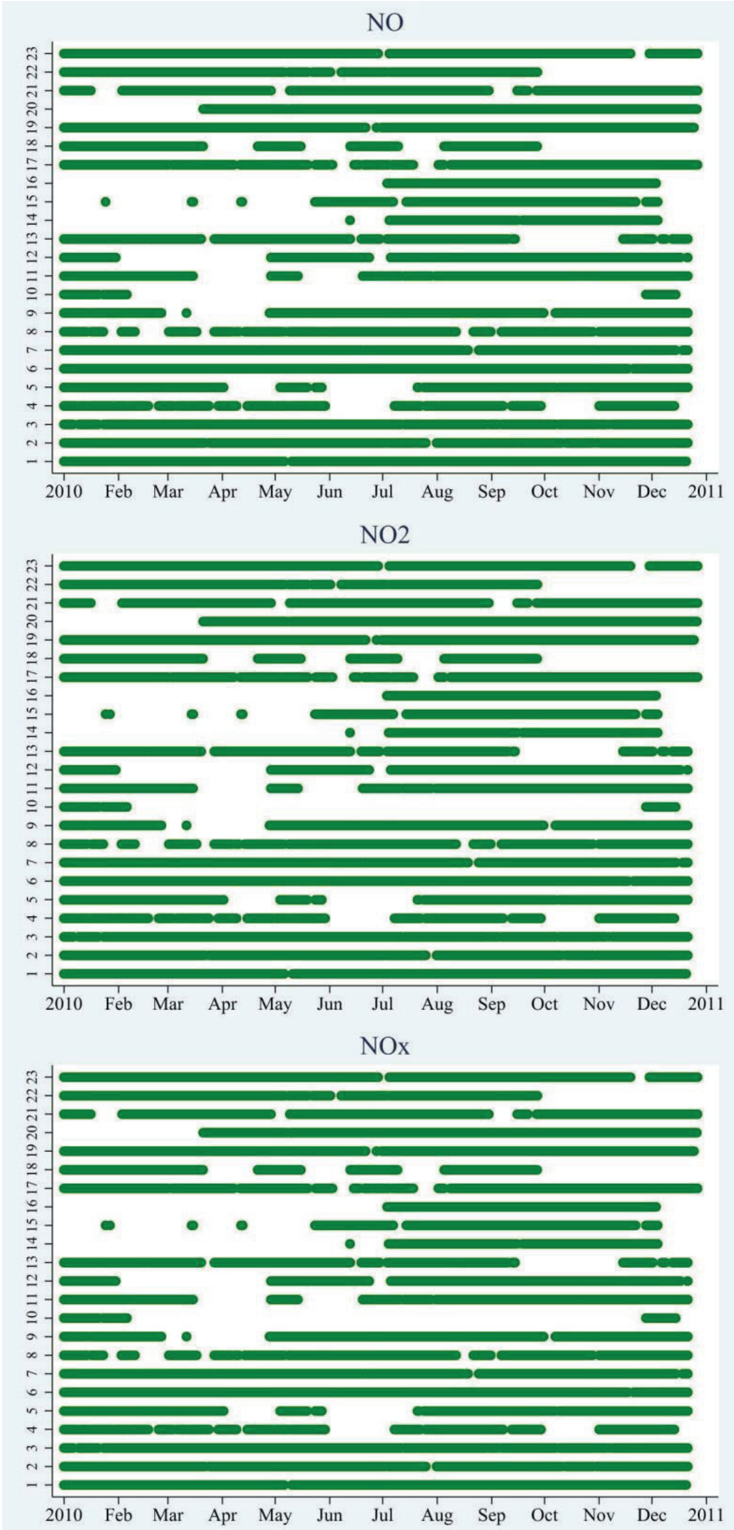

Figure S2. Details of the data available for each air quality monitoring station. The x-axis shows time in months and y-axis shows available data for each of stations out of 23. The green color for each station shows that the data were available and the white areas are missing data.

Imputation of missing data

The Amelia program was used for imputation of the missing data (Figure S2 shows missing NO, NO_2 and NO_X measurements) [1]. The program uses a new expectation-maximization algorithm with bootstrapping to impute missing values and return a complete dataset. We provided the program with all available hourly concentrations from the different stations, along with the month, day, and hours of measurement. In order to evaluate the precision of the missing data estimates we ran the Amelia program 10 times for each pollutant, and calculated the resulting 10 annual and seasonal averages for each monitoring station. Next, we calculated the coefficient of variation (CV) between the 10 annual and seasonal means. If the CV was small (less than about 5%), the estimates were considered acceptable. If not, the station was removed from further analyses because of the low precision of the annual and/or seasonal estimates.

The maximum CVs for the 23 stations used to model NO ranged from 3.9% for the annual to 4.5% for the cooler season. The maximum CVs for the 23 stations used to model NO_2 ranged from 3.8% for the warmer season to 5.5% for the cooler season. For 23 NO_X stations, the maximum CVs were 2.9% for the warmer season to 3.2% for the cooler season. The CV averages for NO stations ranged from 0.8% for the annual to 1.1% for the warmer season. The CV averages for NO_2 stations ranged from 0.7% for the warmer season to 1.0% for the cooler season. The CV averages for NO_X stations ranged from 0.7% for the annual to 0.8% for the cooler and warmer seasons (Table S1).

Table S1. The coefficient of variation (CV) for the mean annual, cooler season, and warmer season in 10 times missing data imputation for checking reliability of the estimates.

	CVs for NO (%)			CVs for NO_2 (%)			CVs for NO_X (%)		
Station	Annual	Cooler Season	Warmer Season	Annual	Cooler Season	Warmer Season	Annual	Cooler Season	Warmer Season
1	0.2	0.2	0.4	0.1	0.1	0.1	0.1	0.1	0.2
2	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.2	0.2
3	0.3	0.4	0.3	0.1	0.2	0.1	0.2	0.3	0.2
4	0.8	1.2	2.0	0.5	1.0	0.3	0.6	0.7	1.1
5	0.4	0.3	1.6	0.2	0.1	0.4	0.4	0.2	1.1
6	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1
7	0.3	0.3	1.0	0.2	0.2	0.3	0.2	0.2	0.2
8	0.4	0.6	0.5	0.3	0.4	0.2	0.4	0.6	0.3
9	0.2	0.3	0.6	0.1	0.2	0.1	0.2	0.2	0.4
10	1.2	1.0	1.8	1.6	1.1	2.3	1.8	1.3	2.7
11	0.4	0.4	1.3	0.1	0.1	0.2	0.2	0.2	0.6
12	0.6	0.6	0.9	0.3	0.5	0.3	0.7	0.8	0.8
13	0.5	0.5	1.1	0.2	0.3	0.2	0.4	0.5	0.5
14	3.9	4.5	4.2	4.8	5.5	3.8	2.7	3.1	2.9
15	2.0	2.4	1.3	1.9	2.2	1.5	1.1	1.5	0.5
16	3.6	4.0	3.3	2.9	2.9	2.9	3.0	3.2	2.9
17	0.4	0.1	1.5	0.4	0.1	1.2	0.4	0.1	1.4
18	1.0	1.4	0.8	1.4	2.1	1.0	1.0	1.2	0.8
19	0.1	0.1	0.2	0.0	0.1	0.1	0.1	0.1	0.2
20	0.5	1.0	0.1	1.3	1.9	0.2	0.7	1.2	0.1
21	0.2	0.2	0.5	0.2	0.2	0.4	0.3	0.2	0.5
22	0.7	1.0	0.3	1.4	2.2	0.4	0.8	1.3	0.4
23	0.2	0.3	0.3	0.2	0.3	0.1	0.1	0.2	0.2

Model development and diagnostics

We developed a systematic algorithm that considered 10 key pieces of information:

(1) Take the log transformation of the response variable
(2) Check for normality using the Shapiro-Wilk test [2]
(3) Apply a power transformation if not normally distributed
(4) Linearize the relationships between the transformed variables and the PPVs using log and power transformations on the PPVs, and then proceed with the original algorithm [3] such that steps (5) through (8) are done for every iteration (i.e. the addition of each new PPV to the model):
(5) Check the direction of the effect of each PPV in the model for consistency with *a priori* assumptions (Table 1) to ensure that final models did not contradict knowledge about pollution emissions and dispersion
(6) Ensure a p-value of < 0.1 for each PPV
(7) Ensure that each new PPV increases the coefficient of determination (R^2) for a leave-one-out cross-validation (LOOCV)[4]
(8) Calculate a multicollinearity index called the variance inflation factor (VIF)[5]
(9) Finally, restrict the number of predictor variables in LUR model to $\sqrt{N}$, where N denotes the number of monitoring stations
(10) Check the normality of residuals using the Shapiro-Wilk test.

The rationale for step 1 to 3

We decided to first log-transform the response variable data in step 1 with the benefit that the predictions get non-negative values—though it could also somewhat resolve the challenge of having a response variable that is not normally distributed (step 2). Finally, we tried to use power transformations to have a normally distributed response variable (step 3). Though in general it is required that the residuals or errors should be normally distributed in a linear regression analysis (see step 10), once the response variable data are not normally distributed, most likely the residuals might also not have a normal distribution [6]. We checked the normality assumption by Shapiro-Wilk test [2].

The rationale for step 4

In order to linearize relationship of each explanatory variable with transformed response variable of stage 3, we tried various powers for each predictor variable to find ones that produce most correlation between this power transformation of predictor and the results of stage 3. This step caused inclusion of a variable (OFIC.100 = official/commercial land use areas in buffer 100 m) with the power of 0.1 in the final model of warmer season NOx.

The rationale for step 5

There are two approaches to LUR model building. One approach favors the most predictive model and the other approach favors the most easily interpreted model. The two are not, necessarily, mutually exclusive. In the first approach, the most predictive variables are kept regardless of their sign. We did not feel that this was the right approach for Tehran, because we wanted to be able to readily explain the modeling results to the epidemiologists who will be using them in future. Thus, we used the second approach where variables are only retained in the model if their coefficients are consistent with *a priori* assumptions about the direction of the effect (e.g. decreasing pollutant concentrations with increasing distance from traffic sources). Several other studies have followed this approach, including Henderson et al. (2007) [7], Hoek et al. (2010) [8], Eeftens et al. (2012) [9], Gonzales et al. (2012) [10], Beelen et al. (2013) [11], de Hoogh et al. (2013) [12], Abernethy et al. (2013) [13], and Gulliver et al. (2013) [14]. We made this choice based on our situation in Tehran, to ensure that any associated epidemiologic results to be easily interpreted by policy makers.

The rationale for step 6

Some LUR studies have observed that insignificant predictors (*p*-values > 0.1) can increase the total R^2 of the regression equation [9,10,15,16]. Thus, to prevent the inclusion of such variables in our models, we set another criterion in the sixth piece of the algorithm to include only those variables with significant *p*-values ($p < 0.1$). The $p < 0.1$ was selected because it is widely applied in the LUR community [7,9].

The rationale for step 7

A recent analysis from Girona (Spain) demonstrated that LUR models developed from fewer sites had higher model R^2 values, lower LOOCV R^2 values, and different predictive variables than models developed from more sites [17]. To account for this, we designed a model-building algorithm that selected variables based on the improvements to the LOOCV R^2 value instead of the model R^2 or adjusted R^2. Model R^2 is a measure of internal validity of the model while LOOCV R^2 is a measure of external validity, thus, a more appropriate measure for model selection [18]. We believe this method, especially for study areas with small number of sites, leads to the generation of models with high R^2 and LOOCV R^2 values, as well as generation of temporal models with an internally consistent set of potentially predictive variables.

The rationale for step 8

The VIF is the reciprocal of *Tolerance,* and both are multicollinearity indices. The VIF is calculated as the following equation:

$$VIF = \frac{1}{1 - R_i^2}$$

Where $1 - R_i^2$ is the tolerance and R_i^2 denotes the proportion of variance in the *i*th predictor, which is correlated with the other predictors in the regression equation [5].

There is no consensus in the LUR community about the VIF cutoff that should be used for LUR model building. Henderson et al. (2007) [7], Clougherty et al. (2013) [19], Eeftens et al. (2012) [9], and Gulliver et al. (2013) [14] arbitrarily applied VIFs of ~1.5, 2, 3 and 3, respectively. However, O'brien (2007) suggests caution against removing potentially important variables from regression models with a stringent VIF [5], and Kutner et al. (2004) suggest a value of 10 as the rule of thumb for avoiding multicollinearity [18]. Although we chose this value for our analyses, the VIF of predictor variables was less than 4 in all cases.

The rationale for step 9

A recent analysis from Girona (Spain) demonstrated that LUR models should be restricted to a set of potential predictor variables [20]. We therefore decided to restrict the number of predictor variables in a LUR model to square root of number of measurement sites. We believe this restriction could provide more realistic R^2 values.

The rationale for step 10

This step is one of the assumptions of any regression analysis. In fact, the residuals of final regression model should be normally distributed [21] in order to have valid *p*-values for predictors' coefficients in regression model.

Table S2. The Spearman correlation coefficients between the annual (A), cooler season (C), and warmer season (W) measured concentrations at 23 fixed-sites for NO, NO_2, and NOx in 2010 in Tehran, Iran.

	A_NO	C_NO	W_NO	A_NO_2	C_NO_2	W_NO_2	A_NO_X	C_NO_X	W_NO_X
A_NO	1.00	-	-	-	-	-	-	-	-
C_NO	0.99	1.00	-	-	-	-	-	-	-
W_NO	0.96	0.94	1.00	-	-	-	-	-	-
A_NO_2	0.30	0.31	0.29	1.00	-	-	-	-	-
C_NO_2	0.25	0.25	0.27	0.92	1.00	-	-	-	-
W_NO_2	0.46	0.45	0.43	0.78	0.61	1.00	-	-	-
A_NO_X	0.94	0.94	0.92	0.54	0.50	0.63	1.00	-	-
C_NO_X	0.94	0.95	0.91	0.52	0.50	0.59	0.99	1.00	-
W_NO_X	0.87	0.85	0.89	0.47	0.37	0.71	0.92	0.90	1.00

Table S3. Final model results for annual NO. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.78, Adjusted R^2 = 0.71, LOOCV R^2 = 0.66, *p*-value of the regression model = <0.001, RMSE = 32.1, Measured response, mean (min–max)= 88 (23–312), Moran's I = –0.08						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	1.526e+00	6.930e-01	2.2	-	0.042	-
DIST to TACZ	–1.369e-04	2.524e-05	–5.4	0.63	<0.001	1.3
LNDIST to PRSC	6.942e-01	1.319e-01	5.3	0.62	<0.001	**1.8**
GRS.500	–3.103e-06	7.036e-07	–4.4	0.53	<0.001	1.1
SLP	–4.426e-02	1.059e-02	–4.2	0.51	<0.001	1.7
URF.100	–3.033e-05	1.379e-05	–2.2	0.22	0.042	1.1
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is Ln (annual NO); hence, predicted pollutant is Exp (model)						
Radius variable types included in the models were: GRS = green space area URF = urban facilities area						
The linear distance variable included in the model was: DIST to TACZ = distance to traffic access control zone						
The log-linear distance variable included in the model was: LNDIST to PRSC = log distance to the nearest primary school						
Other variable included in the model was: SLP = slope						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S4. Final model results for cooler season NO. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.69, Adjusted R^2 = 0.60, LOOCV R^2 = 0.53, *p*-value of the regression model = <0.001, RMSE = 38.6, Measured response, mean (min–max)= 117 (30–358), Moran's I = –0.09						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	1.919e+00	9.274e-01	2.2	-	0.054	-
LNDIST to PRSC	5.088e-01	1.412e-01	3.6	0.43	0.002	1.4
TPDC.2500	4.691e-05	1.822e-05	2.6	0.28	0.020	**1.5**
DIST to BST	–1.096e-04	4.266e-05	–2.6	0.28	0.020	1.2
DIST to PST	–3.205e-04	1.278e-04	–2.5	0.27	0.023	1.3
GRS.400	–2.088e-06	1.091e-06	–1.9	0.18	0.073	1.0
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is Ln (cooler season NO); hence, predicted pollutant is Exp (model)						
Radius variable type included in the model was: GRS = green space area						
The linear distance variables included in the model were: DIST to BST = distance to bus terminal DIST to PST = distance to petrol stations						
The log-linear distance variable included in the model was: LNDIST to PRSC = log distance to the nearest primary school						
Other variable included in the model was: TPDC = population density excluding unemployed and children <5 years						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S5. Final model results for warmer season NO. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.72, Adjusted R^2 = 0.64, LOOCV R^2 = 0.59, *p*-value of the regression model = <0.001, RMSE = 36.9, Measured response, mean (min–max)= 60 (17–268), Moran's I = –0.07						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	6.793e-01	8.270e-01	0.82	-	0.423	-
DIST to TACZ	–1.551e-04	3.157e-05	–4.9	0.59	<0.001	1.5
LNDIST to PRSC	7.442e-01	1.571e-01	4.7	0.57	<0.001	1.8
SLP	–6.259e-02	1.440e-02	–4.3	0.53	<0.001	**2.2**
GRS.500	–2.021e-06	8.209e-07	–2.5	0.26	0.025	1.7
DIST to GRS	9.359e-04	3.992e-04	2.3	0.24	0.031	1.9
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is Ln (warmer season NO); hence, predicted pollutant is Exp (model)						
Radius variable type included in the model was: GRS = green space area						
The linear distance variables included in the model were: DIST to TACZ = distance to traffic access control zone DIST to GRS = distance to green space area						
The log-linear distance variable included in the model was: LNDIST to PRSC = log distance to the nearest primary school						
Other variable included in the model was: SLP = slope						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S6. Final model results for annual NO_2. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.69, Adjusted R^2 = 0.62, LOOCV R^2 = 0.57, *p*-value of the regression model = <0.001, RMSE = 9.9, Measured response, mean (min–max)= 53 (22–96), Moran's I = –0.07						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	2.897e+00	3.813e-01	7.6	-	<0.001	-
OFIC.300	1.111e-05	2.295e-06	4.8	0.57	<0.001	1.2
DIST to SNS	–1.537e-04	3.984e-05	–3.9	0.45	0.001	1.0
LNDIST to PRSC	1.702e-01	6.211e-02	2.7	0.29	0.013	**1.3**
OTHR.300	2.214e-05	9.434e-06	2.3	0.23	0.031	1.2
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is Ln (annual NO); hence, predicted pollutant is Exp (model)						
Radius variable types included in the models were: OFIC = official/commercial land use area OTHR = other land use area						
The linear distance variable included in the model was: DIST to SNS = distance to sensitive area						
The log-linear distance variable included in the model was: LNDIST to PRSC = log distance to the nearest primary school						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S7. Final model results for cooler season NO_2. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.75, Adjusted R^2 = 0.68, LOOCV R^2 = 0.58, p-value of the regression model = <0.001, RMSE = 9.2, Measured response, mean (min–max)= 62 (21–103), Moran's I = –0.03						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	–5.711e+01	2.575e+01	–2.2	-	0.040	-
OFIC.300	5.946e-04	1.079e-04	5.5	0.64	<0.001	1.1
ELEV	1.062e-01	2.317e-02	4.6	0.55	<0.001	3.6
DIST to AIR	–4.120e-03	1.184e-03	–3.5	0.42	0.003	**3.8**
OTHR.400	8.346e-04	3.109e-04	2.7	0.3	0.016	1.3
ARD.100	–1.549e-03	6.866e-04	–2.3	0.23	0.038	1.1
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is (Ln (cooler season NO_2))^3; hence, predicted pollutant is Exp (model$^{0.33}$)						
Radius variable types included in the model were: OFIC = official/commercial land use area OTHR = other land use area ARD = arid/undeveloped area						
The linear distance variable included in the model was: DIST to AIR = distance to airport or air cargo facilities						
Other variable included in the model was: ELEV = elevation						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S8. Final model results for warmer season NO_2. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.64, Adjusted R^2 = 0.58, LOOCV R^2 = 0.51, *p*-value of the regression model = <0.001, RMSE = 10.2, Measured response, mean (min–max)= 45 (23–89), Moran's I = –0.11						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	3.270e-01	2.551e-02	12.8	-	<0.001	-
OFIC.300	–6.812e-07	1.615e-07	–4.2	0.48	<0.001	1.1
DIST to SNS	1.179e-05	2.910e-06	4.1	0.46	<0.001	1.0
LNDIST to PRSC	–1.044e-02	4.259e-03	–2.5	0.24	0.024	**1.2**
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is (Ln (warmer season NO_2))$^{-1}$; hence, predicted pollutant is Exp (model^{-1})						
Radius variable type included in the model was: OFIC = official/commercial land use area						
The linear distance variable included in the model was: DIST to SNS = distance to sensitive area						
The log-linear distance variable included in the model was: LNDIST to PRSC = log distance to the nearest primary school						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S9. Final model results for annual NO_X. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.71, Adjusted R^2 = 0.62, LOOCV R^2 = 0.58, *p*-value of the regression model = <0.001, RMSE = 52.7, Measured response, mean (min–max)= 142 (66–385), Moran's I = –0.04						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	1.526e+00	6.930e-01	7.8	-	<0.001	-
DIST to TACZ	2.017e-06	3.735e-07	5.4	0.63	<0.001	1.7
LNDIST to PRSC	–6.481e-03	1.679e-03	–3.9	0.47	0.001	1.7
DIST to OFIC	2.620e-05	7.121e-06	3.7	0.44	0.002	**1.7**
LNDIST to HZRFAC	–3.210e-03	1.097e-03	–2.9	0.33	0.009	1.4
BGD.400	–1.248e-03	5.629e-04	–2.2	0.22	0.041	1.3
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is (Ln (annual NO_X))$^{-2}$; hence, predicted pollutant is Exp (model$^{-0.5}$)						
The linear distance variables included in the model were: DIST to TACZ = distance to traffic access control zone DIST to OFIC = distance to official/commercial area						
The log-linear distance variables included in the model were: LNDIST to PRSC = log distance to the nearest primary school LNDIST to HZRFAC = log distance to hazardous facilities						
Other variable included in the model was: BGD = product of bridge length in a buffer radii divide to distance to the bridges						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S10. Final model results for cooler season NO_X. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.79, Adjusted R^2 = 0.73, LOOCV R^2 = 0.63, *p*-value of the regression model = <0.001, RMSE = 37.1, Measured response, mean (min–max)= 180 (76–435), Moran's I = –0.03						
Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	2.941e-01	2.188e-02	13.4	-	<0.001	-
DIST to TACZ	5.800e-06	7.633e-07	7.6	0.77	<0.001	**1.9**
LNDIST to HZRFAC	–1.129e-02	2.462e-03	–4.6	0.55	<0.001	1.9
URF.100	1.648e-06	4.142e-07	4.0	0.48	<0.001	1.5
GRS.400	8.761e-08	2.322e-08	3.8	0.46	0.002	1.3
LNDIST to PRSC	–9.239e-03	2.780e-03	–3.3	0.39	0.004	1.1
For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters. Response of the model is (Ln (cooler season NO_X))$^{-1}$; hence, predicted pollutant is Exp (model^{-1})						
Radius variable types included in the model were: GRS = green space area URF = urban facilities area						
The linear distance variable included in the model was: DIST to TACZ = distance to traffic access control zone						
The log-linear distance variables included in the model were: LNDIST to HZRFAC = log distance to hazardous facilities LNDIST to PRSC = log distance to the nearest primary school						
Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor						

Table S11. Final model results for warmer season NO_X. Variables are ordered by partial R^2, and those in bold indicate consistencies between models for the same pollutant.

R^2 = 0.61, Adjusted R^2 = 0.50, LOOCV R^2 = 0.42, *p*-value of the regression model = 0.004, RMSE = 44.8, Measured response, mean (min–max)= 105 (49–336), Moran's I = –0.08

Predictors	Coefficients	SE	t	Partial R^2	*p*-value	VIF
Intercept	7.106e-03	1.400e-03	5.1	-	<0.001	-
LNDIST to PRSC	–8.153e-04	2.373e-04	–3.4	0.41	0.003	**1.9**
DIST to TACZ	1.286e-07	4.798e-08	2.7	0.3	0.016	1.5
$(OFIC.100)^{0.1}$	–3.977e-04	1.531e-04	–2.6	0.28	0.019	1.6
BGD.400	–1.349e-04	7.224e-05	–1.9	0.17	0.079	1.2
SLP	3.376e-05	1.813e-05	1.9	0.17	0.080	1.6

For variables of the form XXX.YYY the XXX indicates the variable type, and the YYY indicates the buffer size, in meters.
Response of the model is (Ln (warmer season NO_X))$^{-4}$; hence, predicted pollutant is Exp (model$^{-0.25}$)

Radius variable types included in the models were:
OFIC = official/commercial land use area

The linear distance variable included in the model was:
DIST to TACZ = distance to traffic access control zone

The log-linear distance variable included in the models was:
LNDIST to PRSC = log distance to the nearest primary school

Other variable included in the model was:
BGD = product of bridge length in a buffer radii divide to distance to the bridges
SLP = slope

Abbreviations: LOOCV, leave-one-out cross-validation; RMSE, root mean square error; SE, standard error; VIF, variance inflation factor

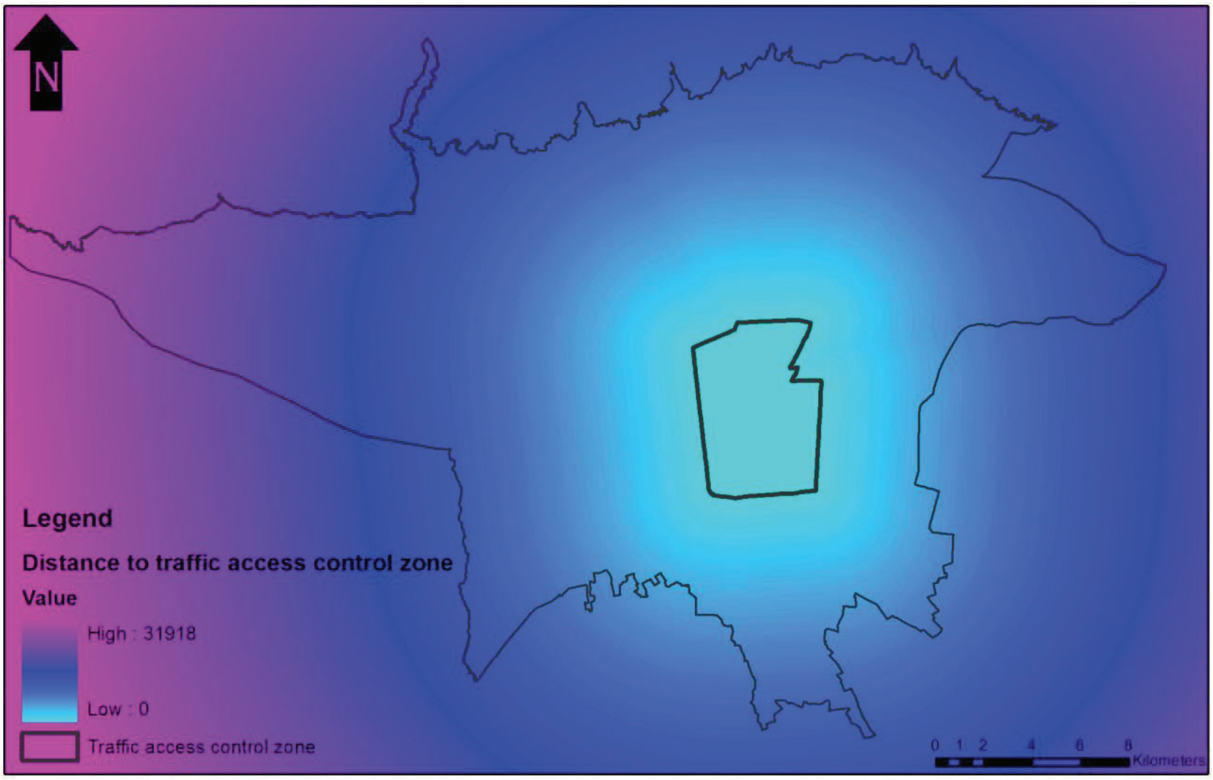

Figure S3. Spatial variability of distance to traffic access control zone (TACZ) in 2010 in Tehran, Iran. The figure is generated using ESRI's ArcGIS 10.2.1 for Desktop (http://www.esri.com/) [22].

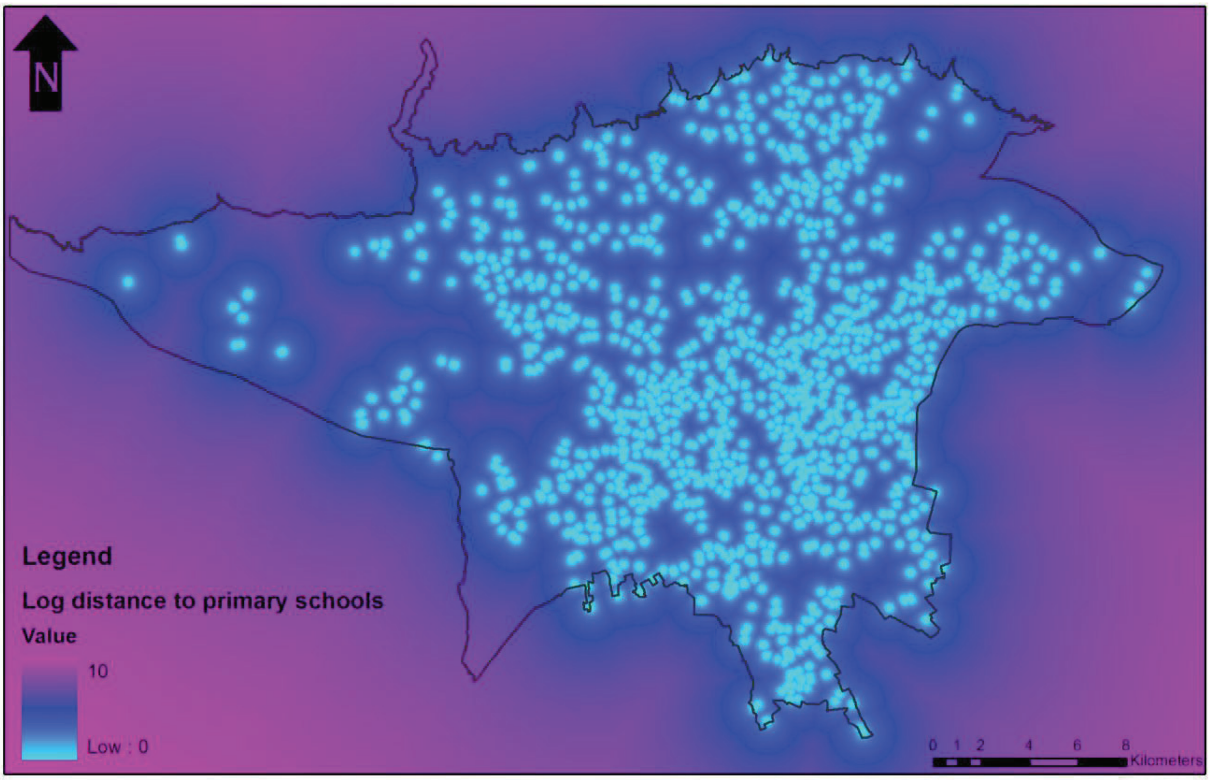

Figure S4. Spatial distribution of primary schools in Tehran (in 2010) and natural logarithm of distance to the nearest primary school. The figure is generated using ESRI's ArcGIS 10.2.1 for Desktop (http://www.esri.com/) [22].

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Article 3: Spatiotemporal description of BTEX volatile organic compounds in a Middle Eastern megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)

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Spatiotemporal description of BTEX volatile organic compounds in a Middle Eastern megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)☆

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ABSTRACT

The spatiotemporal variability of ambient volatile organic compounds (VOCs) in Tehran, Iran, is not well understood. Here we present the design, methods, and results of the Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR) on ambient concentrations of benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene (BTEX), and total BTEX. To date, this is the largest study of its kind in a low- and middle-income country and one of the largest globally. We measured BTEX concentrations at five reference sites and 174 distributed sites identified by a cluster analytic method. Samples were taken over 25 consecutive 2-weeks at five reference sites (to be used for temporal adjustments) and over three 2-week campaigns in summer, winter, and spring at 174 distributed sites. The annual median (25^{th}–75^{th} percentile) for benzene, the most carcinogenic of the BTEX species, was 7.8 (6.3–9.9) μg/m^3, and was higher than the national and European Union air quality standard of 5 μg/m^3 at approximately 90% of the measured sites. The estimated annual mean concentrations of BTEX were spatially highly correlated for all pollutants (Spearman rank coefficient 0.81–0.98). In general, concentrations and spatial variability were highest during the summer months, most likely due to fuel evaporation in hot weather. The annual median of benzene and total BTEX across the 35 sites in the Tehran regulatory monitoring network (7.7 and 56.8 μg/m^3, respectively) did a reasonable job of approximating the additional 144 city-wide sites (7.9 and 58.7 μg/m^3, respectively). The annual median concentrations of benzene and total BTEX within 300 m of gas stations were 9.1 and 67.3 μg/m^3, respectively, and were higher than sites outside this buffer. We further found that airport did not affect annual BTEX concentrations of sites within 1 km. Overall, the observed ambient concentrations of toxic VOCs are a public health concern in Tehran.

1. Introduction

Air pollution has a profound effect on population health (Cohen et al., 2017; GBD 2015 Risk Factors Collaborators, 2016; Künzli et al., 2000). It crosses borders and is responsible for more annual deaths than HIV/AIDS, tuberculosis, and road injuries combined (Lancet, 2016). A recent report from the World Bank estimated that premature deaths attributable to air pollution could be associated with global costs of $225 billion in lost labor income and $5.11 trillion in lost welfare in 2013. These values are higher than the gross domestic products of many large countries, such as India and Canada (World Bank and Institute for Health Metrics and Evaluation, 2016). Even so, the estimates only

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considered the impacts of fine particulate matter ($PM_{2.5}$) and ozone, and they would have been even higher if a wider range of pollutants and health outcomes had been included (Amini et al., 2014a, 2016).

Low and middle income countries (LMICs) are more affected by air pollution than high income countries (Brauer et al., 2016), partially because of inconsistent, ineffective, or nonexistent air quality standards (Künzli et al., 2015; Kutlar Joss et al., 2017). Iran is an LMIC in the Eastern Mediterranean Region (EMRO) of the World Health Organization (WHO), and its larger cities are currently facing an air pollution crisis due to continued urbanization, and increasingly dense motor vehicle traffic with high emissions (Banitalebi and Hosseini, 2015; Hassani and Hosseini, 2016; Heydarpour et al., 2014). The capital city of Iran has been profoundly affected by these changes (Naddafi et al., 2012). Recent studies have reported that concentrations of criteria air pollutants are well beyond the national standards, and close to 100% of the population lives in areas where the WHO guideline values are exceeded (Amini et al., 2014b, 2016).

A recent emissions inventory of Tehran reported that most air pollution in 2013 originated from mobile sources, including 46% of nitrogen oxides, 97% of carbon monoxide, 70% of particulate matter, and 86% of volatile organic compounds (VOCs) (Shahbazi et al., 2016b). The rest of 14% of VOCs in 2013 emitted from stationary sources including gas stations (10.5%), energy conversion (1.6%), households and commercials (1.4%), industries (0.3%), and terminals (0.15%) (Hosseini and Shahbazi, 2016; Shahbazi et al., 2016b). The VOCs have a wide range of pollutants classified into alkanes, alkylbenzenes, chlorinated hydrocarbons, terpenes, and other miscellaneous VOCs, such as ethyl acetate, butyl acetate, acetophenone, and so forth (Baldasano et al., 1998). The group of alkylbenzenes includes benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, and *o*-xylene (BTEX), which are toxic aromatic VOCs (Bolden et al., 2015). The International Agency for Research on Cancer has classified benzene as *carcinogenic to humans* (Group 1) (International Agency for Research on Cancer, 2016), and the other BTEX species have a range of adverse health effects, even at low concentrations. These effects mainly include non-communicable diseases (NCDs), such as reproductive and developmental outcomes (Donald et al., 1991)—sperm abnormalities and reduced fetal growth—and effects on cardiovascular disease, respiratory dysfunction, asthma, sensitization to common antigens, among others (Aguilera et al., 2009; Bolden et al., 2015; Delfino et al., 2003).

Previous studies in Tehran have shown that the concentrations of toxic VOCs in the ambient air were much higher than national and European Union (EU) ambient air quality standards (Atabi et al., 2013; Dehghani et al., 2016; Sarkhosh et al., 2013). However, these conclusions were based on measurements from a limited number of locations over a short period or in a single district. Furthermore, they partly were taken in highly polluted areas that were not representative of the exposure experienced by the general population. As such, we have evidence that VOCs may be of particular concern in Tehran, but little information about their spatial and temporal variability. Here we present the design, methods, and results of the Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR[1]), which was a comprehensive and collaborative Swiss-Iranian effort to fill this knowledge gap. Although our focus here is on VOCs, the overall objective of Tehran SEPEHR was to better characterize air quality in the city by measuring nitrogen dioxide, sulfur dioxide, ozone, and BTEX.

[1] SEPEHR means "sky" in Persian.

2. Materials and methods

2.1. Study area and period

Tehran covers a large area of over 613 km^2 and is divided into 22 administrative districts. It is located at 35°41′ of North and 51°25′ of East, with the Alborz Mountains in the north, a desert in the south, and the populated areas ranging from 1000 m to 1800 m above sea level (Fig. 1). The annual mean daily temperature is 18.5 °C, with highs around 43 °C in July and lows around −15 °C in January. The average annual precipitation is 220 mm, with the maximum in March (39 mm) and the minimum in September (1 mm). The weather is typically sunny, with an annual average of 2800 h of bright sunshine and a mean cloud cover of 30%. The prevailing winds blow from west and north. Tehran is the most populous city in Iran, with approximately 9 million urban residents, and a daytime population of more than 10 million people due to commuters from the outlying areas (Amini et al., 2016). The air sampling study was conducted from April 2015 through May 2016.

2.2. Study design

2.2.1. Measurement sites

We sampled VOCs at 179 sites, including five reference sites, chosen via systematic methods and consultation with local collaborators (Fig. 1). Prior to sampling we visited and recorded the characteristics of 276 potential sampling locations within the city where permission to deploy the samplers could be obtained, including many in residential areas. The budget could not support sampling at all locations, so we identified a subset of 179 sites using expert consultation and a cluster analytic method (CAM) integrating prior knowledge about the spatial variability of air pollution in Tehran, as described below.

Our previous work found the following variables to be important predictors of ambient air pollution concentrations: (1) length of the streets within 300 m; (2) distance to highways; (3) distance to bus terminals; (4) population density within 1 km; (5) official/commercial land use areas within 500 m; and (6) other land use areas within 300 m (Amini et al., 2014b, 2016). The overall goal of the CAM algorithm was to optimally represent the full spatial distribution of the eligible sites while also optimally representing these six key variables. For this purpose, the variables were orthogonalized using principal component analysis and the resulting principal components were then used in a cluster analysis. We computed a distance measure between pairs of sites (Equation (1)) to identify clusters.

$$\textit{Euclidean distance} = \sqrt{\sum_{k=1}^{6}\left(Z_{ik} - Z_{jk}\right)^2} \quad (1)$$

where Z_{ik} denotes the score of site *i* on the *k*th principal component. Using this distance metric, the 276 sites were partitioned into 93 clusters of 2–3 sites each (Figure S1) and 32 isolated sites. For each of the 93 clusters, the site with the highest population density within 1 km was typically selected, but 35 sites that were part of the regulatory air quality monitoring network were chosen even when they did not have the highest surrounding population density. Five of these 35 sites were chosen as the reference sites, as described below. All of the 32 isolated sites were selected for the study. The CAM analyses were done in SAS software (SAS Institute Inc., Cary, NC, USA). We selected the remaining 54 sites *purposefully* to ensure that: (1) visually identified spatial gaps in the study area were filled; (2) the numbers of monitoring sites per administrative district were balanced; and (3) sites of particular interest were included.

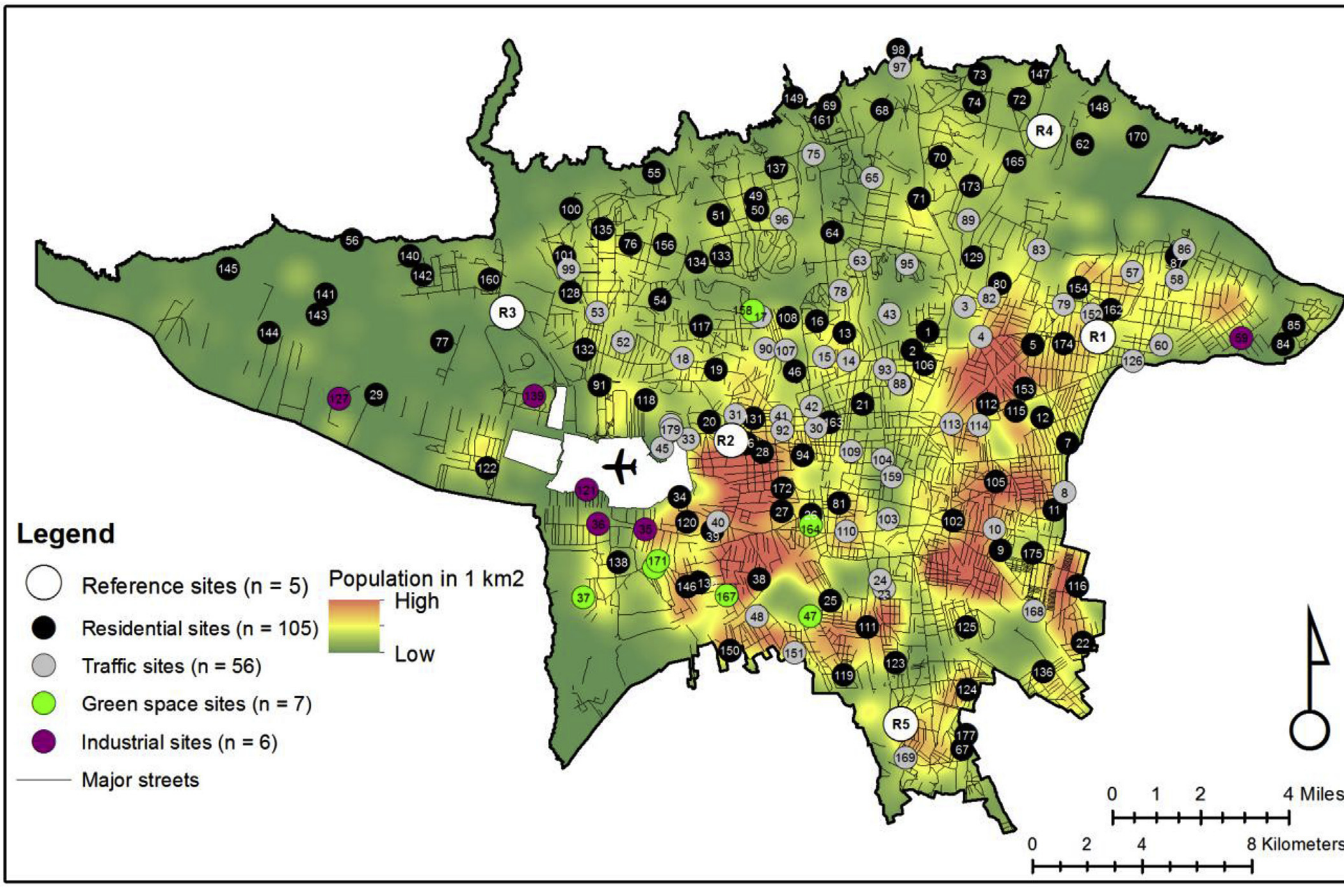

Fig. 1. The study area and locations of 179 measurement sites for Tehran SEPEHR in Tehran megacity, Iran. The site ID is labeled on each site.

The five reference sites were co-located with routine network monitoring stations managed by the Tehran Air Quality Control Company (AQCC). Specifically, we used the Golbarg (R1), Mantagheh 10 (R2), Park-e-Roz (R3), Aghdasieh (R4), and Shahr-e-Rey (R5) stations (Fig. 1). These sites represent a wide range of traffic (residential at R1 to highway at R2), elevation (1053 m at R5 to 1549 m at R4), and emissions (61 tons/year at R3 to 360 tons/year at R2) (supplemental information (SI), Table S1).

To summarize, we included a total of 179 sampling sites. Of these, 125 were selected using the CAM algorithm and 54 were manually selected to address specific objectives. Of the 125 sites selected by the CAM algorithm, 35 were co-located with sites in the regulatory air quality monitoring network, and 5 of these were reference sites at which we took measurements during the entire study period. Further, expert opinion was used to classify the non-references sites into the following strata: residential; traffic-impacted; green space; and industrial. These strata were based on previous studies where different emissions and characteristics were found within each group (Beelen et al., 2013; Eeftens et al., 2012).

2.2.2. Sampling methods

Serial 2-week measurements were taken throughout the study period at the five reference sites to enable imputation of pollutant concentrations at the other 174 sites during periods between measurement campaigns. All 179 sites were concurrently sampled during three 2-week campaigns in summer (July 23 – August 6, 2015), winter (February 4–18, 2016), and spring (April 28 – May 12, 2016). We could not measure in autumn because of logistic constraints.

We used passive BTEX samplers developed by the Swiss company Passam (Passam Co. Männedorf, Switzerland), which also led the laboratory analyses. The samplers are built from a glass pipe that is open at both ends and filled with activated charcoal. Both openings are then filled with a cellulose acetate diffusion barrier. Ambient air diffuses into the samplers, which we covered with protective Passam shelters to reduce the effects of meteorological conditions, such as wind and precipitation (Figure S2). Any BTEX species absorbed onto the activated charcoal during the 2-week exposure period were desorbed by carbon disulphide, and the concentrations of individual species and total BTEX were analyzed by gas chromatography (Passam Co, 2016).

2.2.3. Quality assurance/quality control

In order to evaluate the precision of the passive samplers, we used duplicates and blanks (50% field blanks, 50% lab blanks) for 5% of the serial 2-week samples taken at the reference sites throughout the year. Duplicates were deployed at all five reference sites during the three seasonal campaigns. In addition, we deployed duplicates and blanks at 5% of the 174 non-reference sites during the three campaigns. These quality assurance/quality control (QAQC) procedures in Tehran SEPEHR resulted in 123 duplicated samples and 44 blanks for each pollutant.

2.3. Statistical methods

2.3.1. Calculation of the annual mean

One goal of the three measurement campaigns was to estimate the annual mean concentrations of ambient BTEX across

Tehran. The usual method to derive the annual mean from a small set of 2-week measurements requires them to be compared with concurrent measurements at reference stations where concentrations have been measured over an entire year. Based on the respective ratios or differences, annual average pollutant concentrations can be imputed. Both the multiplicative and the additive imputation methods have been used widely in air pollution exposure science and epidemiology (Beelen et al., 2013; Eeftens et al., 2012). We compared these approaches using mixed linear regression models with random effects by site to evaluate which method produced the more robust results based on the Akaike information criterion (AIC) (Sakamoto et al., 1986). Models for both approaches assumed random site intercepts. The additive model used the matched 2-week measurement of the selected reference site as an offset along with random intercepts. The multiplicative model used this measurement both as a fixed and a random effect while constraining the fixed intercept and the random intercepts to 0. These analyses indicated that the multiplicative approach was more suitable for the context of Tehran (see SI, page S5).

Because we had five reference sites, we tried three different weighting approaches to estimate annual means for each pollutant in all sites. In all three approaches, reference values for a given non-reference site i were obtained as weighted means of the concurrent measurements at the five reference stations. These weights are denoted by $w(i,k)$, where k is the reference site. In method 1 (M1) $w(i,k)$ was taken to be proportional to $\frac{1}{1-\text{cosine}(\alpha)^2}$, where α is the angle between the vector of the three 2-week measurements at the non-reference site i and the vector of the three concurrent 2-week measurements at reference site k. In method 2 (M2) $w(i,k)$ was taken to be proportional to the inverse of the distance between the non-reference site i and reference site k. Finally, in method 3 (M3) $w(i,k)$ was taken to be proportional to the inverse of the squared distance between the non-reference site i and reference site k. The resulting weights were normalized to satisfy $w(i,1)+w(i,2)+\ldots+w(i,5)=1$.

In order to compare the results of M1, M2, and M3, we ran pollutant-specific descriptive analyses and cross-validations for each method. In summary, each of the 2-week measurements was left out of the analysis once, and the algorithm was used to estimate the omitted measurement. This estimate was compared with the measured value, and the difference of the two values calculated. The absolute values of these differences were summed, and then divided by the number of iterations to get the mean absolute error. The differences were also squared to calculate the root mean squared error (See SI, page S6).

2.3.2. Description of ambient BTEX

We assessed the normality of the BTEX measurements at the reference sites and across all sites using the Shapiro-Wilk test and visual inspection of the histograms and Q-Q plots. Depending on the results we reported the mean and standard deviation (SD) or the median and interquartile range (25^{th}–75^{th} percentile).

Our final objective for this study was to describe the temporal and spatial patterns in BTEX concentrations using year-long measurements from the five reference sites, seasonal measurements from all 179 sites, and estimate annual averages for the 174 non-reference sites. There was a complete year of serial 2-week measurements for each of the reference sites, and we started by calculating the within-site and between-site Spearman correlations between BTEX species over the study period.

We further calculated the coefficient of divergence (COD) for all pairs of reference sites to quantitatively evaluate the spatial heterogeneity over the entire year (Equation (2)).

$$COD_{jk} = \sqrt{\frac{1}{p}\sum_{i=1}^{p}\left(\frac{X_{ij}-X_{ik}}{X_{ij}+X_{ik}}\right)^2} \quad (2)$$

where p is number of paired values (concentrations, X) for the sites j and k. The COD ranges in value from 0 (homogeneous) to 1 (heterogeneous), and values above 0.2 are considered to be spatially heterogeneous (Sawvel et al., 2015; Wongphatarakul et al., 1998).

Similarly, there were complete sets of city-wide measurements for each of the three seasonal campaigns and estimates for the annual averages. We used box plots to summarize the information by season, and we used pollutant-specific correlations to evaluate differences between seasons.

We assessed pollutant-specific spatial variability across the city using the coefficient of variation (CV) statistic for measured seasonal and estimated annual means by site strata, including: reference; residential; traffic-impacted; green space; and industrial. In addition, we compared measurements taken at the 35 locations within the current air quality monitoring network with measurements from the other 144 sites. The purpose of this comparison was to evaluate how well concentrations measured at the network locations reflected those experienced by the wider population, as this has been raised as a concern in Tehran (Goudarzi et al., 2009). We also compared measurements within 300 m of gas stations with those outside of this buffer to better evaluate the impacts of fugitive emissions, especially in summer, because Atabi et al. (2013) reported higher concentrations of benzene in these areas (Atabi et al., 2013). Finally, we compared the measured concentrations in buffer of 1 km around Mehrabad International Airport with sites outside this buffer per interest in impact of airport on long-term VOCs pollution (Gaeta et al., 2016).

3. Results and discussion

3.1. Sampler precision

The agreement between the 123 duplicate benzene samples was very high with an intra-class correlation of 0.94. The median (IQR) concentration of the 246 benzene samples was 6.8 (3.1) $\mu g/m^3$ and the mean difference (SD) between duplicates was 0.03 (1.04) $\mu g/m^3$. There was no bias observed in the Bland-Altman plots (Figure S3). In addition, none of the lab or field blanks were above the limits of detection. The agreement between duplicate Passam samples for BTEX indicates that they have high precision. Furthermore, previous studies have reported that Passam and other types of passive VOC samplers do provide accurate results when compared with more rigorous reference methods (LANUV, 2014; Marc et al., 2015; Stevenson et al., 2001).

3.2. Estimation of annual means using reference sites

Measurements at the reference sites were used to estimate the annual mean concentrations at city-wide sites using the M2 method (inverse distance weighting). The M2 provided lower RMSE results than M1 and M3 in cross-validations, indicating that it was the better approach for Tehran (SI, page S6). Two of the five reference sites (R2 and R5) were located in highly populated areas and showed higher pollution concentrations and different density curves compared with the other three (Figure S4). These differences could be driven by different meteorological conditions between the northern and southern areas of the city, which differ by up to 800 m in elevation. Although we used protective shelters to reduce the impacts of important factors such as wind, the sampling rates may have been affected by these differences. The correlations between the estimated site-specific annual means and the corresponding means obtained by simply averaging the three 2-week measurements at each site showed that seasonality was an important factor. As such, measurements from the reference sites were necessary to obtain good estimates of the annual mean at other sampled sites in Tehran.

3.3. Description of BTEX at the reference sites

We successfully measured 25 of the 2-week periods in the 53-week study period at all five reference sites, without any lost samples. Three non-consecutive weeks were missing due to technical and logistic constraints. One measurement from one reference site (R3) was set to missing because the laboratory result was unrealistically low. The annual median benzene concentrations ranged from 4.7 to 10.1 μg/m^3 across the five sites, and varied ranges for the other BTEX compounds (Table S2). Most of the data were not normally distributed, but approached a log-normal distribution. The ranked median concentrations of all BTEX pollutants were highest at the Shahrdari Mantagheh 10 (R2) site and lowest at the Park-e-Roz (R3) site with the Shahr-e-Rey (R5), Aghdasieh (R4), and Golbarg (R1) sites in between (Figure S5). The traffic around R2 and R5 was high with estimated VOCs emissions of, respectively, 360 and 115 tons/year while R1 and R3 were located in residential and green space areas with estimated emissions of 11 and 61 tons/year, respectively (Table S1). Our findings at the reference sites were consistent with previous VOC emissions estimates (Shahbazi et al., 2016b) with a correlation coefficient of 0.9 between measured benzene and emissions. The annual median benzene concentrations were above the national (Hosseini and Shahbazi, 2016) and EU (Marco and Bo, 2013) standard of 5 μg/m^3 at all reference sites except R3, which it is located in a large park.

Overall, the time-series of 25 2-week measurements at the five reference sites indicated that concentrations were highest in summer and lowest in spring, especially during celebration of the Iranian New Year (Fig. 2). These season-specific patterns were also reflected in the results of the three seasonal measurement campaigns at 179 sites (Figure S6). However, Miri et al. found that most of BTEX species were highest in Spring in Tehran (Miri et al., 2016), and a study in Balikesir, Turkey showed higher benzene concentrations in winter (Tecer and Tagil, 2014). These discrepancies could be due to the low number of measurement sites in the other studies, meteorological conditions in Tehran, differences in measurement methods, and variations in emissions over different measurement periods and years (Miri et al., 2016; Shahbazi et al., 2016b).

Given the high summer temperatures, evaporation plays an important role in extreme concentrations of VOCs in Tehran during the hotter months. On the other hand, the atmospheric mixing height is lower in the winter and inversion conditions might lead to smog formation (Mohammadi et al., 2012), which might be associated with higher concentrations during the colder months. However, our temporally and spatially comprehensive data suggest that high temperatures, rather than low mixing heights, are the primary driver of high ambient VOC concentrations in Tehran. One exception was a wintertime peak (Feb 18th to March 3rd, 2016) in *p*-xylene concentrations, observed at three reference sites (R1, R2, and R5) located in densely populated areas (Fig. 2). This peak may have been caused by localized emissions and/or meteorology in these populated areas.

The temporal between-pollutant within-site correlations for the reference sites ranged from 0.47 to 0.96, with the lower correlations between benzene and *p*-xylene and highest correlations between ethylbenzene and xylenes (SI, page S12). These patterns are consistent with the findings of a similar study conducted in Los Angeles, California (Delfino et al., 2003). The within-pollutant between-site spatial correlations for the reference sites ranged from 0.24 to 0.93, with the strongest correlations for *m*-xylene (R2 vs R5) and the weakest for toluene (R3 vs R5) (Fig. 3). The high correlations were generally between sites R2 and R5 and between sites R3 and R4 for all pollutants (Fig. 3). This suggests that meteorological conditions and source patterns may be similar in the central/southern (R2 and R5) and northeastern/northwestern parts of the city (R3 and R4) (Figs. 1 and 3). The elevation is higher in northern parts of the city and the meteorology is more variable in these areas. Low correlations between sites R3, R4 and R5, especially for toluene (range = 0.23–0.29), further support this conclusion.

The median COD values were above 0.2 for all pollutants except benzene, indicating spatial heterogeneity in the BTEX compounds across the reference sites. The COD values ranged from 0.12 to 0.37 for benzene, 0.14 to 0.41 for toluene, 0.13 to 0.39 for ethylbenzene, 013 to 0.35 for *p*-xylene, 0.14 to 0.42 for *m*-xylene, 0.14 to 0.37 for *o*-xylene, and 0.13 to 0.39 for total BTEX (Fig. 3). Generally, the maximum heterogeneity was observed between R2 vs R3 and R3 vs R5. There was a negative relation between CODs and the Spearman rank correlation, indicating agreement between these approaches (Fig. 3 and SI, page S11).

3.4. Description of BTEX across the city

Measurements taken at the five reference sites during the three sampling campaigns were included in the analyses of data from all 179 sites. Measurements were successful at 177 of these 179 sites during the summer 2015 campaign, at all 179 sites during the winter 2016 campaign, and at 178 of the sites during the spring 2016 campaign. These high success rates demonstrated that the carefully chosen locations were at low risk of vandalism, similar to other measurement campaigns in large high income cities (Henderson et al., 2007; Kheirbek et al., 2012; Matte et al., 2013).

As with the five reference sites, measurements from all sites were not normally distributed but they approached a log-normal distribution. The US National Health and Nutrition Examination Survey (NHANES) found similar results where the distributions of ten different VOCs were not normal (Jia et al., 2008b). This partially reflects large contrasts in the spatial variation of ambient VOCs within Tehran. The annual median (25th–75th percentile) concentrations were as follows: 7.8 (6.3–9.9) μg/m^3 for benzene; 23.2 (17.8–28.6) μg/m^3 for toluene; 5.7 (4.5–6.8) μg/m^3 for ethylbenzene; 5.6 (4.6–6.5) μg/m^3 for *p*-xylene; 10.4 (8.1–12.5) μg/m^3 for *m*-xylene; 6.1 (4.6–7.3) μg/m^3 for *o*-xylene; and 58.6 (46.0–70.8) μg/m^3 for total BTEX (Table 1). Only 18 of the 179 locations (~10%) had annual benzene concentrations below the national (Hosseini and Shahbazi, 2016) and EU standard (Marco and Bo, 2013) of 5 μg/m^3. Most sites had concentrations between 5 and 10 μg/m^3 (122 sites, 68%), while 39 sites (22%) had very high concentrations ranging between 10 and 26 μg/m^3 (Fig. 4). These results are consistent with our previous work, which has shown that the entire population of Tehran lives in areas exceeding similar guideline values for criteria pollutants such as PM_{10} and SO_2 (Amini et al., 2014b).

The concentrations of BTEX compounds in Tehran are much higher than in many other cities. Though there have been numerous studies conducted on small number of sites over short periods and mostly using active sampling devices globally (Bolden et al., 2015; Delfino et al., 2003), not many have simultaneously sampled a large numbers of sites (>100) over one year using passive samplers to derive the annual mean. Therefore, the comparison of our results with studies conducted in other cities should be made with caution. Kheirbek et al. (2012) measured VOCs by Radiello passive samplers at 70 sites over the spring season of 2011 in New

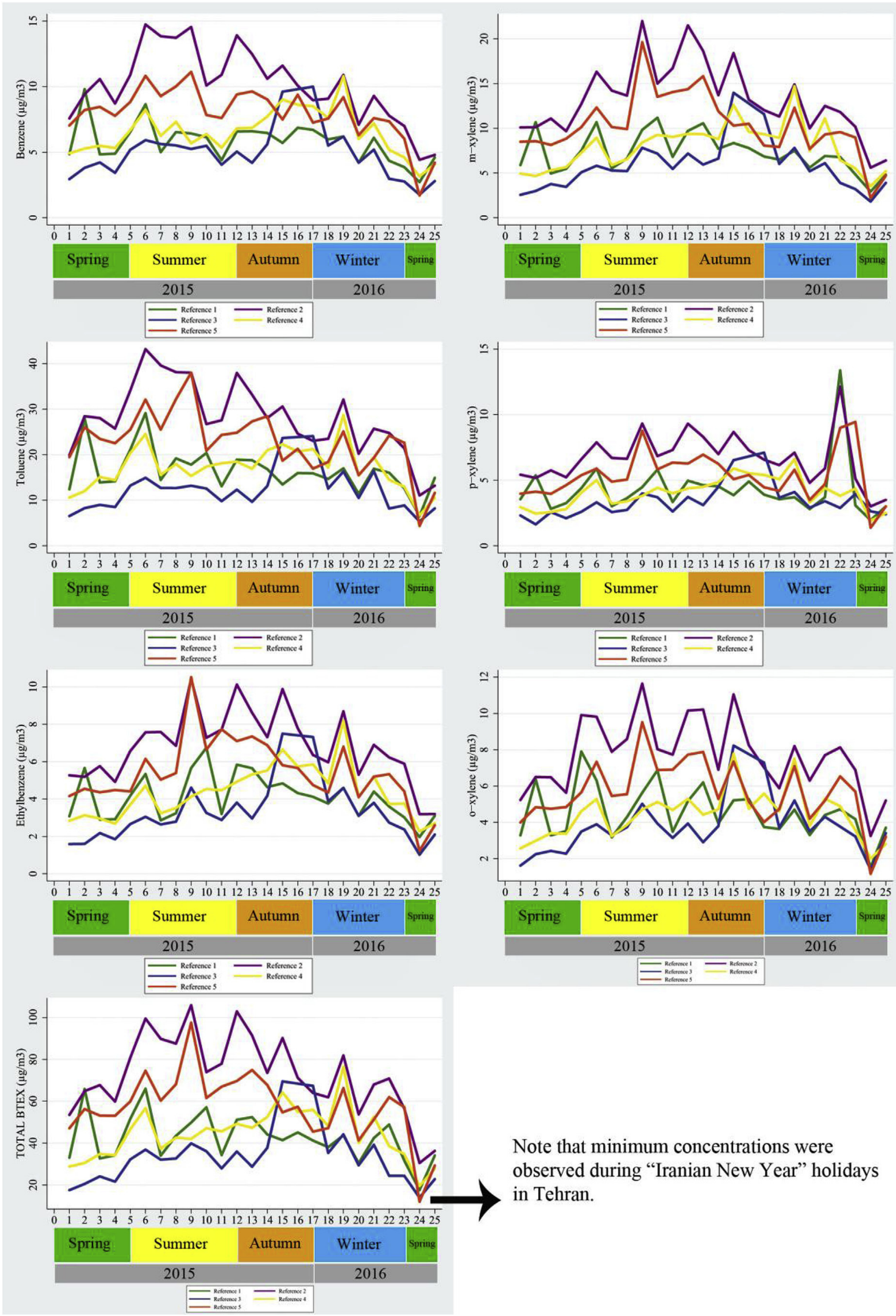

Fig. 2. Time-series of five reference sites in Tehran SEPEHR, Tehran megacity, Iran. The sampling start date was from April 2015 until May 2016 with 25 biweekly measurements.

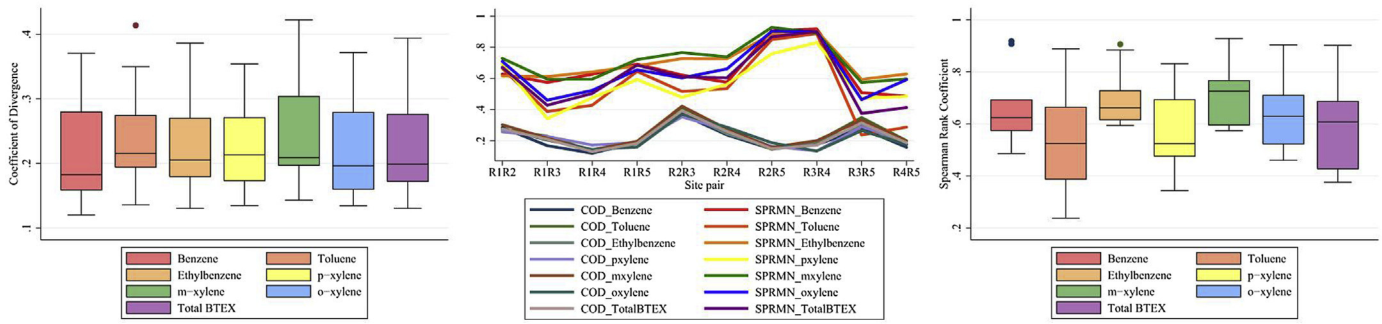

Fig. 3. Coefficient of divergence (COD) and Spearman rank coefficient for five reference sites over the entire year in Tehran SEPEHR. The COD values above 0.2 indicate heterogeneity. Note that toluene had the highest variability over the five reference sites. See supplemental information (page S11) for heat maps and exact values.

York City to develop spatial models for exposure assessment (Kheirbek et al., 2012). The benzene and total BTEX concentrations in New York City were almost 10 times lower than our measurements in Tehran. Wheeler et al. (2008) monitored benzene and toluene throughout 2004 at 54 locations in Windsor (Canada) using 3M #3500 badges, and reported annual mean concentrations of 0.9 μg/m^3 and 2.7 μg/m^3, respectively, compared with 7.8 μg/m^3 and 23.2 μg/m^3 in Tehran (Wheeler et al., 2008). Jia et al. (2008a,b) monitored the suburban, urban, and industrial communities of Ann Arbor, Ypsilanti, and Dearborn, respectively, in southeast Michigan (USA) at 227 sites using passive samplers (Jia et al., 2008a) and reported annual means of 1.1 μg/m^3 for benzene and 2.6 μg/m^3 for toluene. Overall, BTEX concentrations reported for North America have been approximately 1/10 of the concentrations we have reported for Tehran.

In a more similar setting, Matysik et al. (2010) measured VOCs using 3M #3500 passive samplers at 10 sites in Cairo (Egypt) between 2005 and 2007 (Matysik et al., 2010) and reported mean values of 7.8 μg/m^3 for benzene and 22.8 μg/m^3 for toluene. A study in Ardabil, Iran also reported BTEX concentrations similar to those in Tehran (Hazrati et al., 2016), but the concentrations in Ahvaz, Iran (Rad et al., 2014) were considerably lower. Miri and colleagues more recently measured BTEX in Tehran and reported annual mean concentrations of 3.4 μg/m^3 for benzene (Miri et al., 2016). These concentrations are considerably lower than what we report here, but measurements were taken using different methods in 2012–2013 at only seven sites, six of which were residential. In addition, Miri et al. reported minimum concentrations of benzene in summer (1.9 μg/m^3) while we observed the maximum concentrations in summer (9.4 μg/m^3). Conversely, they reported maximum values in spring while we found minimum concentrations in spring. Atabi et al. (2013) also measured ambient benzene at 33 locations in one of the 22 administrative districts of Tehran. Measurements were taken over one year using an active sampling device. They reported an annual mean of 39.3 μg/m^3 in 2010–2011 (Atabi et al., 2013), which is more than four times higher than what we measured at 13 sites in the same district. Overall, our results should though be cautiously compared with the findings of other studies in Tehran (Atabi et al., 2013; Dehghani et al., 2016; Miri et al., 2016; Sarkhosh et al., 2013) given differences in the study periods, sampling sites, sampling methods, and analyses.

3.5. Annual and seasonal correlations

The estimated annual mean concentrations over 179 sites were spatially correlated for all pollutants (range = 0.81–0.98). The correlations between annual mean benzene and other compounds ranged from 0.81 to 0.96, with a minimum for *o*-xylene and a maximum for ethylbenzene (Fig. 5). The high correlations between BTEX species are likely because their emission sources are the same. This is consistent with the findings of Shahbazi et al., (2016a,b) who reported that approximately 86% of VOCs are emitted from mobile sources in Tehran (Shahbazi et al., 2016b). Very similar results are seen for BTEX inter-correlations elsewhere (Delfino et al., 2003; Hoque et al., 2008; Kheirbek et al., 2012; Miri et al., 2016). Delfino et al. (2003) measured BTEX pollutants in the ambient air of Los Angeles (USA) from November 1999 to January 2000 using an active sampling device (Delfino et al., 2003), and reported Spearman correlations of 0.71 for benzene and ethylbenzene, 0.75 for benzene and toluene, and 0.90 for ethylbenzene and toluene while in our study these values were 0.96, 0.91, and 0.93, respectively. Hoque et al. (2008) evaluated BTEX compounds in the outdoor air of Delhi (India) using passive samplers for a one year period (Hoque et al., 2008) and reported respective values ranging from 0.86 to 0.91. The very high correlations between ethylbenzene and xylenes in our study suggest that they have originated from gas stations and vehicles (Wang et al., 2002). Miri and colleagues reported lower correlations among BTEX in Tehran, with Spearman correlations of ranging from 0.53 to 0.70 (Miri et al., 2016). These lower correlations suggest that the measured

Table 1
Measured season-specific and estimated annual concentrations (μg/m^3) for ambient benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene and total BTEX in Tehran, Iran. The coefficient of variation (CV) indicates spatial variability, indicating variability between sites in relation to the mean (in percentage).

	Summer			Winter			Spring			Annual		
	n	Median (range)	CV%	n	Median (range)	CV%	n	Median (range)	CV%	n	Median (range)	CV%
Benzene	177	9.5 (2.1–72.2)	65.3	179	7.2 (0.4–20.7)	32.6	178	4.8 (1.2–15.4)	40.2	179	7.8 (2.1–25.8)	39.7
Toluene	177	29.9 (6.9–287.6)	76.1	179	21.3 (0.4–84.2)	40.6	178	14.6 (3.8–50.1)	44.4	179	23.2 (6.1–88.9)	43.7
Ethylbenzene	177	5.5 (1.6–34.4)	55.1	179	5.3 (0.4–11.2)	35.3	178	3.2 (0.9–11.6)	41.3	179	5.7 (1.4–9.8)	38.1
p-xylene	177	5.4 (1.4–37.0)	58.3	179	4.7 (0.4–9.7)	33.7	178	3.3 (1.2–10.8)	38.2	179	5.6 (1.7–16.8)	36.4
m-xylene	177	10.2 (2.3–73.8)	61.2	179	9.0 (0.4–30.1)	39.3	178	6.0 (1.1–22.1)	44.2	179	10.4 (2.6–34.7)	42.0
o-xylene	177	6.2 (1.8–40.5)	69.6	179	5.6 (0.4–17.7)	38.4	178	4.4 (1.1–14.5)	40.4	179	6.1 (2.1–17.8)	40.3
Total BTEX	177	67.8 (17.0–538.1)	65.7	179	52.7 (2.4–154.6)	35.2	178	36.3 (9.5–124.7)	40.0	179	58.6 (16.4–195.0)	40.4

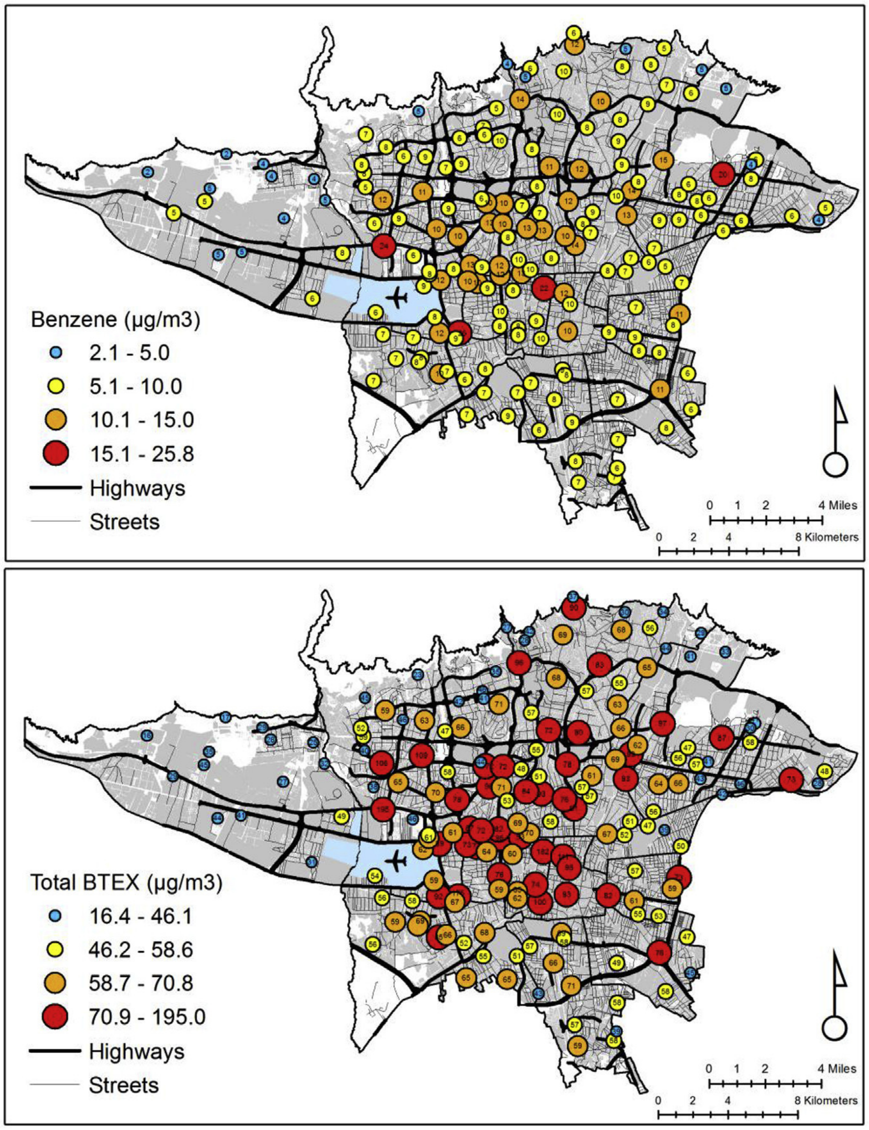

Fig. 4. Estimated annual mean benzene and Total BTEX over 179 Tehran SEPEHR sites. The classification is based on the quantile of observed values except for benzene, where 5 µg/m^3 was selected as the first break for ease of comparison with standard values. Sites are labeled by their rounded annual mean concentration. Patterns were similar for other pollutants (Figure S9).

ethylbenzene and xylenes may have come from emissions other than traffic, which is consistent with the fact that only one of the seven sites was situated to capture traffic impacts.

The spatial correlation of seasonal VOCs across all sites was higher between summer and winter than between summer and spring, and the minimum spatial correlation was observed between winter and spring. Specifically, the correlation between summer and winter measurements ranged from 0.73 for benzene to 0.77 for *o*-xylene. These values for summer vs spring ranged from 0.60 for toluene to 0.73 for *o*-xylene. The lowest seasonal spatial correlations were observed between winter and spring ranging from 0.57 for toluene to 0.66 for *m*-xylene.

3.6. Spatial variability

Based on the CV, the highest spatial variability of annual mean estimates in all sites was observed for toluene (43.7%) followed by *m*-xylene (42.0%) > *o*-xylene (40.3%) > benzene (39.7%) > ethylbenzene (38.1%) > *p*-xylene (36.4%). Toluene had the highest spatial variability in all seasons (summer = 76.1%; winter = 40.6%; spring = 44.4%), which might be associated with specific source emissions (Table 1).

For benzene, the most carcinogenic of the BTEX species, the highest spatial variability was observed in summer, followed by spring and winter. The same was observed for other pollutants and total BTEX (Table 1), which is consistent with our hypothesis about the importance of high summer temperatures driving fugitive emissions. The median of estimated annual mean concentrations were higher at traffic sites for all pollutants except *o*-xylene, which was higher at industrial sites (Fig. 6 and Figure S7). The estimated annual mean total BTEX values had higher spatial variability at residential sites (n = 105), followed by traffic (n = 56), reference (n = 5), industrial (n = 6), and green space (n = 7) sites, respectively (Table S2).

Studies in Detroit (USA) and Windsor (Canada) reported similar results for spatial variability in total BTEX with a CV of 44.6% compared with 40.4% in Tehran (Miller et al., 2010). The high concentrations of BTEX compounds in traffic locations are also

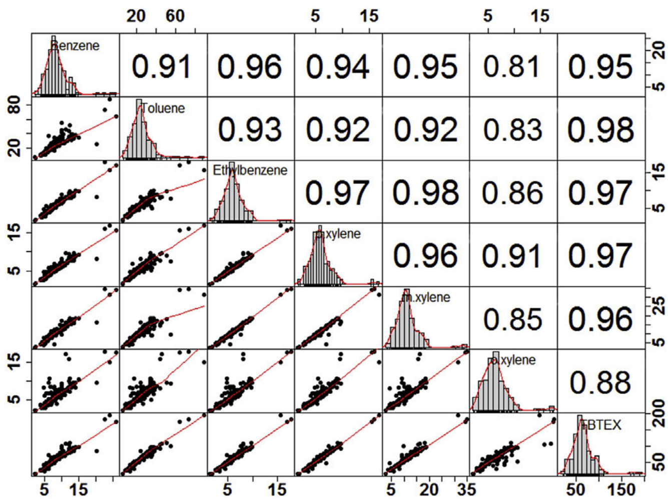

Fig. 5. The scatter-matrix, histogram, and Spearman rank correlation-matrix of estimated annual means for benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene and total BTEX over 179 Tehran SEPEHR sites. The p-value of all correlations was ≤0.001.

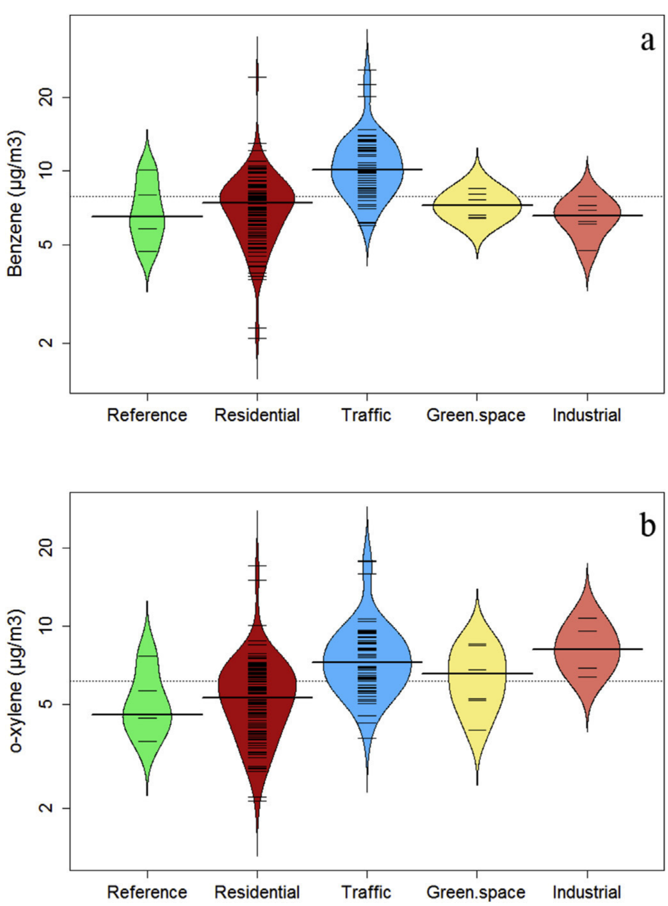

Fig. 6. The strata-specific bean plots for estimated annual mean ambient benzene (a) and *o*-xylene (b) over different site categories in Tehran. It is a combination of boxplot, density plot, and rug plot. The long line on each bean is the median of observations, the shape of the bean is a mirrored density curve, and the short black bars represent each data point. The dotted horizontal line across the plot is set to overall median. Distributions of other pollutants were similar to benzene (Figure S7). Note that traffic sites had the highest values for all pollutants except *o*-xylene where it was higher in the industrial sites.

consistent with findings from other cities (Kheirbek et al., 2012; Tecer and Tagil, 2014). The higher spatial variability at residential sites might be due to the high number of sites in this stratum, which might be affected by a wider range of emission sources than the sites in other strata. In fact, there were some residential sites with very high concentrations of VOCs, leading to higher standard deviation in this stratum, thus, higher CV.

3.7. BTEX at regulatory sites, around gas stations, and near to the airport

The annual median concentration of benzene and total BTEX was similar across the 35 network monitoring sites (7.7 and 56.8 µg/m^3) compared with the other 144 sites (7.9 and 58.7 µg/m^3), and the same was observed for other pollutants (Figure S8). This suggests that the annual medians of BTEX species over the regulatory monitoring network did a reasonable job of approximating those across the entire city. However, the five reference sites chosen for the study did not fully approximate the concentrations measured across the entire city (Fig. 6).

Atabi et al. (2013) reported very higher benzene concentrations around gas stations in district one of Tehran, mainly due to the lack of evaporation control (Atabi et al., 2013). The annual median (25th–75th percentiles) concentrations of benzene and total BTEX within 300 m of gas stations (nine sites) in Tehran SEPEHR were 9.1 (8.6–10.2) µg/m^3 and 67.3 (60.6–75.9) µg/m^3, respectively, which were both higher than for sites outside this buffer. This indicates that fugitive emissions from gas stations are likely an important source of VOCs in Tehran, which is consistent with the findings of (Shahbazi et al., 2016b) and (Atabi et al., 2013). An analysis of gasoline evaporation in Tehran estimated that out of the 12 million liters consumed daily, 54000 L are evaporated into the ambient air (Afshin et al., 2014).

Gaeta et al. (2016) measured VOCs (benzene, toluene, acrolein and formaldehyde) at 46 sampling sites around an Italian airport in Rome (Ciampino Airport) to assess long-term spatial variability of these pollutants. They reported that presence of the airport was associated with increased presence of acrolein, but not benzene or toluene (Gaeta et al., 2016). We compared the annual median benzene and total BTEX concentrations in a buffer of 1000 m around Mehrabad International Airport with the rest of city-wide sites. The annual mean benzene and total BTEX concentrations at these 10 sites were 7.8 µg/m^3 and 57.3 µg/m^3, respectively, while they were 7.9 µg/m^3 and 58.7 µg/m^3 at the city-wide sites. Our findings are consistent with the findings of Gaeta and colleagues (Gaeta et al., 2016), suggesting that airports do not affect BTEX concentrations within 1 km.

4. Conclusions

This study is the largest effort, to date, to measure spatial and temporal variability of BTEX in a LMIC megacity and one of the largest of its kind in the world. We found that the annual concentrations of benzene consistently exceeded recommendations and standards set to protect public health. In light of its known carcinogenic effects, the related burden needs to be quantified in terms of morbidity, mortality, and their related costs. These data will be used to generate exposure models that will make epidemiology study of these VOC effects possible in Tehran.

We found higher concentrations of BTEX around gas stations, and most of the hotspots were sites in areas with high traffic. Evaporation from fueling stations and vehicles, and unburned gasoline in the carburetors of cars, trucks, and motorcycles are likely major contributing factors (Afshin et al., 2014; Hassani and Hosseini, 2016; Shahbazi et al., 2016a). Approximately 86% of

VOCs are emitted from mobile sources in Tehran (Shahbazi et al., 2016b), confirming the need for appropriate actions against vehicular traffic, such as applying state-of-the-art technologies to reduce emissions, and implementation of low emissions zones. Epidemiologic evidence is needed to support implementation of such policies.

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Conflict of interest

Vahid Hosseini and Hossein Hassankhany declare that they are affiliated to Tehran AQCC. The views expressed in this manuscript are those of the authors and do not necessarily reflect the views or policies of the Tehran AQCC. The rest of authors declare that they have no actual or potential financial competing interests.

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Appendix A. Supplementary data

The document contains 15 additional pages, 9 additional figures and 2 additional tables. This material is available via the Internet at http://www.sciencedirect.com/.

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.04.027.

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Supplemental information (SI) to:

Spatiotemporal description of BTEX volatile organic compounds in a Middle Eastern megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)

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The document contains:
15 pages
9 figures
2 tables

Table S1. The characteristics of five reference sites in Tehran SEPEHR, Tehran, Iran

Site	Name	Type	Elevation (meters)	Distance to Highways (meters)	Distance to Airport (meters)	VOCs Emissions[1] (Tons/year)	Benzene[2] $\mu g/m^3$
R1	Golbarg	Residential	1285	333	3016	10.7	5.8
R2	Mantagheh 10	Highway	1176	21	1693	360.1	10.1
R3	Park-e-Roz	Park	1302	27	2184	61.2	4.7
R4	Aghdasieh	Street	1549	417	9805	94.0	6.5
R5	Shahr-e-Rey	Busy street	1053	246	5022	114.8	8.0

[1]from Shahbazi et al. (2016b)

[2]Annual mean values

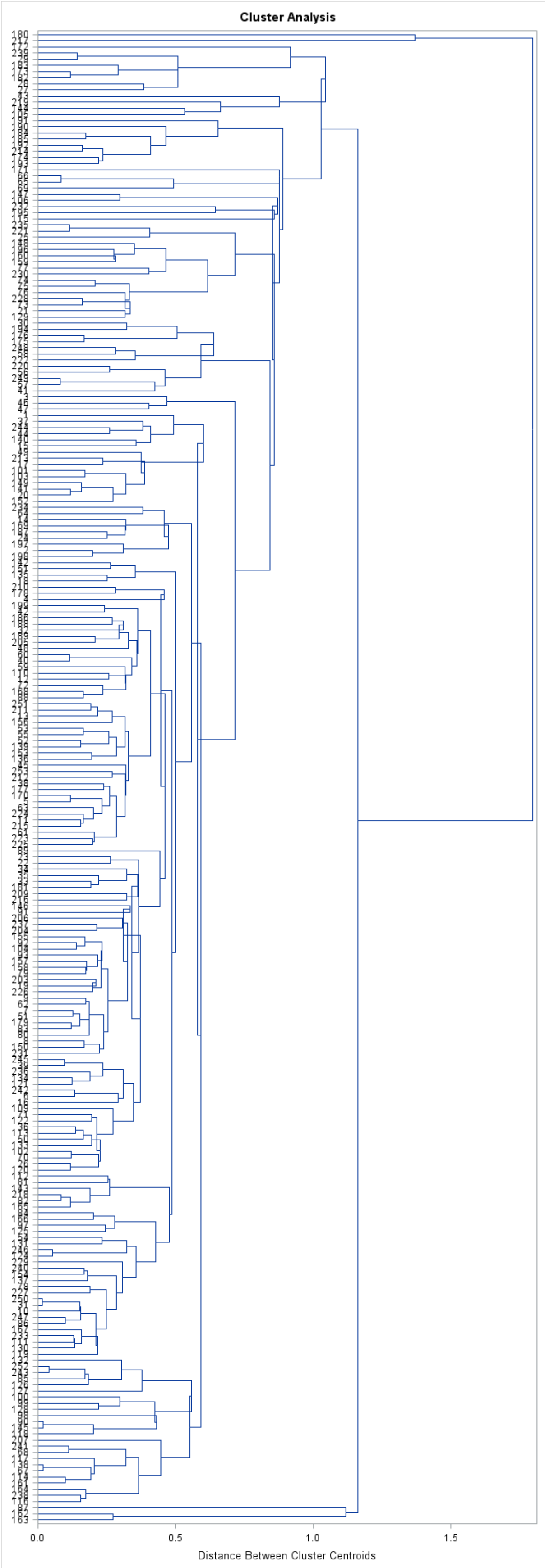

Figure S1. Clusters of two or three “similar” sites based on the calculated Euclidean distance

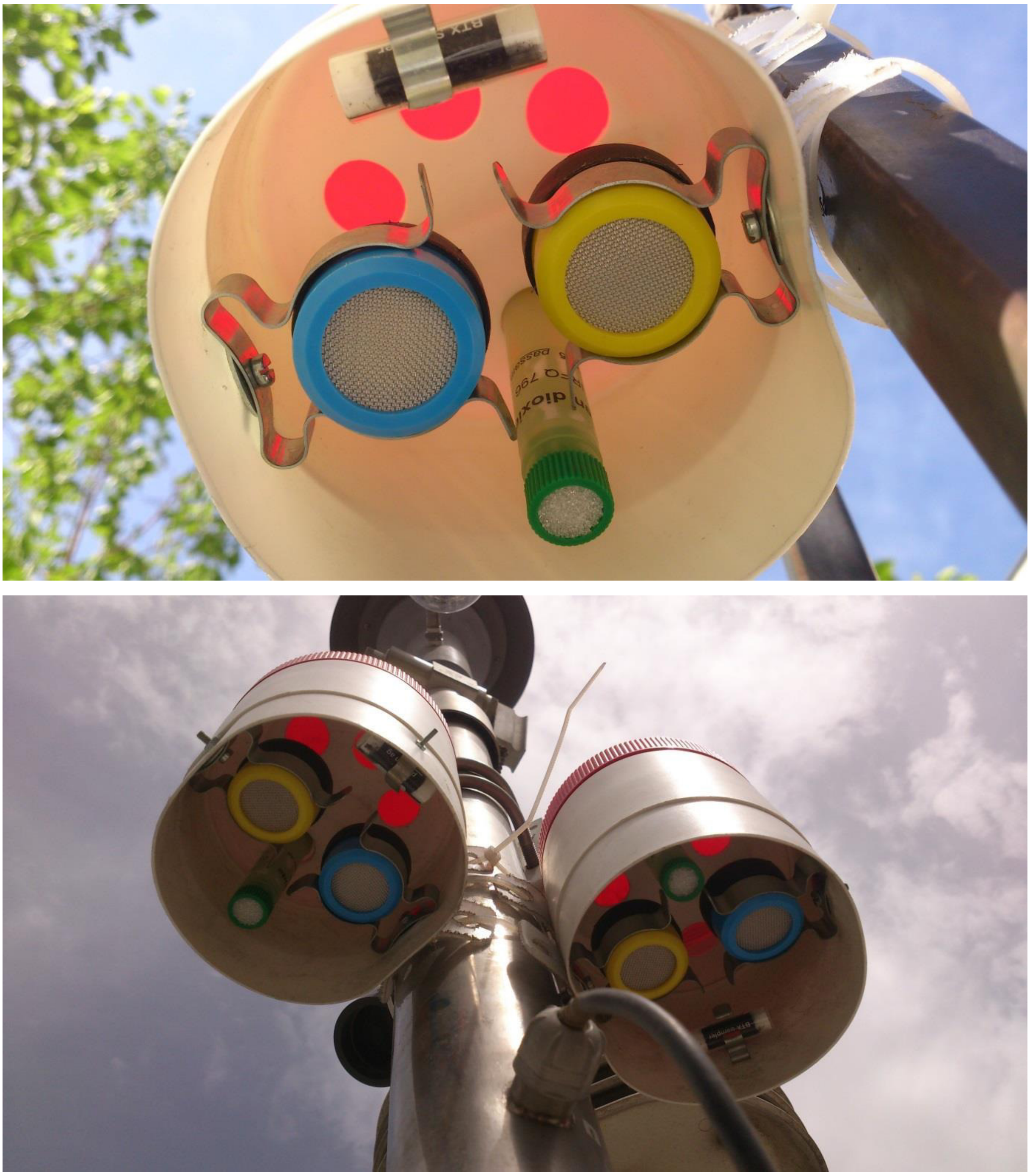

Figure S2. Examples of the mounted passive samplers for Tehran SEPEHR in Tehran, Iran.

Comparison of multiplicative vs. additive approach

Multiplicative and additive mixed linear regression models were compared to see which of the two methods provided a better fit of the data. The comparison was based on AIC (Akaike information criterion) where the criterion is "smaller = better."

Benzene

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	3076	3203
Reference site 2	2925	3188
Reference site 3	3039	3197
Reference site 4	3065	3199
Reference site 5	2937	3192

Toluene

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	4482	4564
Reference site 2	4329	4560
Reference site 3	4566	4564
Reference site 4	4498	4563
Reference site 5	4306	4560

Ethylbenzene

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	2448	2461
Reference site 2	2289	2431
Reference site 3	2405	2448
Reference site 4	2452	2447
Reference site 5	2267	2433

***p*-xylene**

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	2355	2430
Reference site 2	2272	2411
Reference site 3	2426	2432
Reference site 4	2429	2424
Reference site 5	2276	2415

***m*-xylene**

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	3084	3208
Reference site 2	3037	3199
Reference site 3	3132	3209
Reference site 4	3321	3209
Reference site 5	3043	3199

***o*-xylene**

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	2728	2768
Reference site 2	2670	2759
Reference site 3	2760	2769
Reference site 4	2818	2764
Reference site 5	2685	2758

TOTAL BTEX

	Akaike's information criterion based on multiplicative approach	Akaike's information criterion based on additive approach
Reference site 1	5201	5294
Reference site 2	5073	5292
Reference site 3	5252	5294
Reference site 4	5264	5293
Reference site 5	5061	5292

Overall, these analyses showed the superiority of the multiplicative approach for the situation of Tehran.

The cross validation results: The performance of methods is indicated by lower root mean square error (RMSE). The best methods for each pollutant are shown by green color. Week 8, week 21, and week 25 are the weeks where we had measurements simultaneously at 179 sites.

Benzene — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	6.24	3.17	2.13	3.85
M2 - inverse distance weighting	5.84	3.04	1.99	3.62
M3 - inverse distance squared weighting	5.88	3.04	2.07	3.66

Thus, M2 performs best for benzene

Toluene — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	23.77	12.3	8.65	14.91
M2 - inverse distance weighting	23.42	12	7.8	14.41
M3 - inverse distance squared weighting	23.67	12.64	7.96	14.76

Thus, M2 performs best for toluene

Ethylbenzene — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	3	2.14	1.44	2.19
M2 - inverse distance weighting	2.67	2.13	1.29	2.03
M3 - inverse distance squared weighting	2.71	2.16	1.33	2.07

Thus, M2 performs best for ethylbenzene

p-xylene — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	3.07	1.9	1.52	2.16
M2 - inverse distance weighting	2.92	1.81	1.42	2.05
M3 - inverse distance squared weighting	2.91	1.81	1.43	2.05

Thus, M2 performs best for p-xylene

m-xylene — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	5.96	4.17	2.66	4.26
M2 - inverse distance weighting	5.64	4.14	2.55	4.11
M3 - inverse distance squared weighting	5.65	4.12	2.58	4.12

Thus, M2 performs best for m-xylene

o-xylene — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	4.41	3.12	1.97	3.17
M2 - inverse distance weighting	4.27	2.82	1.95	3.01
M3 - inverse distance squared weighting	4.3	2.82	2.01	3.04

Thus, M2 performs best for o-xylene

Total BTEX — Root mean squared error (RMSE)

	W8	W21	W25	Mean
M1 - weighting by 1 / [1 - cos(alpha)^2]	44.44	25.3	17.63	29.12
M2 - inverse distance weighting	42.36	23.69	15.92	27.32
M3 - inverse distance squared weighting	42.62	24.13	16.24	27.66

Thus, M2 performs best for total BTEX

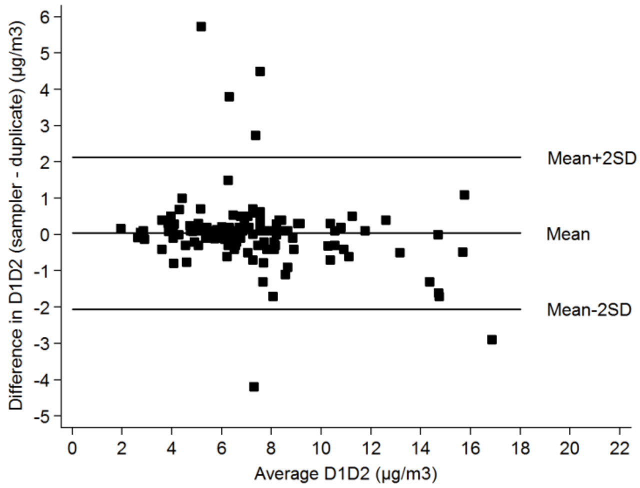

Figure S3. Bland-Altman plot for agreement of samplers (D1) and duplicates (D2) over all benzene pairs.

As can be seen, 6 out of 123 (4.9%) observations are beyond the limits of agreement between passive samplers and duplicates.

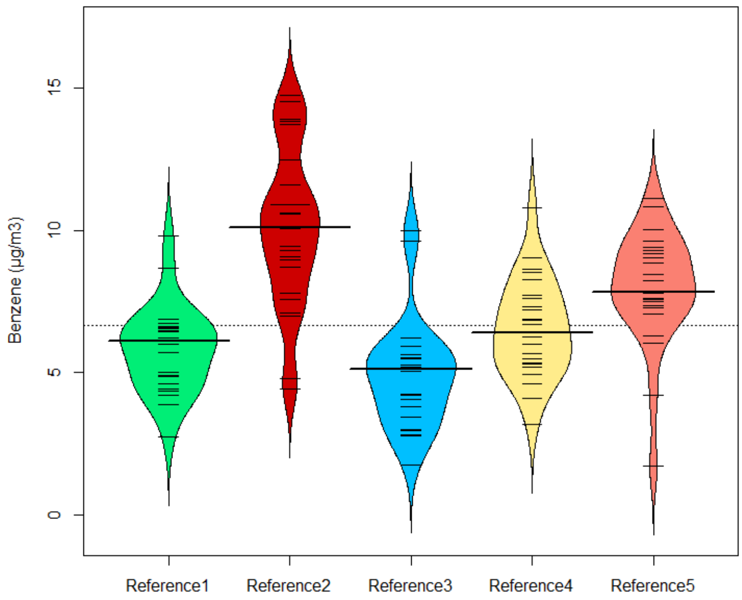

Figure S4. The reference-site-specific bean plot for annual ambient benzene over 25 biweekly measurements in Tehran, Iran.

Table S2. The strata-specific results for estimated annual ambient benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene and Total BTEX (μg/m³) in Tehran, Iran.

	Reference sites			Residential sites			Traffic sites			Green space sites			Industrial sites		
	n	Median (range)	CV%	n	Median (range)	CV%	n	Median (range)	CV%	n	Median (range)	CV%	n	Median (range)	CV%
Benzene	5	6.5 (4.7 – 10.1)	29.8	105	7.4 (2.1 – 24.0)	35.5	56	10.1 (6.0 – 25.8)	33.7	7	7.3 (6.4 – 8.4)	11.3	6	6.6 (4.7 – 7.8)	16.5
toluene	5	17.1 (11.7 – 27.9)	32.6	105	21.8 (6.1 – 88.9)	45.4	56	27.8 (15.3 – 73.2)	35.6	7	22.5 (17.1 – 28.7)	16.9	6	20.1 (13.9 – 36.4)	37.4
ethylbenzene	5	4.3 (3.2 – 6.8)	29.2	105	5.3 (1.4 – 15.5)	35.1	56	7.4 (4.2 – 17.8)	32.2	7	5.2 (3.9 – 6.8)	19.1	6	4.9 (4.7 – 5.7)	8.1
p-xylene	5	4.3 (3.3 – 6.7)	27.9	105	5.1 (1.7 – 16.8)	35.6	56	6.9 (3.8 – 15.9)	30.6	7	5.3 (4.3 – 6.4)	15.0	6	5.5 (4.8 – 7.0)	13.4
m-xylene	5	7.9 (5.5 – 13.2)	33.8	105	9.4 (2.6 – 31.4)	38.9	56	12.8 (7.3 – 34.7)	35.5	7	9.9 (7.7 – 12.5)	17.9	6	9.0 (4.3 – 10.0)	25.0
o-xylene	5	4.5 (3.6 – 7.7)	30.4	105	5.2 (2.2 – 17.1)	39.2	56	7.2 (3.7 – 17.8)	35.9	7	6.6 (4.0 – 8.5)	26.7	6	8.1 (6.4 – 10.7)	19.6
Total BTEX	5	44.3 (32.0 – 72.6)	31.3	105	55.5 (16.3 – 195.0)	40.5	56	72.0 (40.5 – 181.7)	32.9	7	55.6 (43.5 – 69.4)	15.9	6	54.8 (44.2 – 73.3)	17.8

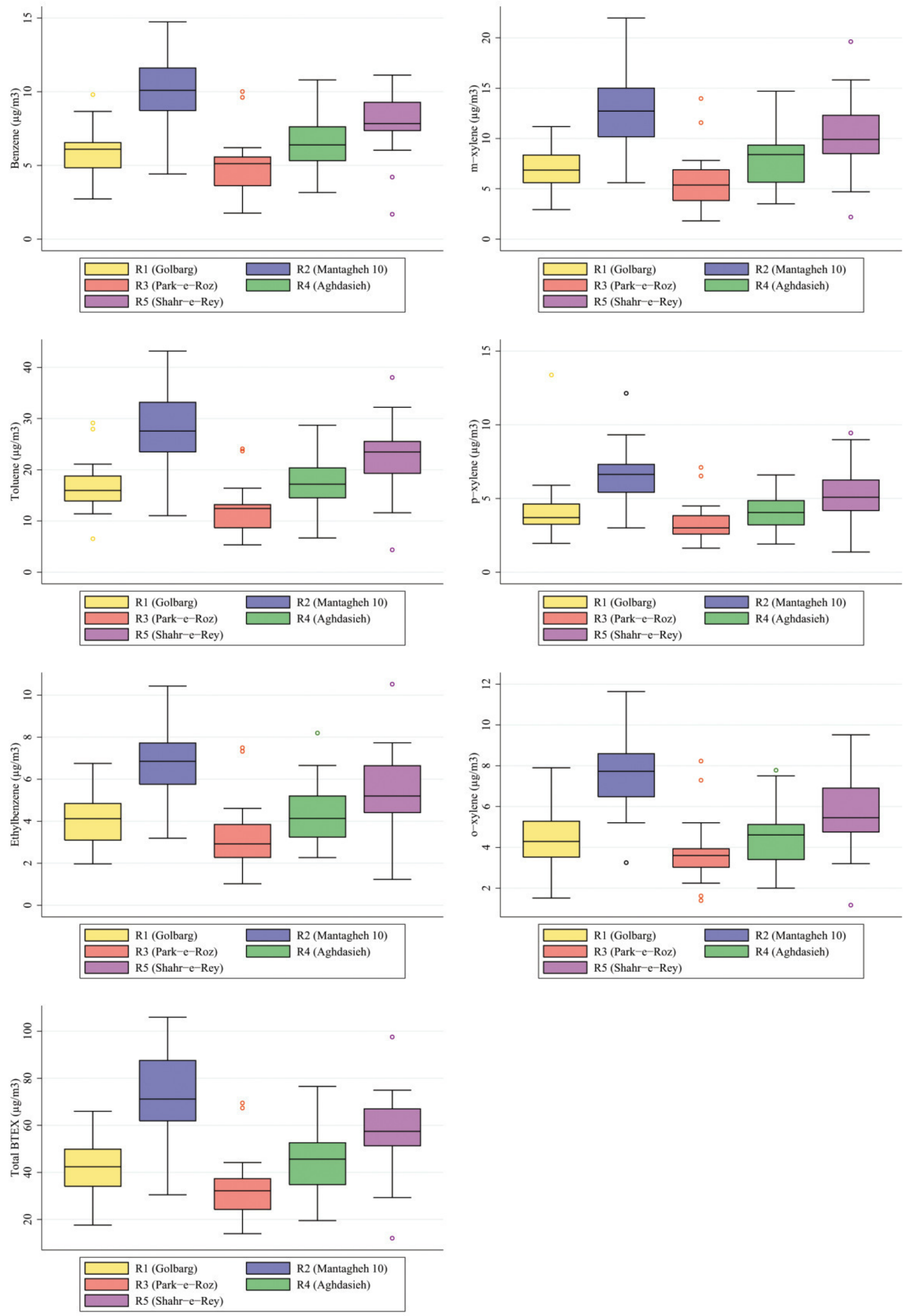

Figure S5. The reference-site-specific box plots for annual ambient benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene and Total BTEX over 25 biweekly measurements in Tehran, Iran.

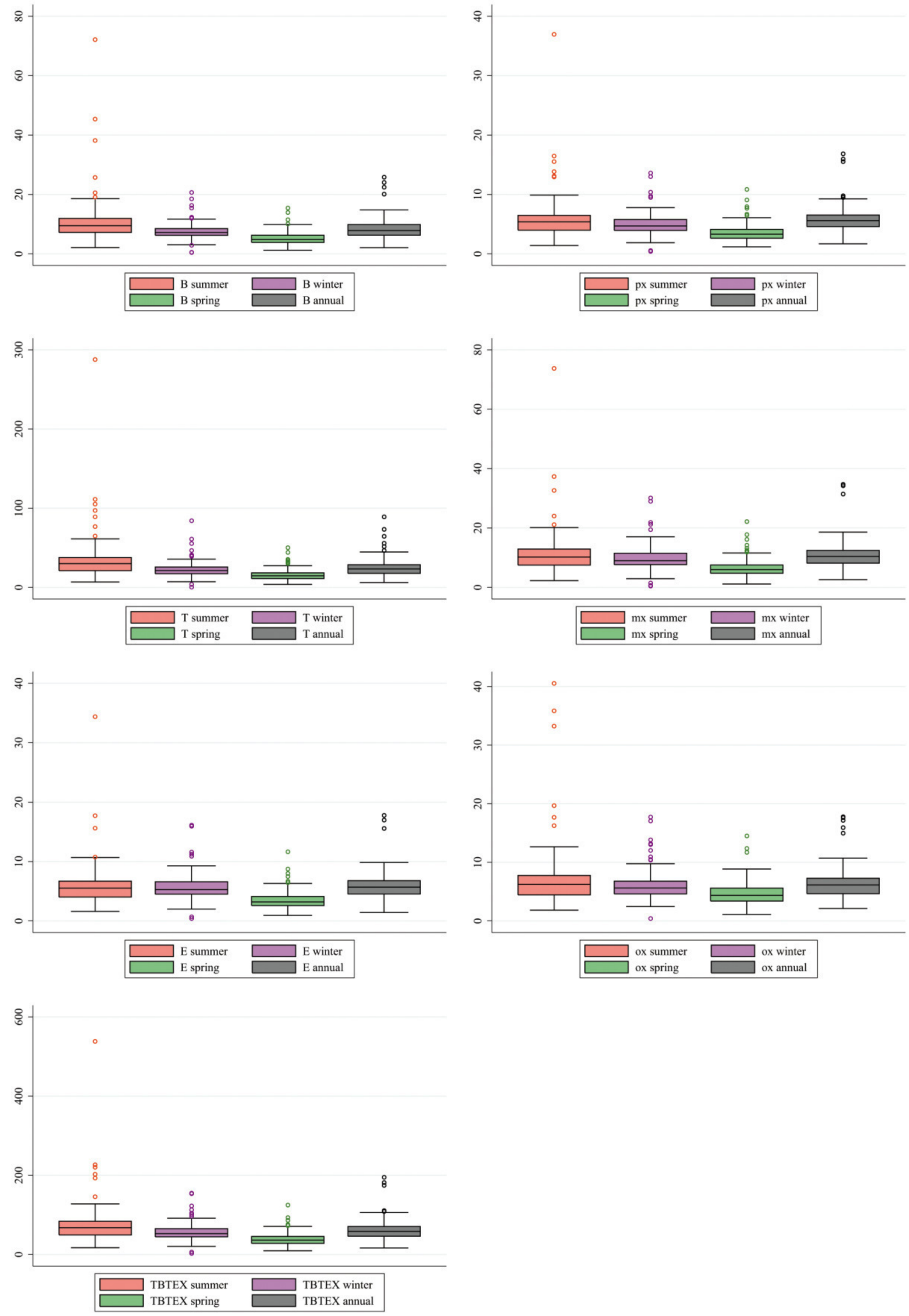

Figure S6. Distribution of annual and season-specific benzene (B), toluene (T), ethylbenzene (E), *p*-xylene (px), *m*-xylene (mx), *o*-xylene (ox), and total BTEX (TBTEX) concentrations (µg/m^3) over 179 Tehran SEPEHR sites in Tehran, Iran

Spatiotemporal spearman correlations and coefficient of divergence (COD) over five reference sites for the entire year

Spearman rank coefficient for Benzene

	R1	R2	R3	R4
R2	0.63			
R3	0.57	0.62		
R4	0.63	0.58	0.92	
R5	0.69	0.91	0.51	0.49

CODs for Benzene

	R1	R2	R3	R4
R2	0.29			
R3	0.17	0.37		
R4	0.12	0.24	0.17	
R5	0.19	0.15	0.28	0.16

Correlation between Spearman rank coefficient and CODs for Benzene: -0.30

Spearman rank coefficient for Toluene

	R1	R2	R3	R4
R2	0.66			
R3	0.39	0.52		
R4	0.43	0.53	0.89	
R5	0.65	0.85	0.24	0.29

CODs for Toluene

	R1	R2	R3	R4
R2	0.27			
R3	0.23	0.41		
R4	0.14	0.26	0.19	
R5	0.20	0.15	0.35	0.20

Correlation between Spearman rank coefficient and CODs for Toluene: -0.34

Spearman rank coefficient for Ethylbenzene

	R1	R2	R3	R4
R2	0.62			
R3	0.61	0.73		
R4	0.64	0.73	0.91	
R5	0.68	0.88	0.59	0.63

CODs for Ethylbenzene

	R1	R2	R3	R4
R2	0.27			
R3	0.22	0.39		
R4	0.13	0.25	0.19	
R5	0.18	0.16	0.30	0.18

Correlation between Spearman rank coefficient and CODs for Ethylbenzene: -0.21

Spearman rank coefficient for *p*-xylene

	R1	R2	R3	R4
R2	0.69			
R3	0.34	0.48		
R4	0.48	0.56	0.83	
R5	0.59	0.76	0.47	0.49

CODs for *p*-xylene

	R1	R2	R3	R4
R2	0.26			
R3	0.23	0.35		
R4	0.17	0.27	0.13	
R5	0.19	0.16	0.29	0.20

Correlation between Spearman rank coefficient and CODs for *p*-xylene: -0.48

Spearman rank coefficient for *m*-xylene

	R1	R2	R3	R4
R2	0.73			
R3	0.60	0.77		
R4	0.60	0.74	0.89	
R5	0.72	0.93	0.57	0.60

CODs for *m*-xylene

	R1	R2	R3	R4
R2	0.30			
R3	0.22	0.42		
R4	0.14	0.28	0.20	
R5	0.20	0.16	0.33	0.20

Correlation between Spearman rank coefficient and CODs for *m*-xylene: -0.07

Spearman rank coefficient for *o*-xylene

	R1	R2	R3	R4
R2	0.71			
R3	0.46	0.60		
R4	0.52	0.66	0.90	
R5	0.66	0.90	0.46	0.59

CODs for *o*-xylene

	R1	R2	R3	R4
R2	0.28			
R3	0.20	0.37		
R4	0.14	0.29	0.13	
R5	0.16	0.19	0.27	0.18

Correlation between Spearman rank coefficient and CODs for *o*-xylene: -0.24

Spearman rank coefficient for Total BTEX

	R1	R2	R3	R4
R2	0.67			
R3	0.43	0.61		
R4	0.50	0.60	0.90	
R5	0.69	0.87	0.38	0.41

CODs for Total BTEX

	R1	R2	R3	R4
R2	0.28			
R3	0.21	0.39		
R4	0.13	0.26	0.17	
R5	0.18	0.15	0.32	0.19

Correlation between Spearman rank coefficient and CODs for *Total BTEX*: -0.26

Correlations between pollutants by reference site

Correlation of pollutants in reference site 1

	Benzen~1	Toluen~1	Ethylb~1	pxylen~1	mxylen~1	oxylen~1	TOTALB~1
Benzene_R1	1.0000						
Toluene_R1	0.8069	1.0000					
Ethylbenze~1	0.7234	0.7599	1.0000				
pxylene_R1	0.7103	0.7772	0.8337	1.0000			
mxylene_R1	0.7790	0.7598	0.9504	0.8713	1.0000		
oxylene_R1	0.6867	0.8248	0.8474	0.8376	0.8507	1.0000	
TOTALBTEX_R1	0.7977	0.9223	0.8765	0.9292	0.9098	0.9090	1.0000

Correlation of pollutants in reference site 2

	Benzen~2	Toluen~2	Ethylb~2	pxylen~2	mxylen~2	oxylen~2	TOTALB~1
Benzene_R2	1.0000						
Toluene_R2	0.9448	1.0000					
Ethylbenze~2	0.8202	0.6738	1.0000				
pxylene_R2	0.7398	0.6292	0.8662	1.0000			
mxylene_R2	0.8875	0.7546	0.9592	0.8785	1.0000		
oxylene_R2	0.8155	0.7631	0.8731	0.8546	0.8846	1.0000	
TOTALBTEX_R1	0.5832	0.6108	0.5185	0.6338	0.6085	0.6877	1.0000

Correlation of pollutants in reference site 3

	Benzen~3	Toluen~3	Ethylb~3	pxylen~3	mxylen~3	oxylen~3	TOTALB~1
Benzene_R3	1.0000						
Toluene_R3	0.9085	1.0000					
Ethylbenze~3	0.7739	0.8093	1.0000				
pxylene_R3	0.6009	0.6641	0.8791	1.0000			
mxylene_R3	0.8037	0.8221	0.9589	0.8102	1.0000		
oxylene_R3	0.7549	0.8154	0.9011	0.8163	0.8873	1.0000	
TOTALBTEX_R1	0.3730	0.3653	0.3635	0.2296	0.4340	0.4136	1.0000

Correlation of pollutants in reference site 4

	Benzen~4	Toluen~4	Ethylb~4	pxylen~4	mxylen~4	oxylen~4	TOTALB~1
Benzene_R4	1.0000						
Toluene_R4	0.9254	1.0000					
Ethylbenze~4	0.8492	0.8392	1.0000				
pxylene_R4	0.8613	0.8532	0.9436	1.0000			
mxylene_R4	0.8300	0.8485	0.9269	0.8802	1.0000		
oxylene_R4	0.7659	0.8494	0.8702	0.8469	0.8917	1.0000	
TOTALBTEX_R1	0.4231	0.4546	0.4138	0.4089	0.4300	0.5051	1.0000

Correlation of pollutants in reference site 5

	Benzen~5	Toluen~5	Ethylb~5	pxylen~5	mxylen~5	oxylen~5	TOTALB~1
Benzene_R5	1.0000						
Toluene_R5	0.8446	1.0000					
Ethylbenze~5	0.7028	0.6432	1.0000				
pxylene_R5	0.4692	0.5992	0.7844	1.0000			
mxylene_R5	0.7554	0.6900	0.9440	0.8162	1.0000		
oxylene_R5	0.6362	0.6446	0.8529	0.8538	0.9100	1.0000	
TOTALBTEX_R1	0.6638	0.6000	0.6478	0.5246	0.6669	0.6123	1.0000

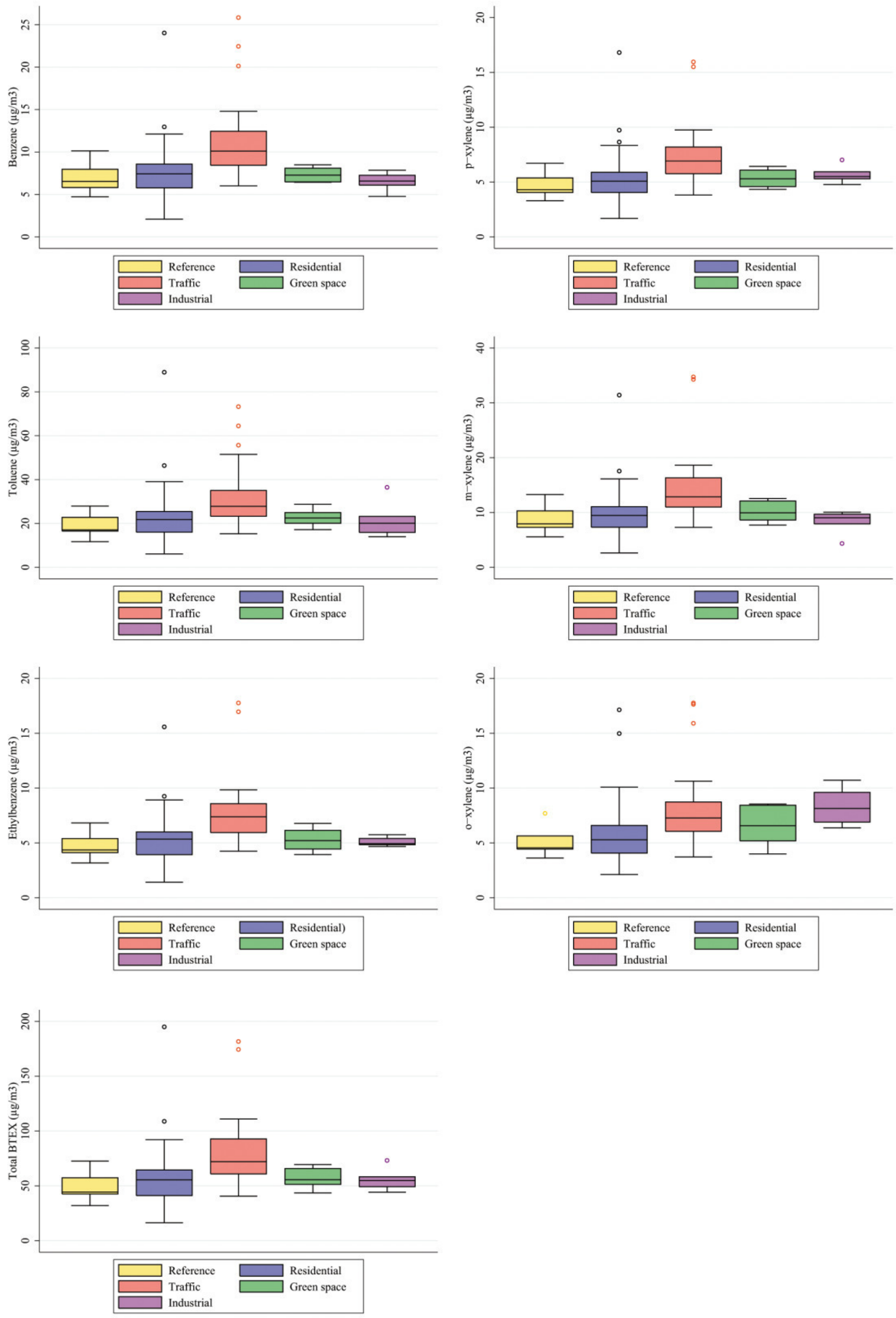

Figure S7. The strata-specific box plots for estimated annual ambient benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene and Total BTEX over different site categories in Tehran, Iran. The number of locations for reference, residential, traffic, green space, and industrial sites were 5, 105, 56, 7, and 6, respectively. Note that traffic sites had the highest values for all pollutants except *o*-xylene where it was higher in industrial sites.

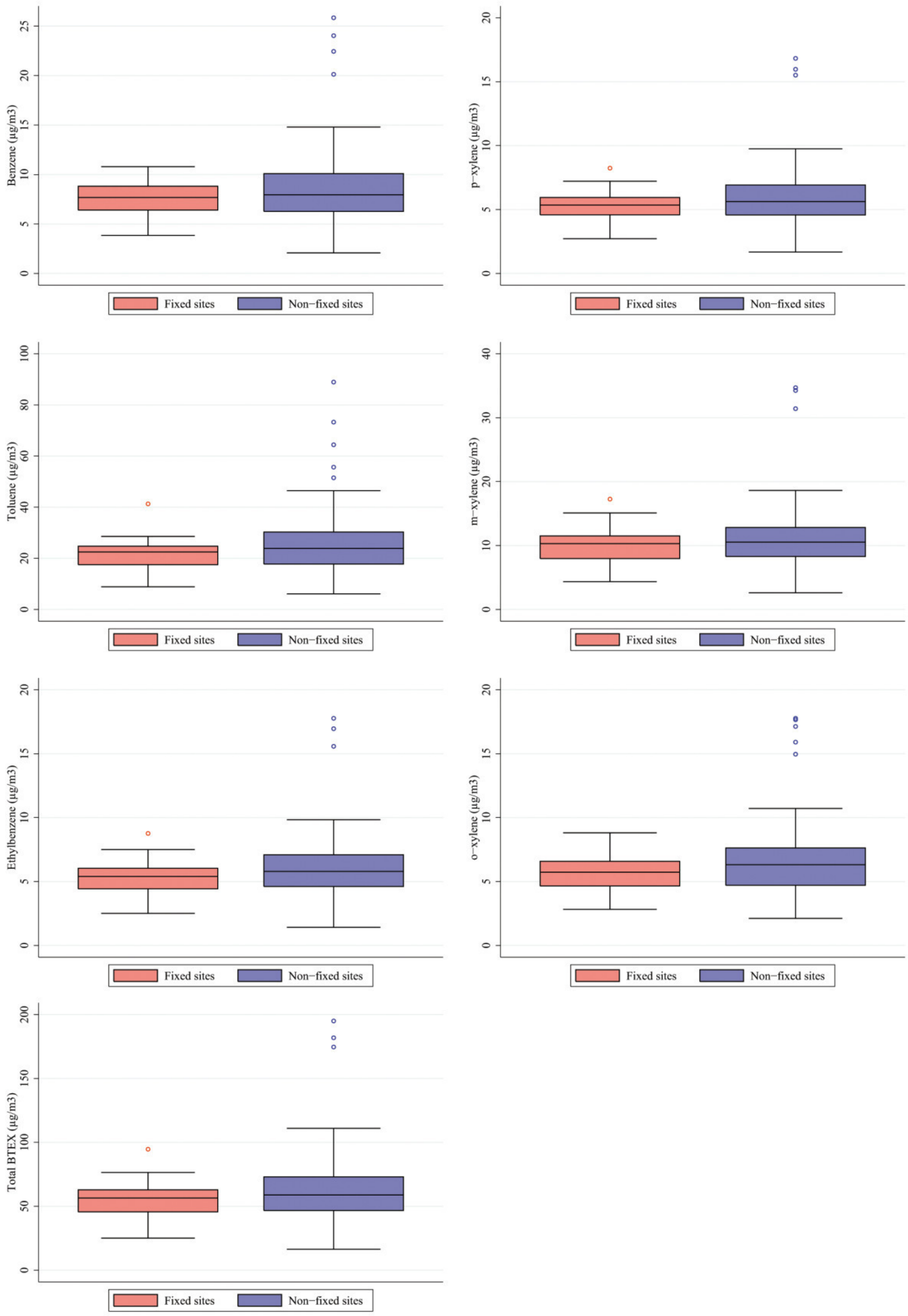

Figure S8. Distribution of annual benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene, and total BTEX concentrations (µg/m^3) over fixed-sites-co-located vs non-fixed-site samplers in Tehran, Iran.

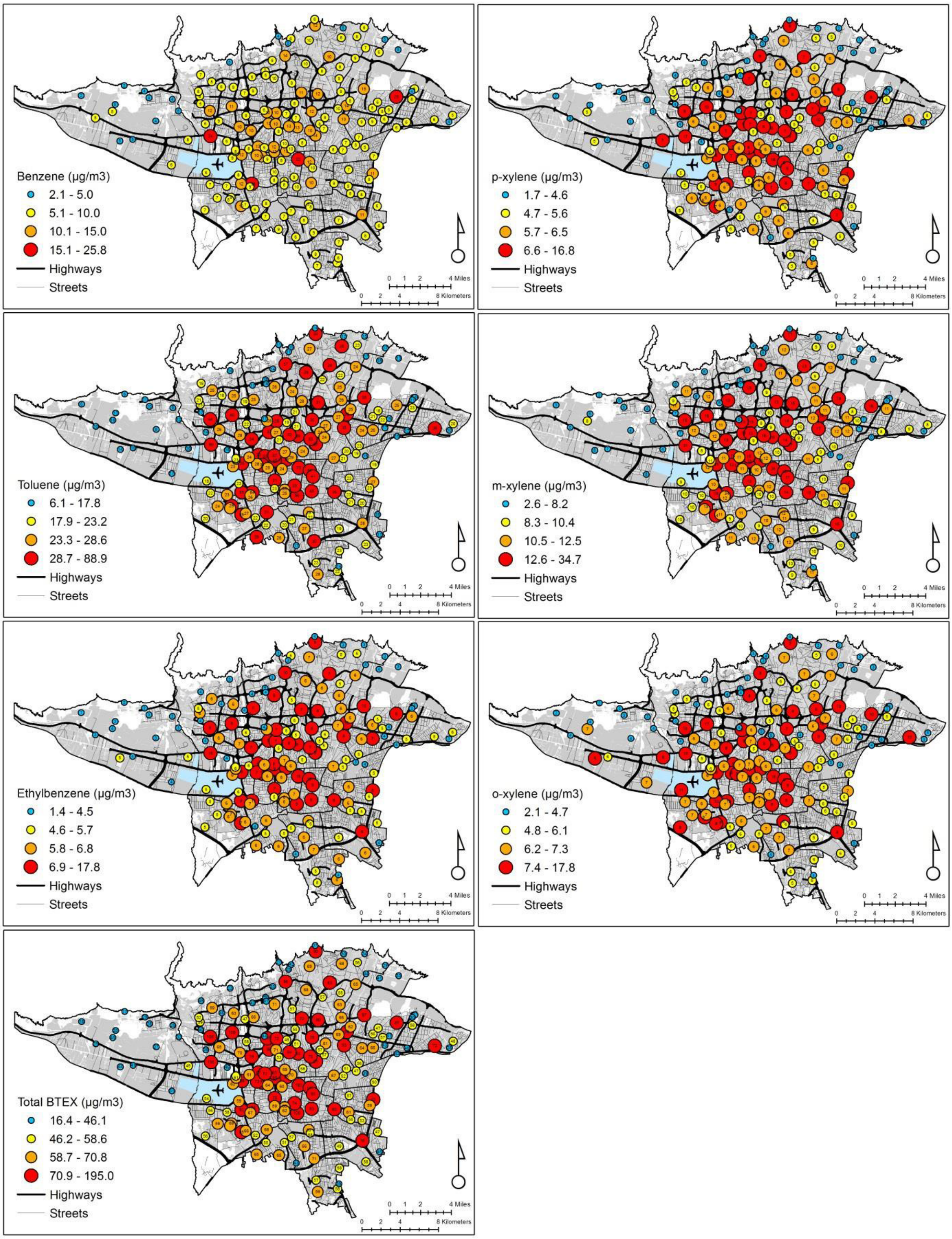

Figure S9. Estimated annual mean VOCs over 179 Tehran SEPEHR sites in Tehran, Iran.

Article 4: Land use regression models for alkylbenzenes in a Middle Eastern megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)

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Land Use Regression Models for Alkylbenzenes in a Middle Eastern Megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)

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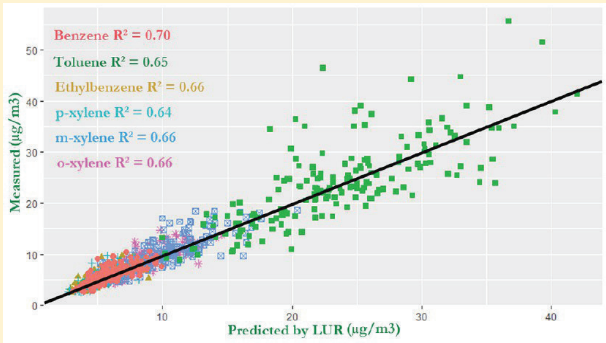
S *Supporting Information*

ABSTRACT: Land use regression (LUR) has not been applied thus far to ambient alkylbenzenes in highly polluted megacities. We advanced LUR models for benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene (BTEX), and total BTEX using measurement based estimates of annual means at 179 sites in Tehran megacity, Iran. Overall, 520 predictors were evaluated, such as The Weather Research and Forecasting Model meteorology predictions, emission inventory, and several new others. The final models with R^2 values ranging from 0.64 for *p*-xylene to 0.70 for benzene were mainly driven by traffic-related variables but the proximity to sewage treatment plants was present in all models indicating a major local source of alkylbenzenes not used in any previous study. We further found that large buffers are needed to explain annual mean concentrations of alkylbenzenes in complex situations of a megacity. About 83% of Tehran's surface had benzene concentrations above air quality standard of 5 $\mu g/m^3$ set by European Union and Iranian Government. Toluene was the predominant alkylbenzene, and the most polluted area was the city center. Our analyses on differences between wealthier and poorer areas also showed somewhat higher concentrations for the latter. This is the largest LUR study to predict all BTEX species in a megacity.



■ INTRODUCTION

Numerous studies have shown that air pollution causes acute and chronic morbidities and premature death[1] resulting in considerable public health consequences.[2,3]

Land use regression (LUR) models have been extensively used for long-term exposure assessment to ambient air pollutants, which is essential for epidemiologic research on chronic health effects of air pollution.[4,5] In LUR, many spatially varying variables are used to predict measured concentrations of air pollutants using regression models. Finally, these explanatory variables can be used to estimate pollution anywhere in the study area.[6]

Air pollution consists of a wide range of particles and gases.[7] Among the gases, there is a group of volatile organic compounds (VOCs) classified into alkanes, alkylbenzenes, chlorinated hydrocarbons, terpenes, and other miscellaneous VOCs.[8] Alkylbenzenes include toxic air pollutants, such as benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, and *o*-xylene (BTEX).

To date, several LUR studies, mainly from North America, have been published where they measured and estimated exposure to VOCs.[9−11] However, these studies were mainly conducted in areas where concentrations have been very low or relevant only for small populations.[9−12] LUR has not been applied so far for alkylbenzenes in highly polluted megacities. In a LUR study from New York City,[12] covering an area with a population of about 8 million people, benzene, total BTEX, and formaldehyde were modeled based on three months of measurements, at very low concentration levels (e.g., with mean benzene = 0.8 $\mu g/m^3$). While several studies modeled (*m*+*p*)-xylene, none looked at *m*- and *p*-xylene separately. Furthermore, none of these LUR studies incorporated meteorological variables, such as wind speed, relative humidity, or temperature. Overall, studies from outside North America and Europe with a wide range of concentrations and different populations are critically needed.[13]

The Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR (means "sky" in Persian))

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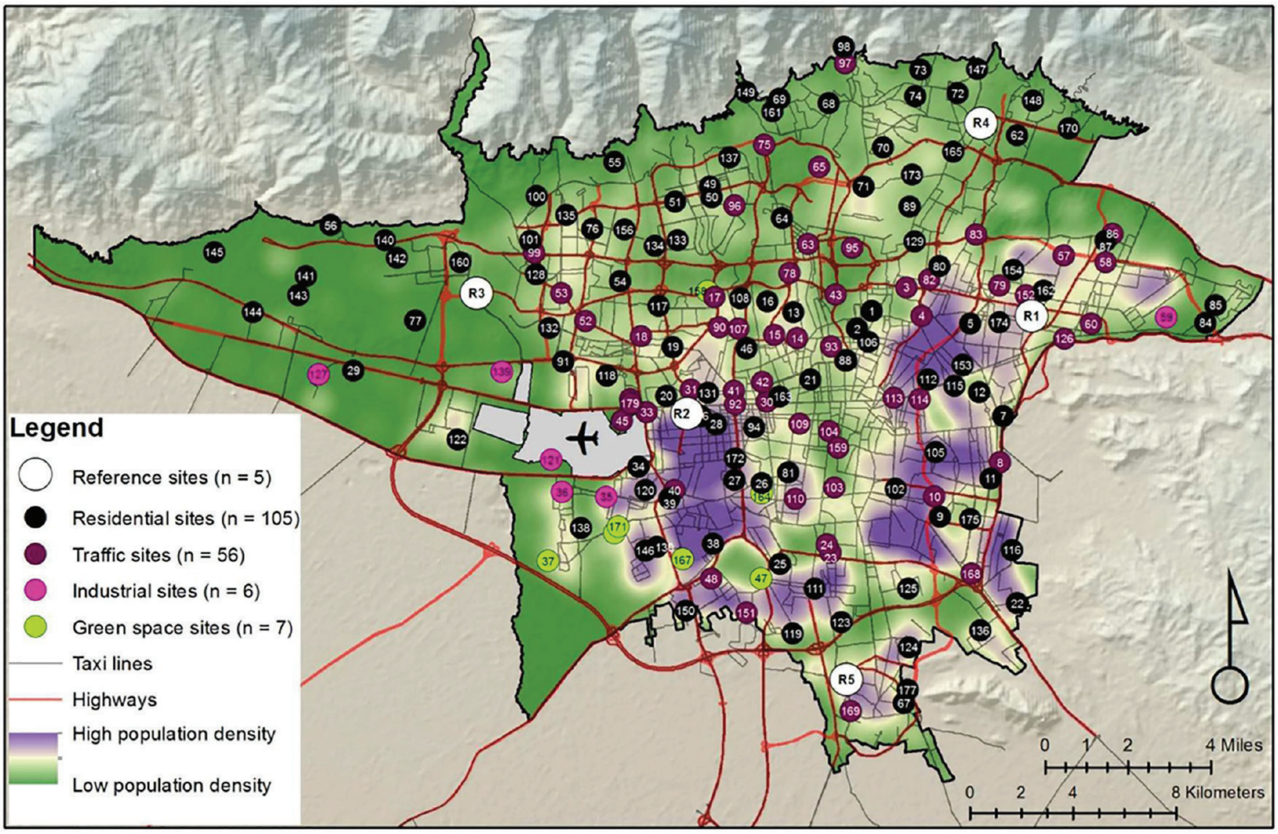

Figure 1. Study area of Tehran SEPEHR, Iran, and location of 179 measurement sites, including the five reference stations. Colors of symbols (labeled with the site ID) relate to different land use categories. The map also visualizes population density.

is a collaborative Swiss–Iranian effort aimed to measure and estimate long-term spatial variability of air pollution—mainly of nitrogen dioxide, sulfur dioxide, ozone, and BTEX—and to estimate chronic exposure of Tehran megacity residents to these pollutants for use in future studies. In line with our previous publications where concentrations of criteria air pollutants were well above the values recommended by the World Health Organization,[14,15] the recent Tehran SEPEHR results demonstrated that ambient concentrations of toxic VOCs were very high and a public health concern in Tehran.[16]

The aims of this study were (a) to develop LUR models for all measured alkylbenzenes in Tehran megacity, using common land use and traffic variables but also evaluating some new predictor variables, (b) to analyze their spatial variability, and (c) to analyze the difference of air quality in advantaged versus disadvantaged areas.

■ EXPERIMENTAL SECTION

Research Field. Tehran SEPEHR was conducted in Tehran, a mega-city with a resident population of about 9 million people and a day-time population of over 10 million due to massive commute from outer areas.[14] The community covers an area of over 613 km^2 with higher population densities in the midwest and mideast to southern areas. The Alborz Mountains surround the northern areas of Tehran and there is desert in the south. As a result, there is a difference of 800 m in altitude from the populated areas in the south to those in the north Tehran (Figure 1). The climate is semiarid with an annual mean temperature of 18.5 °C. Minimum temperatures go down to −15 °C in January and reach 43 °C in July. The sun often shines in Tehran (annual bright sunshine of 2800 h and mean cloud cover of 30%) and there is an annual precipitation of about 220 mm. The maximum of 39 mm and minimum of 1 mm occur, respectively, in January and September.[15]

Measured Alkylbenzenes. The details of research design, methods, and descriptive results of the Tehran SEPEHR on alkylbenzenes are published elsewhere.[16] In brief, we first visited and noted the characteristics of 276 eligible measurement sites in consultation with local collaborators. A subset of 174 sampling sites were selected with respect to sampler deployment permission, budget, and various land uses using a cluster analytic method and prior knowledge about spatial distribution of air pollution in Tehran. Most of the sites were in the residential areas as we were interested at general population's exposure to air pollution. In addition, 5 reference sites were selected to represent a wide range of traffic, elevation, and emissions. BTEX were measured consecutively every 2 weeks at the 5 reference sites throughout the entire year from April 2015 to May 2016 and at other 174 sites over three 2-week periods in summer, winter, and spring seasons by Passam passive samplers (Figure 1). Finally, using the ratios of these measurements to concurrent levels at reference sites, annual mean levels of the different alkylbenzenes were estimated for all sites.[16] They defined the response variables of our LUR models.

Predictors. We developed 520 predictor variables from a wide variety of features categorized into ten classes and according to different buffer zones. These were traffic, nontraffic, population, geography, land use, distance, log-distance, products,

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emission, and meteorology (Supporting Information (SI), Table S1).

The traffic class included lengths (in meters) or counts (#) of the following traffic parameters derived in various buffer sizes from 25 to 5000 m: All roads, highways, main roads, ancillary roads, alleys, all bus lines, bus rapid transportation (BRT) lines, non-BRT lines, taxi lines, bridges, all bus stops, BRT stops, non-BRT stops, taxi stops, and critical traffic points. The non-traffic class included counts of blocks, primary schools, and high schools. The population class included total population density with buffers of 500 to 3000 m. The geography class included variables of ground slope and elevation, which are derived from a digital elevation model. The land use class included areas of residential, green space, urban facilities, industrial, official/commercial, transportation, sensitive, agriculture, arid or undeveloped, and other land uses within various buffers from 25 to 5000 m (in m^2 units) . All derived distance and log-distance variables are listed in the SI, Table S1. The products included the ratio of buffer-based variables in the traffic, non-traffic, and land use classes to the variables in the distance class. The product variables for LUR have been used in previous studies as they might better represent the emission and dispersion processes.[17] We used an emission inventory of VOCs as a potential predictor for alkylbenzenes in LUR. The details of the emission inventory estimations can be found elsewhere.[18,19]

The nonhydrostatic, mesoscale Advanced Research Weather Research and Forecasting model, version 3.4, was used as the meteorological model.[20] This mesoscale model is a state-of-the-art atmospheric simulation system based on the fifth-generation Penn State/The National Center for Atmospheric Research Mesoscale Model.[21] Meteorological data over the Tehran domain including minimum, average, and maximum wind speed, relative humidity, and temperature were calculated using the Weather Research and Forecasting (WRF) model with three nested domains having 27, 9, and 3 km resolutions, respectively. The 27−9−3 km domains were run together efficiently using two-way grid nesting in WRF. The lateral boundary conditions for coarse domain were taken from the National Centers for Environmental Prediction Global Forecast System (0.5° × 0.5°) at 6 h frequency. After calculating the daily means, the annual mean of the above-mentioned estimated meteorological variables were calculated and used as predictors in LUR.

Model Building and Validation Algorithm. Our LUR model building algorithm and validation consisted of 10 steps:

(1) Log-transform the response variable if they were not normally distributed.
(2) Create a box plot for the response variable and remove outlier observations in both ends from the data set (i.e., observations that are larger than the 75th percentile or smaller than the 25th percentile by at least 1.5 times the interquartile range (IQR)).
(3) Conduct a univariate regression by regressing log-transformed monitored concentrations against each of 520 predictors.
(4) Rank the variables based on adjusted R^2 of univariate regression analyses.
(5) Build a "start model" with the variable that gives the highest adjusted explained variance (R^2).
(6) Add the next 519 variables individually and retain them if: (a) adjusted R^2 increases by at least 0.5%, and (b) the direction of the effect is as expected, and (c) the directions of effects of predictors already included in the model do not change, and (d) all variables of the model, including the one added, have p-value <0.1. Repeat the analyses for all remained predictors in each step until no other variable could be added.
(7) Calculate the variance inflation factor (VIF) of each variable for the final model and keep those that are less than 10.[14,22]
(8) Calculate Cook's *D* statistic and remove influential observations that have values above 1 and run the regression again.[23]
(9) Conduct a leave-one-out cross-validation (LOOCV) and report LOOCV R^2
(10) Calculate Moran's Index (*I*) of prediction residuals and report *I* and its *p*-value

Our prior experiences (not shown here) demonstrated that constructing our LUR models based on all observations resulted in very large Cook's *D* values (>1), and consequently led to the removal of about 12 observations. These influential sites were outliers and mainly in areas where no population lived (e.g., inside a park or close to a busy highway), therefore we decided to not consider these measurements as these sites do not represent exposure conditions of any population.

Mapping of Alkylbenzenes. Regression mapping of all estimated alkylbenzenes was done according to our previously published method.[14,15] In brief, we mapped the predictions provided by the final regression equations using the Raster Calculator in the ESRI's ArcGIS 10.2.1 for Desktop (ESRI, Redlands, CA).

Spatial Analyses of Predicted Maps. The profile of predicted pollutants over a transect of about 28.4 km from north to south of the city was sampled and plotted at a 5 × 5 m^2 resolution (5681 cells).

In addition, the maps were divided into north to center (advantaged) and south to center (disadvantaged) areas and summary statistics including north vs south min, mean, and maximum concentrations for all pollutants were calculated.

RESULTS

Alkylbenzenes in Tehran. The concentrations of all measured alkylbenzenes were not normally distributed. The annual medians (IQR) for measured pollutants in $\mu g/m^3$ units were as follow: benzene 7.8 (3.6), toluene 23.2 (10.9), ethylbenzene 5.7 (2.3), *p*-xylene 5.6 (1.9), *m*-xylene 10.4 (4.4), *o*-xylene 6.1 (2.7), and Total BTEX 58.6 (24.8) (Table 1). The spearman spatial correlations of measured alkylbenzenes ranged from 0.81 for benzene and *o*-xylene to 0.98 for ethylbenzene and

Table 1. Summary Statistics of Derived Annual Means of Alkylbenzenes ($\mu g/m^3$) over 179 Measurement Sites in Tehran SEPEHR, Tehran, Iran

					percentiles		
	mean	SD	min	max	25th	50th	75th
benzene	8.4	3.3	2.1	25.8	6.3	7.8	9.9
toluene	24.7	10.8	6.1	88.9	17.7	23.2	28.6
ethylbenzene	5.9	2.2	1.4	17.8	4.5	5.7	6.8
p-xylene	5.8	2.1	1.7	16.8	4.6	5.6	6.5
m-xylene	10.9	4.6	2.6	34.7	8.1	10.4	12.5
o-xylene	6.3	2.5	2.1	17.8	4.6	6.1	7.3
total BTEX	61.8	25.0	16.4	195.0	46.0	58.6	70.8

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Table 2. Final Land Use Regression (LUR) Models for Alkylbenzenes in Tehran SEPEHR, Iran

model predictors/response variable	log_benzene[a]	log_toluene[a]	log_ethylbenzene[a]	log_*p*-xylene[a]	log_*m*-xylene[a]	log_*o*-xylene[a]	log_total BTEX[a]
intercept	2.0 (1.0)	3.3 (0.2)	1.4 (0.1)	1.5 (0.1)	2.2 (0.1)	1.6 (0.07)	4.1 (0.19)
all road (50[b])		0.001 (2.5 × $^{-4}$)	9.9 × $^{-4}$ (2.8 × $^{-4}$)				
all road (5000)	2.7 × $^{-7}$ (4.4 × $^{-8}$)	2.6 × $^{-7}$ (5.3 × $^{-8}$)	2.1 × $^{-7}$ (7.7 × $^{-8}$)	1.9 × $^{-7}$ (4.8 × $^{-8}$)	3.6 × $^{-7}$ (5.3 × $^{-8}$)		3.1 × $^{-7}$ (4.6 × $^{-8}$)
ancillary roads (50)	0.001 (2.5 × $^{-4}$)			0.001 (2.7 × $^{-4}$)	0.001 (3.1 × $^{-4}$)	0.002 (3.0 × $^{-4}$)	9.9 × $^{-4}$ (2.9 × $^{-4}$)
arid or undeveloped land use areas (700)				−4.6 × $^{-7}$ (1.6 × $^{-7}$)			
blocks (250)						0.004 (0.001)	
distance to sewage treatment plants	−3.2 × $^{-5}$ (5.7 × $^{-6}$)	−3.9 × $^{-5}$ (7.7 × $^{-6}$)	−3.1 × $^{-5}$ (6.4 × $^{-6}$)	−2.1 × $^{-5}$ (6.2 × $^{-6}$)	−2.7 × $^{-5}$ (7.1 × $^{-6}$)	−2.8 × $^{-5}$ (7.1 × $^{-6}$)	−2.6 × $^{-5}$ (7.0 × $^{-6}$)
distance to agricultural land use areas						2.9 × $^{-5}$ (1.3 × $^{-5}$)	
distance to all bus terminals	−3.1 × $^{-5}$ (1.3 × $^{-5}$)				−4.1 × $^{-5}$ (1.6 × $^{-5}$)		
distance to all bus parking areas				−1.9 × $^{-5}$ (5.9 × $^{-6}$)		−4.1 × $^{-5}$ (8.2 × $^{-6}$)	
distance to educational areas						7.5 × $^{-5}$ (2.8 × $^{-5}$)	
distance to urban facilities land use areas				3.7 × $^{-4}$ (1.3 × $^{-4}$)			
green space land use areas (5000)				−1.2 × $^{-8}$ (5.3 × $^{-9}$)		−1.7 × $^{-8}$ (6.0 × $^{-9}$)	
highways (250)						5.0 × $^{-5}$ (2.4 × $^{-5}$)	
highways (50)	0.001 (3.4 × $^{-4}$)		8.1 × $^{-4}$ (3.6 × $^{-4}$)		0.001 (4.1 × $^{-4}$)		
industrial land use areas (3500)					3.6 × $^{-8}$ (1.7 × $^{-8}$)		
industrial land use areas (5000)			4.6 × $^{-8}$ (1.1 × $^{-8}$)				
log-distance to alleys		0.03 (0.015)					
log-distance to gas filling stores		−0.07 (0.02)					−0.04 (0.02)
log-distance to official/ commercial land use areas							−0.02 (0.009)
log-distance to taxi lines	−0.044 (0.015)	−0.04 (0.014)	−0.05 (0.02)		−0.04 (0.02)		
official/commercial land use areas (2000)		2.2 × $^{-7}$ (3.9 × $^{-8}$)	1.3 × $^{-7}$ (3.4 × $^{-8}$)	1.6 × $^{-7}$ (3.3 × $^{-8}$)	1.7 × $^{-7}$ (3.9 × $^{-8}$)		1.6 × $^{-7}$ (3.6 × $^{-8}$)
official/commercial land use areas (2500)	9.9 × $^{-8}$ (2.4 × $^{-8}$)						
official/commercial land use areas (3500)						1.5 × $^{-7}$ (1.6 × $^{-8}$)	
ratio of alleys in buffer of 5000 m/distance to alleys						−3.1 × $^{-7}$ (1.2 × $^{-7}$)	
ratio of green space areas in buffer of 5000 m/distance to green spaces		−3.6 × $^{-8}$ (1.2 × $^{-8}$)	−2.2 × $^{-8}$ (1.0 × $^{-8}$)	−2.3 × $^{-8}$ (9.7 × $^{-9}$)		−2.7 × $^{-8}$ (1.1 × $^{-8}$)	−2.6 × $^{-8}$ (1.1 × $^{-8}$)
ratio of highways in buffer of 50 m/distance to highways				0.005 (0.002)			0.005 (0.001)
ratio of taxi lines in buffer of 3500 m/distance to taxi lines						2.8 × −6 (1.5 × $^{-6}$)	
residential land use areas (3500)			1.7 × $^{-8}$ (7.7 × $^{-9}$)				
sensitive land use areas (200)						−2.4 × $^{-6}$ (1.3 × $^{-6}$)	
sensitive land use areas (2000)		−6.9 × $^{-8}$ (1.9 × $^{-8}$)			−6.0 × $^{-8}$ (1.8 × $^{-8}$)		−5.5 × $^{-8}$ (1.7 × $^{-8}$)
sensitive land use areas (400)				−8.5 × $^{-7}$ (3.2 × $^{-7}$)			
sensitive land use areas (500)			−6.2 × $^{-7}$ (2.1 × $^{-7}$)				

Table 2. continued

model predictors/response variable	log_benzene[a]	log_toluene[a]	log_ethylbenzene[a]	log_*p*-xylene[a]	log_*m*-xylene[a]	log_*o*-xylene[a]	log_total BTEX[a]
sensitive land use areas (700)	$-3.3 \times ^{-7}$ ($1.1 \times ^{-7}$)						
taxi lines (25)	0.003 (0.001)		0.002 (0.001)		0.003 (0.001)		
taxi lines (50)				0.001 ($2.3 \times ^{-4}$)		0.001 ($3.2 \times ^{-4}$)	0.001 ($2.5 \times ^{-4}$)
transportation land use areas (5000)						$1.3 \times ^{-8}$ ($5.3 \times ^{-9}$)	
urban facilities land use (200)							$-1.9 \times ^{-6}$ ($9.9 \times ^{-7}$)
urban facilities land use (3500)					$-4.6 \times ^{-8}$ ($1.3 \times ^{-8}$)		
model R^2 (adjusted-R^2)	0.70 (0.68)	0.65 (0.63)	0.66 (0.64)	0.64 (0.62)	0.66 (0.64)	0.66 (0.63)	0.66 (0.64)
LOOCV[c] R^2	0.66	0.60	0.61	0.59	0.61	0.59	0.61
root mean square error	0.17	0.21	0.19	0.18	0.2	0.19	0.19
average (maximum) VIF[d]	1.5 (2.4)	1.4 (1.7)	2.1 (5.6)	1.4 (2.3)	1.5 (2.5)	1.5 (1.9)	1.2 (1.5)
maximum *p*-value among all variables for each model	0.02	0.02	0.04	0.02	0.05	0.07	0.06
max Cook's *D*	0.07	0.1	0.08	0.09	0.07	0.09	0.1
Moran's *I* (*p*-value)	0.01 (0.38)	− 0.01 (0.47)	− 0.02 (0.43)	− 0.02 (0.43)	− 0.01 (0.47)	− 0.01 (0.46)	− 0.01 (0.43)

[a]Results displayed are regression coefficient (standard error). [b]Buffer radii in meters units. [c]Leave one out cross-validation; [d]Variance inflation factor. Note that variable "Distance to sewage treatment plants" was present in all models.

m-xylene. Benzene was highly correlated with ethylbenzene (spearman rank correlation = 0.96) (SI, Table S2). Detailed descriptive results can be found elsewhere.[16]

Final LUR Models. All alkylbenzenes were modeled on the log-scale as they were not normally distributed. Overall, 5 observations for toluene and ethylbenzene, 6 for benzene, *p*-xylene, and *m*-xylene, and 7 for *o*-xylene and total BTEX were removed from the data set for modeling. The variable "all roads in buffer of 5000 m" provided the highest adjusted R^2 among all 520 predictors (ranging from 0.35 for *p*-xylene to 0.40 for benzene) and considered as start model for all pollutants except for *o*-xylene where official/commercial area within a 3500 m buffer qualified as variable to start the model (adjusted R^2 = 0.26). In general, across all alkylbenzenes, 38 predictors were present in any of the models with *p*-values ranging from <0.001 up to 0.067. Among them many appeared in the models of several or all alkylbenzenes. Of these, 16 were from land use class, 7 from traffic class, 6 from distance class, 4 from log-distance class, 4 from products class, and 1 from nontraffic class. The distance to sewage treatment plants was the only variable that was present in all models with a negative direction of the effect. Official commercial land use areas in a buffer of 2000 m and the ratio of green space areas in a buffer of 5000 m, and distance to green spaces were present in five out of the six models; ancillary roads in a buffer of 50 m, log-distance to taxi lines, sensitive land use areas in a buffer of 2000 m, and taxi lines in a buffer of 50 m were present in 50% of models (Table 2). Over all, the number of variables in the final models ranged from 9 for benzene to 15 for *o*-xylene. WRF-based variables, emission inventory variables, distance to airport, and distance to gas stations did not contribute to the explanation of long-term variability of alkylbenzenes in Tehran. Our models could explain between 64% (*p*-xylene) and 70% (benzene) of the variance of annual alkylbenzenes in Tehran. The average VIF of variables was less than 2.2 in all models. In 5 out of 6 models, the maximum VIF of individual variables in the models was lower than 3 but in one model (ethylbenzene) it approached 5. One observation in *o*-xylene and one in total BTEX had Cook's *D* values higher than 1 and were thus removed from the respective models. The LOOCV R^2 values ranged from 0.59 for *p*-xylene and *o*-xylene to 0.66 for benzene. The Moran's I values ranged from −0.02 to 0.01 with *p*-values ranging from 0.38 to 0.47 (Table 2).

Regression Mapping. The final LUR models predicted concentrations of benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene, and total BTEX at 24 505 474 cells of Tehran area (Figure 2 and Figures S1 and S2). The predicted concentrations ranged from 1.9 to 29.0 for benzene, 5.5 to 64.4 for toluene, 1.3 to 17.0 for ethylbenzene, 1.5 to 41.0 for *p*-xylene, 2.4 to 44.0 for *m*-xylene, 2.0 to 19.0 for *o*-xylene, and 18.7 to 472.0 $\mu g/m^3$ for total BTEX. The spatial spearman correlations of predicted alkylbenzenes ranged from 0.78 for benzene and *o*-xylene to 0.96 for ethylbenzene and *m*-xylene (Table S3). The agreement of measured versus predicted alkylbenzenes were relatively good (Figure S3).

Spatial Analyses of Predicted Maps. Overall, about 90% of measured sites had benzene concentrations above the air quality standard of 5 $\mu g/m^3$ set by the European Union,[16] and about 83% of Tehran area had predicted benzene concentrations above this value with maximum values up to 29 $\mu g/m^3$. The profile of predicted alkylbenzenes from north to south over a distance of 28.4 km showed that toluene was the dominant pollutant among all alkylbenzenes in Tehran followed by

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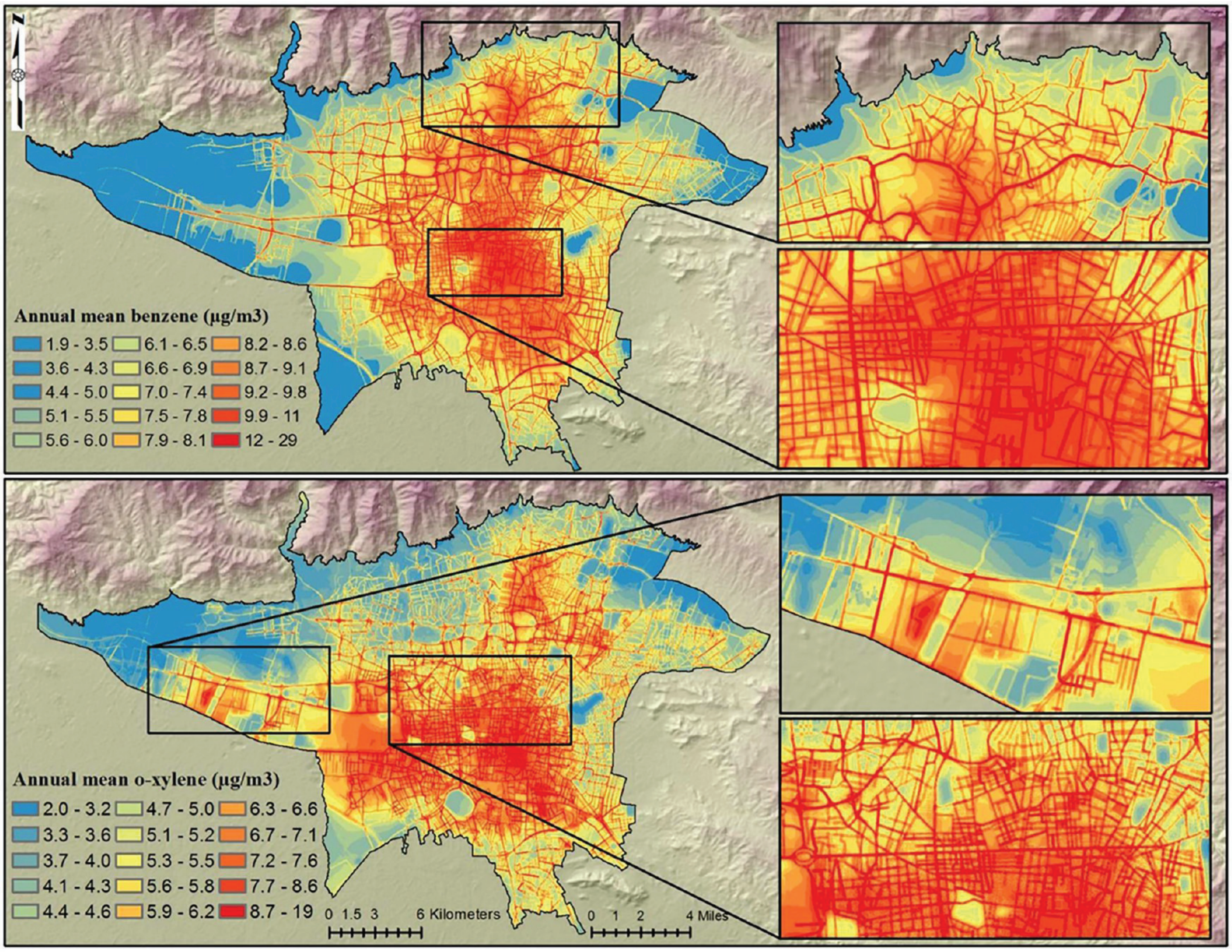

Figure 2. Predicted annual mean concentrations of benzene and *o*-xylene in Tehran SEPEHR, Tehran, Iran. The insets are categorized by quantiles. For ease of interpretation, the first three classes of benzene are shown by blue color indicating areas where annual mean benzene was below 5 $\mu g/m^3$ (an air quality standard used in some countries). Although both pollutants were mainly driven by traffic-related variables, industrial areas, mainly in western part of the city, explained variability of *o*-xylene (top right panel of the *o*-xylene). See Figures S1 and S2 for map of all pollutants. The spatial resolution of maps is 5×5 m^2.

m-xylene, benzene, *o*-xylene, and *p*-xylene. The lowest concentrations of this profile were in the north and the highest in the city center toward south (Figure 3).

Although the maximum concentrations were higher in the wealthier northern to central areas of the city as compared to the disadvantaged southern to central areas (except for toluene and *o*-xylene), the minimum and mean concentrations were somewhat lower for all pollutants in the northern advantaged areas (Table S1 and Figure S4).

■ DISCUSSION

In this study we developed, for the first time, LUR models for alkylbenzenes in a heavily polluted Middle Eastern megacity. To date, there has been no LUR study on alkylbenzenes considering meteorology in the modeling. We further analyzed the spatial variability of the predicted pollutants first over a north south profile and then over north-to-central advantaged versus south-to-center disadvantaged areas of Tehran megacity.

Baldasano and colleagues (1998) tabulated several sources for alkylbenzenes in the ambient air, such as vehicles, gasoline vapor, wastewater treatment, wood combustion, and a range of industrial activities.[8] The LUR studies on VOCs have mainly focused on traffic-related variables and industrial activities as predictors and none have considered the other sources mentioned by Baldasano et al.[8] There are few considerable wood combustion point sources in Tehran but we have included distance to sewage treatment plants as a predictor variable. Interestingly, this predictor was the only one being selected in all LUR models indicating a likely major source of ambient air pollution due to alkylbenzenes. Bell and colleagues (1993) have measured VOCs at various parts of four wastewater treatment plants in Ontario (Canada) and reported very high emissions of VOCs from aeration basins and process vessels, namely 2700 to 3900 g/d or 36 to 50 g/1000 m^3 of wastewater treated, with maximum values of 58 $\mu g/m^3$ for benzene, 1940 $\mu g/m^3$ for toluene, 295 $\mu g/m^3$ for ethylbenzene, 953 $\mu g/m^3$ for (*m*+*p*)-xylene, and 460 $\mu g/m^3$ for *o*-xylene in the off-gas.[24]

As shown in Table S2, and other studies,[11,25,26] benzene is highly spatially correlated with other BTEX species. All LUR studies on alkylbenzenes have modeled at least benzene as a marker of toxic air pollutants. However, Aguilera et al. (2008)

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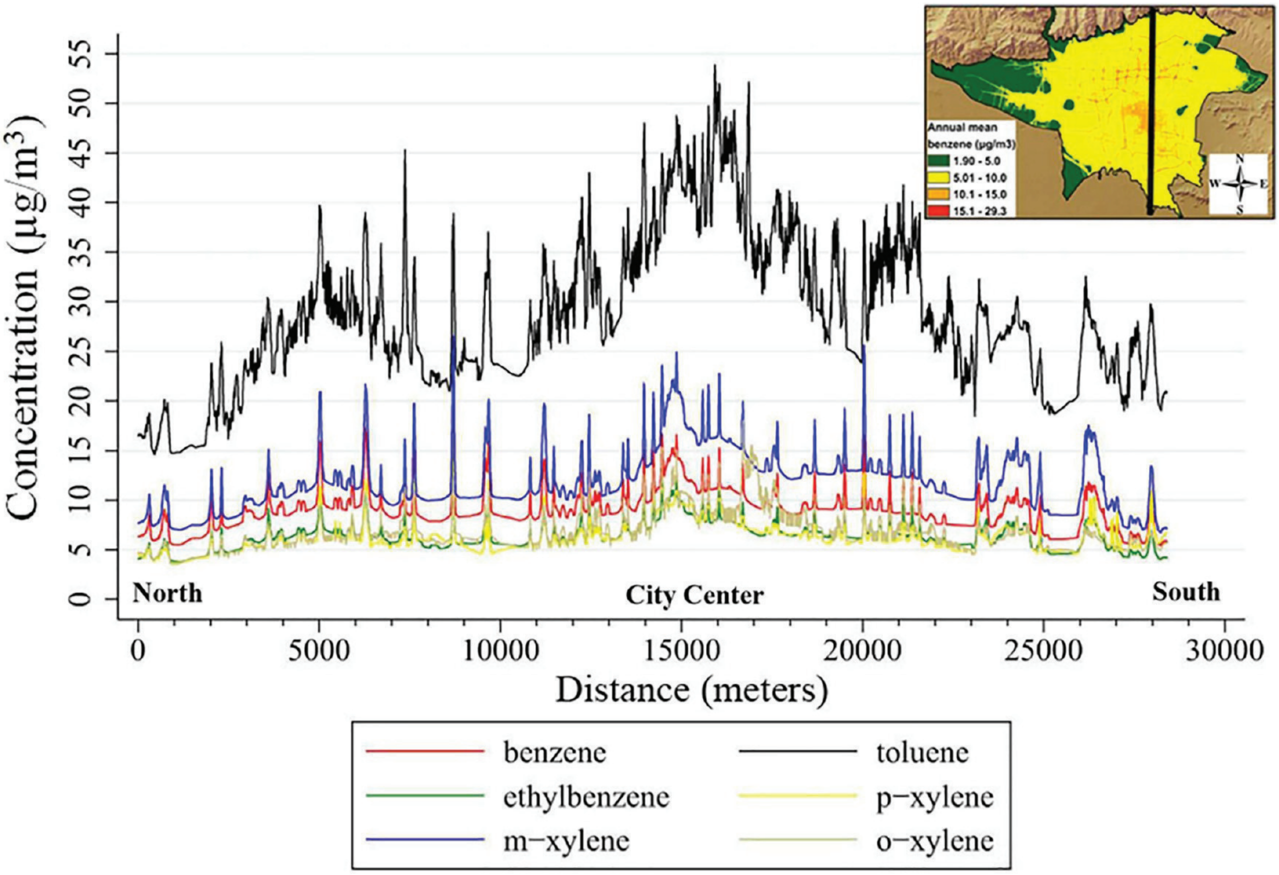

Figure 3. Cross-city concentration profiles of predicted annual mean alkylbenzenes ($\mu g/m^3$) along the transect indicated in the upper right panel by black bar from north to south of Tehran over 28.4 km. As shown, toluene was the predominant pollutant among alkylbenzenes. Spatial peaks all across the profile are mainly caused by main roads or highways. The most polluted area is the city center.

only modeled TBTEX, which is the sum of all BTEX pollutants.[27] Three LUR studies have modeled only benzene, three others modeled all BTEX species, and some others modeled a few VOCs, which could be due to limitations in measurements or the aims and/or interests of the research groups. As we were interested not only in the exposure assessment for epidemiologic research purposes but also in understanding the individual predictors for air quality management and monitoring, we modeled all measured pollutants separately. A few relevant distinctive results were found for Tehran.

The benzene model was mainly driven by surrogates of traffic, such as length of all roads in a buffer of 5000 m, log-distance to taxi lines, ancillary roads in a buffer of 50 m, taxi lines in a buffer of 25 m, and distance to bus terminals. However, distance to sewage treatment plants, official/commercial land use areas, and sensitive areas also explained part of the variability. Previous studies on taxi drivers in central heavily polluted districts of Tehran showed an increased level of chromosome aberration in comparison with taxi drivers of non-polluted areas (in Lahijan city, Iran).[28] This might be associated with the high level of these toxic pollutants in central areas of Tehran and along the major taxi lines (Figure 3). Bus terminals were also explaining long-term variation of criteria air pollutants in our previous analyses[14,15] and need special attention for air quality management given their presence in benzene and *m*-xylene models too. In other contexts, most of the benzene variability has also been explained by traffic-related variables, especially length of roads or highways in small buffer sizes (e.g., 50 to 100 m) but these studies usually have not considered large buffer sizes up to 5000 m.[10,29] Our study suggests that large buffers are needed to explain local annual mean concentrations of benzene in complex situations of a megacity like Tehran. The commercial land use areas both in Tehran (in a buffer of 2500 m) and in Toronto (in a buffer of 2900 m)[10] explained part of the benzene variability. The R^2 values for modeled benzene ranged from 0.43 for Detroit (U.S.A.)[25] to 0.93 for El Paso (U.S.A.).[30] It has been 0.67 in Toronto (population of 2.7 millions) and 0.65 in New York City (population of 8.4 millions) while we reached an R^2 value of 0.70 in Tehran (Table 2).

The predictors of toluene were similar to those of benzene in Tehran but there were some other variables that explained toluene variability, such as log-distance to gas filling stores, log-distance to alleys, and ratio of green space areas in buffer of 5000 m and distance to green spaces. Few LUR studies on VOCs have modeled toluene, with R^2 ranging from 0.31 for Detroit[25] to 0.81 for Sarina (Canada).[11] Some LUR models have reported low to moderate R^2 values for toluene, e.g. 0.41 in Dallas (U.S.A.),[26] 0.46 in Windsor (Canada),[29] and 0.54 in Rome (Italy).[31] However, some studies reported high R^2 values for toluene, e.g., 0.76 in Munich (Germany)[32] and 0.79 in Ottawa (Canada).[9] In Sarnia, in addition to traffic-related variables, toluene was mainly explained by industrial area in a buffer of 2800 m.[11] In Ottawa, National Pollutant Release Inventory

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VOC facility count in a 4 km buffer and National Pollutant Release Inventory toluene facility count in a 8 km buffer explained variability of toluene along with the traffic-related predictors.[9] In Tehran megacity we could explain 65% of toluene spatial variability by the available predictors (Table 2).

The ethylbenzene model in Tehran, in addition to the predictor variables shared with benzene and toluene, had some other explanatory variables. These were industrial land use areas in a buffer of 5000 m and residential land use areas in a buffer of 3500 m. Overall, five LUR studies for VOCs have modeled ethylbenzene.[10,11,25,26,32] The R^2 values of these 5 studies have been 0.40 to 0.63 in seasonal models of Dallas,[26] 0.63 in Detroit,[25] 0.67 in a National Canadian model,[33] 0.79 in Munich,[32] and 0.81 in Sarnia.[11] In the Tehran megacity we could explain 66% of ethylbenzene spatial variability (Table 2). The predictors of ethylbenzene were similar to those of benzene and toluene in other studies.

Overall, four LUR studies for VOCs have developed models for xylenes or (*m*+*p*)-xylene but none has modeled *m*-xylene and *p*-xylene separately.[9,11,25,26] The *m*-xylene and *p*-xylene models in Tehran showed similarity with benzene, toluene, and ethylbenzene models but *o*-xylene behaved a little differently in modeling. It showed the lowest correlation with benzene, with a spearman rank correlation coefficient of 0.81 (Table S2). In fact, not all roads in a buffer of 5000 m but official/commercial land use area in buffer of 3500 m was the starting model for *o*-xylene and three other predictors, namely distance to agricultural land use, block density in a buffer of 250 m, and distance to educational areas, were selected into the final model in addition to predictors shared with other pollutants. Three other studies that modeled *o*-xylene, to date, found R^2 values of 0.37 to 0.60 (seasonal models in Dallas),[26] 0.60 (Detroit),[25] and 0.80 (Sarnia)[11] while we could explain 0.66 of long-term spatial variability in Tehran.

So far four LUR studies on VOCs have developed models for TBTEX.[11,12,25,27] The R^2 values in these studies have been 0.40 for Detroit,[25] 0.70 for New York,[12] 0.74 for Sabadell,[27] and 0.81 for Sarnia,[11] and in Tehran we could explain 0.66 of the variation in the observed values. The predictors of TBTEX were a range of variables mostly shared with other BTEX pollutants.

In light of the Tehran topography and wind patterns, we anticipated weather factors to be potentially influential determinants of the spatial distribution of BTEX. Indeed, our univariate regression analyses showed that maximum adjusted-R^2 for WRF-based predictors ranged from 0.15 for *p*-xylene to 0.21 for toluene. However, in our multivariate spatial models, WRF-based predictors turned out to be sufficiently captured by other main predictors, thus, none of these weather parameters ended up in the final models. To date, no LUR study on VOCs has incorporated long-term meteorological variables in the modeling; however, depending on the availability of spatial data and local conditions, these variables may be relevant predictors in other cities.

Most interestingly, the Tehran VOC emission inventory data did not sufficiently explain spatial variability of any alkylbenzenes to be included in the final models despite significant univariate correlations of several emission inventory data with our measurements. This finding is in contrast to the LUR studies on VOCs in Windsor,[29] Detroit,[25] Ottawa,[9] a National Canadian model,[33] but in line with a NO_2 LUR model in Rome (Italy).[34] The collinearity between emissions and the set of spatial determinants used in our final models may explain this finding. Not to rely on emission inventory data for the spatial modeling of VOCs might be an advantage in cities where those data are not available or where quality of inventories is uncertain.

The average VIF of variables, as a measure of multicollinearity, was less than 2.2 in all models with a maximum VIF of 5.6 for ethylbenzene model. Although there is no consensus in the LUR community about the VIF, we have used a VIF of smaller than 10 as rule of thumb for our modeling as recommended by Kutner et al.[14,22] The Moran's *I* values in our residuals were close to zero, suggesting that our models captured the relevant spatial patterns of average alkylbenzene levels.

Our analyses on differences between wealthier advantaged and poorer disadvantaged areas of Tehran showed somewhat higher concentrations for the latter one. However, on average, these differences are rather small. To better understand the difference in home outdoor exposure between wealthy and disadvantaged people, more specific analyses are needed linking people's residential location and socio-economic status (SES) to our map. This will reveal to what extent SES determines exposure on the local neighborhood scale.

Benzene, as a genotoxic carcinogen has no safe level of exposure and for leukemia, the World Health Organization (WHO) guidelines associate 0.17 $\mu g/m^3$ exposure to airborne benzene with an excess lifetime risk of 1/1 000 000.[35] On the basis of this unit risk, the lifetime exposure to ambient annual mean benzene concentrations in Tehran translates into 49.4 cases per 1 000 000 or about 445 leukemia cases per 9 million residents of Tehran. On the basis of the unit risk used by the U.S. Environmental Protection Agency (7.8×10^{-6} per one $\mu g/m^3$) the estimate for Tehran results in about 600 cases.[36]

We have derived high resolution models of alkylbenzenes in Tehran. These estimates could be used for various health effects studies, urban planning, air quality management, and the monitoring of evidence-based policy making. We have recently systematically reviewed all LUR models for VOCs,[37] and found that this study is the largest to predict all BTEX species in a megacity.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b02238.

Table S1. All 520 variables and respective buffer sizes, assumed direction of the effect, and units derived for the use in LUR models. Table S2. Spatial Spearman correlations of derived annual means. Table S3. The Spearman correlations of predicted annual means. Table S4. Summary statistics of predicted alkylbenzenes concentrations over advantaged (north to center) and disadvantaged (south to center) areas. Figure S1. Predicted annual mean benzene, toluene, and ethylbenzene. Figure S2. Predicted annual mean *p*-xylene, *m*-xylene, *o*-xylene, and total BTEX. Figure S3. The agreement of measured versus predicted concentrations. Figure S4. Predicted annual mean benzene concentrations over advantaged versus disadvantaged areas (PDF)

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Notes

The authors declare the following competing financial interest(s): Vahid Hosseini declares that he is affiliated to Tehran AQCC. The views expressed in this manuscript are those of the authors and do not necessarily reflect the views or policies of the Tehran AQCC. The rest of authors declare that they have no actual or potential financial competing interests.

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Land use regression models for alkylbenzenes in a Middle Eastern megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)

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4 tables

Table S1. All 520 land use variables and respective buffer sizes, assumed direction of the effect, and units derived for the use in land use regression (LUR) models in Tehran SEPEHR, Iran.

Class	Variable	Buffer radii (meters)	Direction	Units
Traffic	All roads	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Highways	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Main roads	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Ancillary roads	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Alleys	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	-	m
Traffic	All bus lines	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Bus rapid transportation (BRT) lines	100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Non-BRT lines	100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Taxi lines	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m
Traffic	Bridges	300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	?	m
Traffic	All bus stops (points)	100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	#
Traffic	BRT stops (points)	500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	#
Traffic	Non-BRT stops (points)	500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	#
Traffic	Taxi stops (points)	500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	#
Traffic	Critical traffic points	1000, 1500, 2000, 2500, 3500, 5000	+	#
Non-traffic	Blocks	25, 50, 100, 125, 200, 250, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	#
Non-traffic	Primary schools (points)	100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	?	#
Non-traffic	High schools (points)	100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	?	#
Population	Population density	500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000	+	#
Land use	Residential land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m^2
Land use	Green space land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	-	m^2
Land use	Urban facilities land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	?	m^2
Land use	Industrial land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m^2
Land use	Official/commercial land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m^2
Land use	Transportation land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	+	m^2
Land use	Sensitive land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	?	m^2
Land use	Agriculture land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	-	m^2
Land use	Arid or undeveloped land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	-	m^2
Land use	Other land use areas	25, 50, 100, 200, 300, 400, 500, 700, 1000, 1500, 2000, 2500, 3500, 5000	?	m^2
Distance	Distance to all roads	Not applicable (NA)	-	m
Distance	Distance to highways	NA	-	m
Distance	Distance to main roads	NA	-	m
Distance	Distance to ancillary roads	NA	-	m

Distance	Distance to alleys	NA	+	m
Distance	Distance to all bus lines	NA	-	m
Distance	Distance to BRT lines	NA	-	m
Distance	Distance to non-BRT lines	NA	-	m
Distance	Distance to taxi lines	NA	-	m
Distance	Distance to bridges	NA	?	m
Distance	Distance to blocks	NA	-	m
Distance	Distance to all bus stops (points)	NA	-	m
Distance	Distance to BRT stops (points)	NA	-	m
Distance	Distance to non-BRT stops (points)	NA	-	m
Distance	Distance to taxi stops (points)	NA	-	m
Distance	Distance to critical traffic points	NA	-	m
Distance	Distance to primary schools (points)	NA	?	m
Distance	Distance to high schools (points)	NA	?	m
Distance	Distance to residential land use areas	NA	-	m
Distance	Distance to green space land use areas	NA	+	m
Distance	Distance to urban facilities land use areas	NA	?	m
Distance	Distance to industrial land use areas	NA	-	m
Distance	Distance to official/commercial land use areas	NA	-	m
Distance	Distance to transportation land use areas	NA	-	m
Distance	Distance to sensitive land use areas	NA	?	m
Distance	Distance to agriculture land use areas	NA	+	m
Distance	Distance to arid or undeveloped land use areas	NA	+	m
Distance	Distance to other land use areas	NA	?	m
Distance	Distance to traffic access control zone	NA	-	m
Distance	Distance to traffic access control zone in critical air pollution episodes	NA	-	m
Distance	Distance to selected gas stations	NA	-	m
Distance	Distance to all gas stations	NA	-	m
Distance	Distance to taxi terminals	NA	-	m
Distance	Distance to all bus parking areas	NA	-	m
Distance	Distance to all bus terminals	NA	-	m
Distance	Distance to bus regional terminals	NA	-	m
Distance	Distance to green space areas	NA	+	m
Distance	Distance to educational areas	NA	+	m
Distance	Distance to airport	NA	?	m

Distance	Distance to ambulance centers	NA	?	m
Distance	Distance to food and vegetable shops	NA	?	m
Distance	Distance to hazardous industrial areas	NA	-	m
Distance	Distance to mosques	NA	+	m
Distance	Distance to sport lands	NA	+	m
Distance	Distance to firefighting centers	NA	?	m
Distance	Distance to garbage collection areas	NA	?	m
Distance	Distance to sewage treatment plants	NA	-	m
Log-distance	Log-distance to all roads	NA	-	-
Log-distance	Log-distance to highways	NA	-	-
Log-distance	Log-distance to main roads	NA	-	-
Log-distance	Log-distance to ancillary roads	NA	-	-
Log-distance	Log-distance to alleys	NA	+	-
Log-distance	Log-distance to all bus lines	NA	-	-
Log-distance	Log-distance to BRT lines	NA	-	-
Log-distance	Log-distance to non-BRT lines	NA	-	-
Log-distance	Log-distance to taxi lines	NA	-	-
Log-distance	Log-distance to bridges	NA	?	-
Log-distance	Log-distance to blocks	NA	-	-
Log-distance	Log-distance to all bus stops (points)	NA	-	-
Log-distance	Log-distance to BRT stops (points)	NA	-	-
Log-distance	Log-distance to non-BRT stops (points)	NA	-	-
Log-distance	Log-distance to taxi stops (points)	NA	-	-
Log-distance	Log-distance to critical traffic points	NA	-	-
Log-distance	Log-distance to primary schools (points)	NA	?	-
Log-distance	Log-distance to high schools (points)	NA	?	-
Log-distance	Log-distance to residential land use areas	NA	-	-
Log-distance	Log-distance to green space land use areas	NA	+	-
Log-distance	Log-distance to urban facilities land use areas	NA	?	-
Log-distance	Log-distance to industrial land use areas	NA	-	-
Log-distance	Log-distance to official/commercial land use areas	NA	-	-
Log-distance	Log-distance to transportation land use areas	NA	-	-
Log-distance	Log-distance to sensitive land use areas	NA	?	-
Log-distance	Log-distance to agriculture land use areas	NA	+	-
Log-distance	Log-distance to arid or undeveloped land use areas	NA	+	-
Log-distance	Log-distance to other land use areas	NA	?	-

Log-distance	Log-distance to traffic access control zone	NA	-	-
Log-distance	Log-distance to traffic access control zone in critical air pollution episodes	NA	-	-
Log-distance	Log-distance to selected gas stations	NA	-	-
Log-distance	Log-distance to all gas stations	NA	-	-
Log-distance	Log-distance to taxi terminals	NA	-	-
Log-distance	Log-distance to all bus parking areas	NA	-	-
Log-distance	Log-distance to all bus terminals	NA	-	-
Log-distance	Log-distance to bus regional terminals	NA	-	-
Log-distance	Log-distance to green space areas	NA	+	-
Log-distance	Log-distance to educational areas	NA	+	-
Log-distance	Log-distance to airport	NA	?	-
Log-distance	Log-distance to ambulance centers	NA	?	-
Log-distance	Log-distance to food and vegetable shops	NA	?	-
Log-distance	Log-distance to hazardous industrial areas	NA	-	-
Log-distance	Log-distance to mosques	NA	+	-
Log-distance	Log-distance to sport lands	NA	+	-
Log-distance	Log-distance to firefighting centers	NA	?	-
Log-distance	Log-distance to garbage collection areas	NA	?	-
Log-distance	Log-distance to sewage treatment plants	NA	-	-
Products	Ratio of all roads in buffer 5000 m/distance to all roads	NA	+	-
Products	Ratio of highways in buffer 50 m/distance to highways	NA	+	-
Products	Ratio of main roads in buffer 5000 m/distance to main roads	NA	+	-
Products	Ratio of ancillary roads in buffer 5000 m/distance to ancillary roads	NA	+	-
Products	Ratio of alleys in buffer 5000 m/distance to alleys	NA	-	-
Products	Ratio of all bus lines in buffer 5000 m/distance to all bus lines	NA	+	-
Products	Ratio of BRT lines in buffer 5000 m/distance to BRT lines	NA	+	-
Products	Ratio of non-BRT lines in buffer 5000 m/distance to non-BRT lines	NA	+	-
Products	Ratio of taxi lines in buffer 3500 m/distance to taxi lines	NA	+	-
Products	Ratio of bridges in buffer 5000 m/distance to bridges	NA	?	-
Products	Ratio of blocks in buffer 5000 m/distance to blocks	NA	+	-
Products	Ratio of all bus stops in buffer 5000 m/distance to all bus stops	NA	+	-
Products	Ratio of BRT stops in buffer 5000 m/distance to BRT stops	NA	+	-
Products	Ratio of non-BRT stops in buffer 5000 m/distance to non-BRT stops	NA	+	-
Products	Ratio of taxi stops in buffer 5000 m/distance to taxi stops	NA	+	-
Products	Ratio of critical traffic points in buffer 3500 m/distance to critical traffic points	NA	+	-

Products	Ratio of primary schools in buffer 5000 m/distance to primary schools	NA	?	-
Products	Ratio of high schools in buffer 5000 m/distance to high schools	NA	?	-
Products	Ratio of residential areas in buffer 5000 m/distance to residential areas	NA	+	-
Products	Ratio of green space areas in buffer 5000 m/distance to green space areas	NA	-	-
Products	Ratio of urban facilities areas in buffer 5000 m/distance to urban facilities areas	NA	?	-
Products	Ratio of industrial areas in buffer 300 m/distance to industrial areas	NA	+	-
Products	Ratio of official/commercial areas in buffer 5000 m/distance to official/commercial areas	NA	+	-
Products	Ratio of transportation areas in buffer 5000 m/distance to transportation areas	NA	+	-
Products	Ratio of sensitive areas in buffer 3500 m/distance to sensitive areas	NA	?	-
Products	Ratio of agriculture areas in buffer 1500 m/distance to agriculture areas	NA	-	-
Products	Ratio of arid or undeveloped areas in buffer 1000 m/distance to arid or undeveloped areas	NA	-	-
Products	Ratio of other land use areas in buffer 2000 m/distance to other land use areas	NA	?	-
Meteorology	WRF min wind speed	NA	?	m/s
Meteorology	WRF max wind speed	NA	?	m/s
Meteorology	WRF average wind speed	NA	?	m/s
Meteorology	WRF min relative humidity	NA	?	%
Meteorology	WRF max relative humidity	NA	?	%
Meteorology	WRF average relative humidity	NA	?	%
Meteorology	WRF min temperature	NA	?	°C
Meteorology	WRF max temperature	NA	?	°C
Meteorology	WRF average temperature	NA	?	°C
Emission	VOC emission inventory	NA	?	Tons/year
Geography	Ground slope in percentage	NA	?	%
Geography	Ground slope in degrees	NA	?	°
Geography	Elevation	NA	?	m

Table S2. Spatial spearman correlations of derived annual means for alkylbenzenes over 179 measurement sites in Tehran SEPEHR, Iran

	Benzene	Toluene	Ethylbenzene	*p*-xylene	*m*-xylene	*o*-xylene	Total BTEX
Benzene	1						
Toluene	0.91	1					
Ethylbenzene	0.96	0.93	1				
p-xylene	0.94	0.92	0.97	1			
m-xylene	0.95	0.92	0.98	0.96	1		
o-xylene	0.81	0.83	0.86	0.91	0.85	1	
Total BTEX	0.95	0.98	0.97	0.97	0.96	0.88	1

Table S3. The Spearman correlations of predicted concentrations of alkylbenzenes in Tehran SEPEHR, Iran

	Benzene	Toluene	Ethylbenzene	*p*-xylene	*m*-xylene	*o*-xylene	Total BTEX
Benzene	1						
Toluene	0.89	1					
Ethylbenzene	0.95	0.93	1				
p-xylene	0.88	0.89	0.92	1			
m-xylene	0.93	0.91	0.96	0.91	1		
o-xylene	0.78	0.81	0.87	0.86	0.84	1	
Total BTEX	0.92	0.95	0.95	0.93	0.94	0.84	1

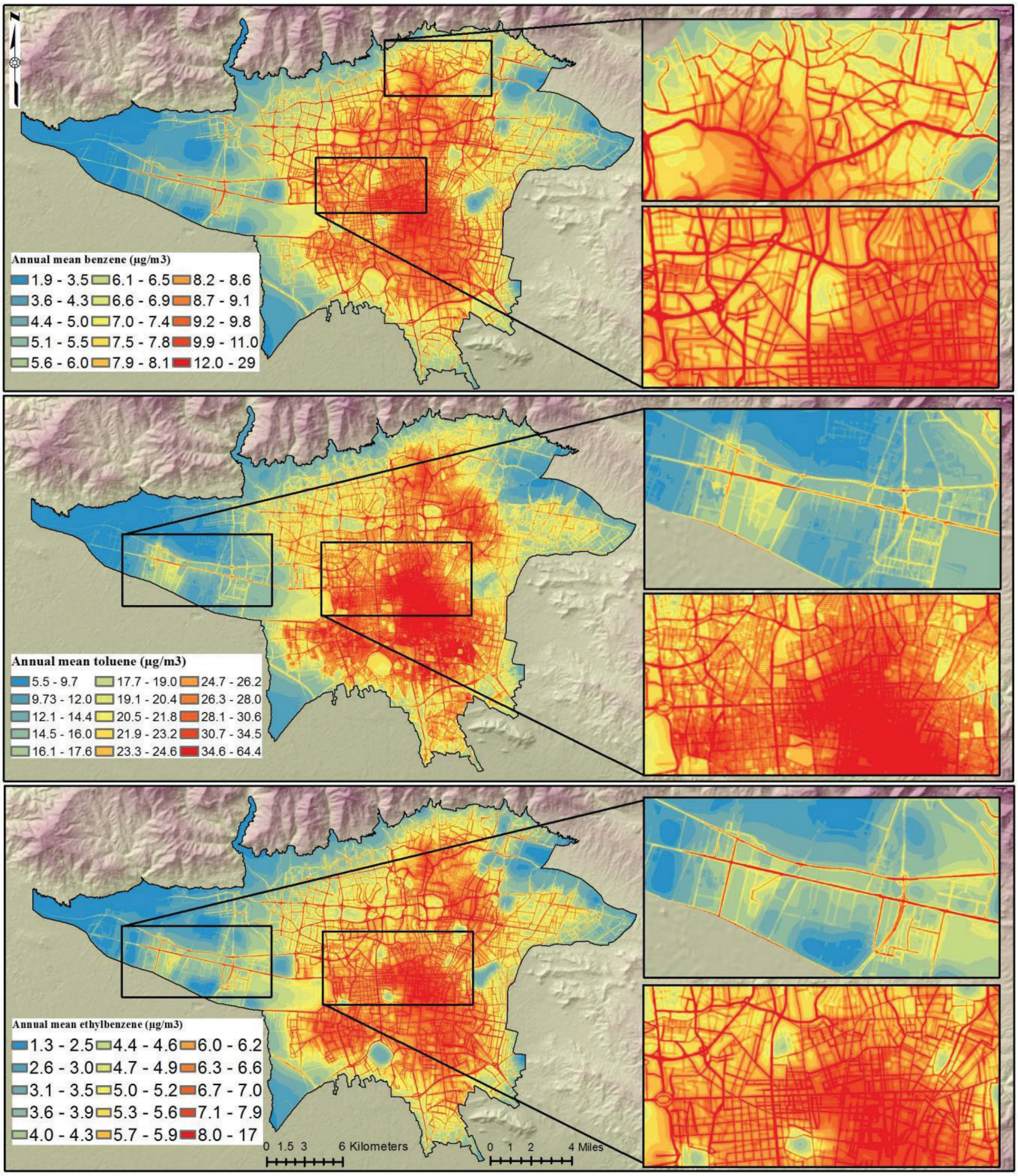

Figure S1. Predicted annual mean benzene, toluene, and ethylbenzene concentrations over Tehran SEPEHR, Iran

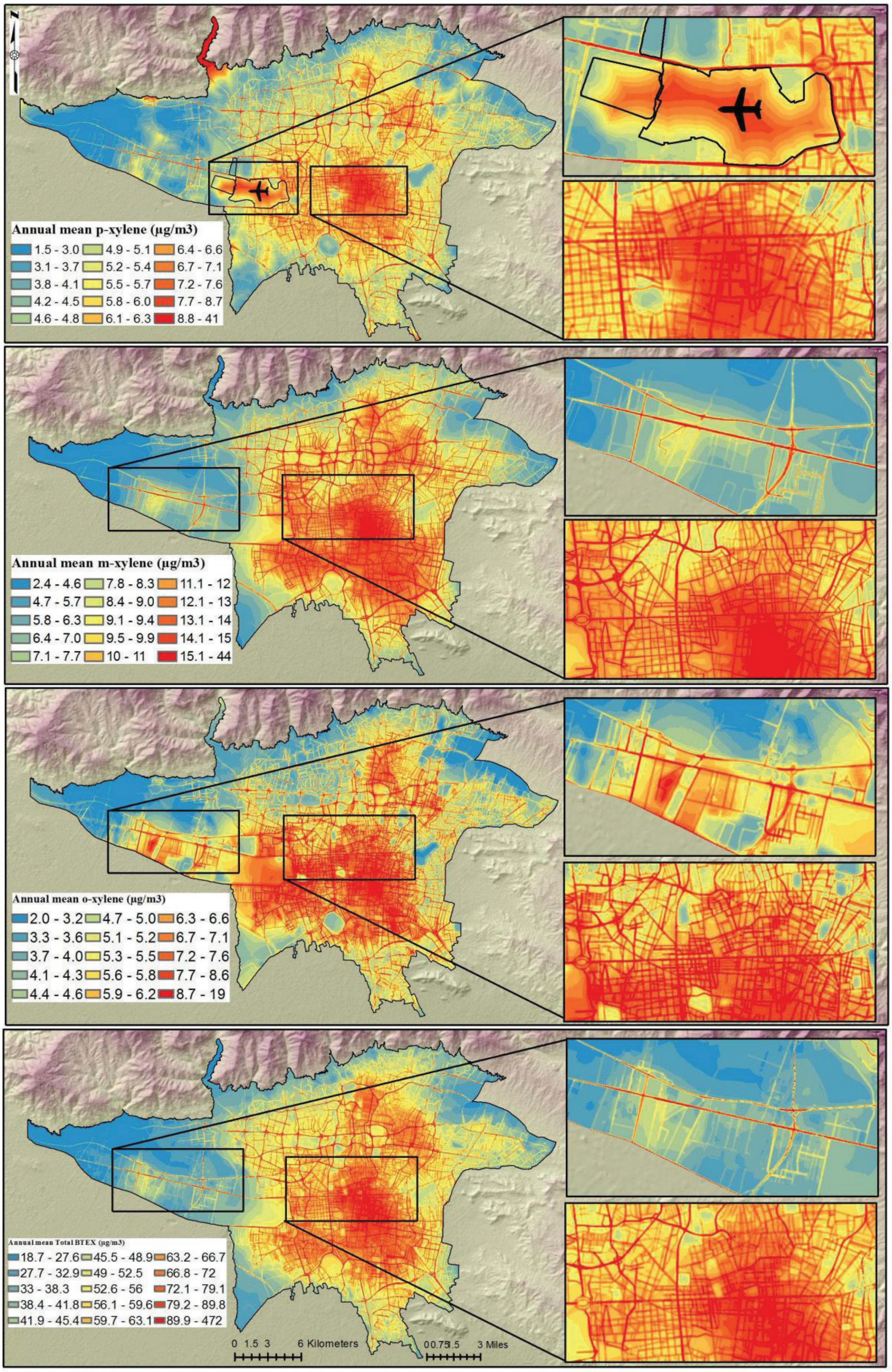

Figure S2. Predicted annual mean p-xylene, m-xylene, o-xylene, and Total BTEX concentrations over Tehran SEPEHR, Iran

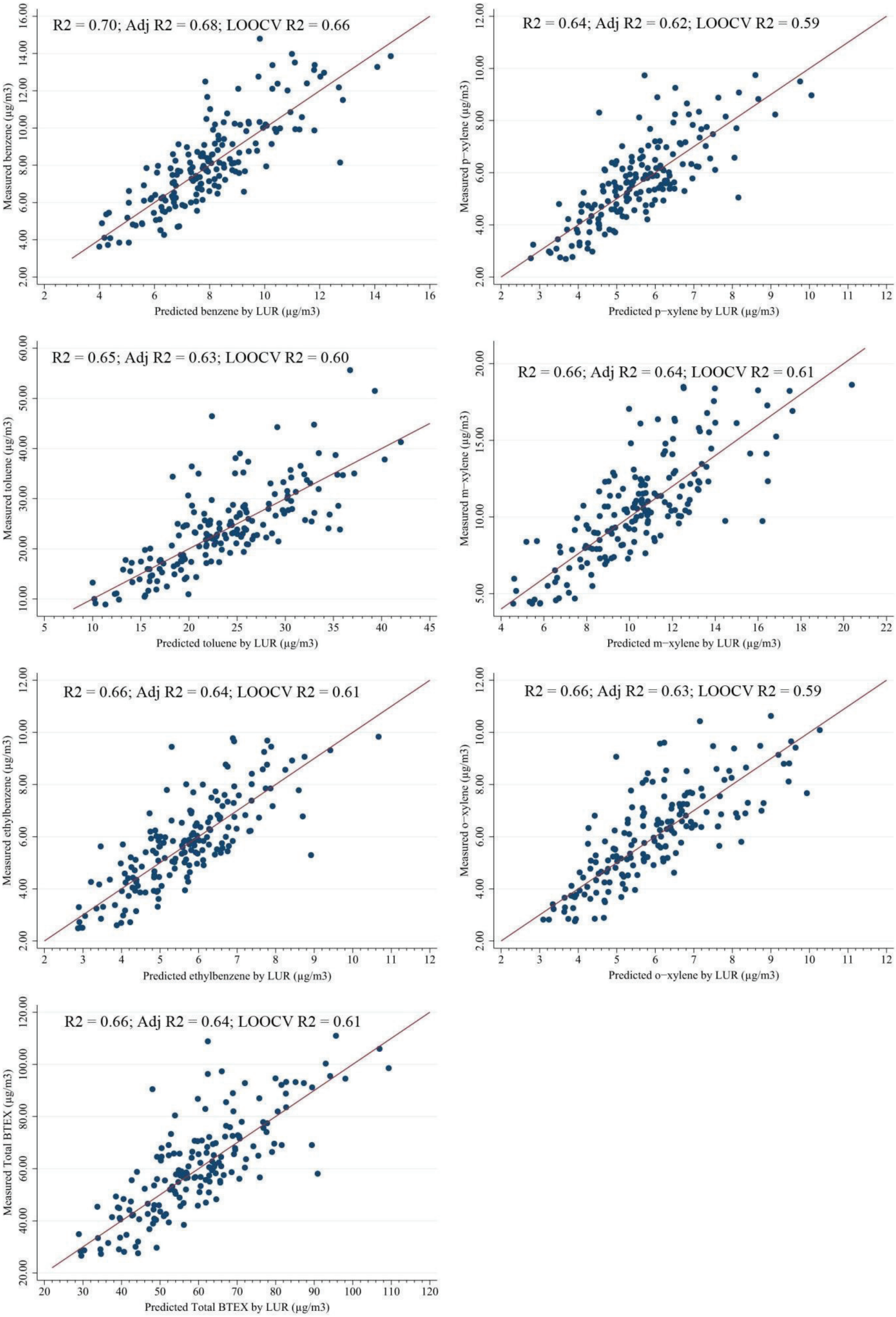

Figure S3. The agreement of measured versus predicted concentrations of alkylbenzenes.

Table S4. Summary statistics of predicted alkylbenzenes concentrations over advantaged (north to center) and disadvantaged (south to center) areas in Tehran SEPEHR

Pollutant	North min	South min	North mean	South mean	North max	South max
Benzene	1.9	2.8	6.8	7.4	29.3	25.9
Toluene	5.5	7.1	19.3	23.8	57.9	64.7
Ethylbenzene	1.3	2.1	4.7	5.5	17.1	16.7
p-xylene	1.5	2.2	5.0	5.7	41.4	30.6
m-xylene	2.4	3.7	8.4	10.4	44.0	42.3
o-xylene	2.0	2.8	4.9	6.4	17.6	19.3
Total BTEX	18.7	22.2	48.8	57.8	471.6	340.4

The cut-off for distinction of southern vs northern areas in Tehran is considered as those below or above the Azadi and Enghelab streets (see Figure S2)

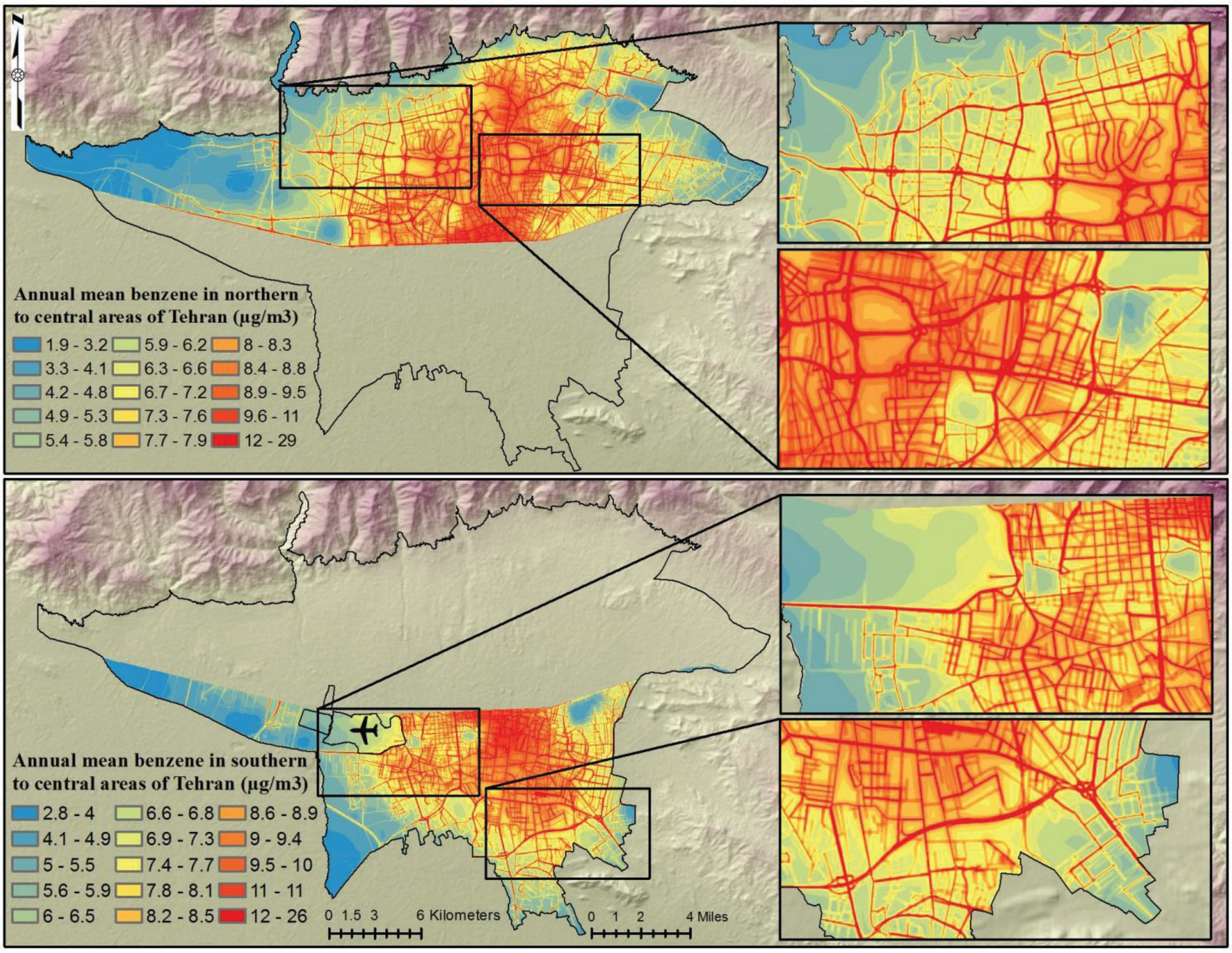

Figure S4. Predicted annual mean benzene concentrations over northern to central advantaged areas versus southern to central disadvantaged areas of Tehran, Iran

Article 5: A systematic review of land use regression models for volatile organic compounds

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Review article

A systematic review of land use regression models for volatile organic compounds

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GRAPHICAL ABSTRACT

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ABSTRACT

Various aspects of land use regression (LUR) models for volatile organic compounds (VOCs) were systematically reviewed. Sixteen studies were identified published between 2002 and 2017. Of these, six were conducted in Canada, five in the USA, two in Spain, and one each in Germany, Italy, and Iran. They were developed for 14 different individual VOCs or groupings: benzene; toluene; ethylbenzene; *m*-xylene; *p*-xylene; (*m/p*)-xylene; *o*-xylene; total BTEX; 1,3-butadiene; formaldehyde; *n*-hexane; total hydro carbons; styrene; and acrolein. The models were based on measurements ranging from 22 sites in El Paso (USA) to 179 sites in Tehran (Iran). Only four studies in Rome (Italy), Sabadell (Spain), Tehran, and Windsor (Canada) met the Cocheo's criterion of having at least one passive sampler per 3.4 km^2 of study area. The range of R^2 values across all models was from 0.26 for 1,3-butadiene in Dallas (USA) to 0.93 for benzene in El Paso. The average R^2 values among two or more studies of the same VOCs were as follows: benzene (0.70); toluene (0.60); ethylbenzene (0.66); (*m/p*)-xylene (0.65); *o*-xylene (0.61); total BTEX (0.66); 1,3-butadiene (0.46); and formaldehyde (0.56). The common spatial predictors of studied VOC concentrations were dominated by traffic-related variables, but they also included proximity to ports in the USA, number of chimneys in Canada, altitude in Spain, northern latitudes in Italy, and proximity to sewage treatment plants and to gas filling stores in Iran. For the traffic-related variables, the review suggests that large buffers, up to 5,000 m, should be considered in large cities. Although most studies reported logical directions of association for predictors, some reported inconsistent results. Some studies included log-transformed predictors while others divided one variable by another. Only six studies provided the p-values of predictors. Future work may incorporate chemistry-transport models, satellite observations, meteorological

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variables, particularly temperature, consider specific sources of aromatic vs aliphatic compounds, or may develop hybrid models. Currently, only one national model has been developed for Canada, and there are no global LUR models for VOCs. Overall, studies from outside North America and Europe are critically needed to describe the wide range of exposures experienced by different populations.

1. Introduction

Approximately 8% of global deaths and 4% of global disability-adjusted life-years (DALYs) were attributed to ambient air pollution in 2015, making it one of the leading modifiable risk factors for the Global Burden of Disease (GBD) worldwide (Cohen et al., 2017). These estimates were based on exposure to particulate matter ≤2.5 μm ($PM_{2.5}$) and ozone (O_3) (Brauer et al., 2016), for ischemic heart disease (IHD), cerebrovascular disease (ischemic stroke and hemorrhagic stroke), lung cancer, chronic obstructive pulmonary disease (COPD), and lower respiratory infections (LRI) (Cohen et al., 2017). The GBD estimates would be considerably higher if more air pollutants and health outcomes where included in the analyses (Amini et al., 2014a). For example, pollutants such as nitrogen dioxide (NO_2) and air toxics have been independently associated with increased risk of morbidity and mortality from the health outcomes already considered (Cesaroni et al., 2013; Filippini et al., 2015; Samoli et al., 2006; Thomas et al., 2014). On the other hand, health outcomes such as leukemia and other cancers (Lavigne et al., 2017; Weichenthal et al., 2017), neurodegenerative diseases (Chen et al., 2017; Heydarpour et al., 2014), and many others have been associated with the air pollutants (Bakian et al., 2015; Künzli et al., 2000; Nhung et al., 2017; Thurston et al., 2017; West et al., 2016).

The GBD estimates are partly influenced by the estimated relative risks extracted from cohort studies on long-term exposure to air pollution (GBD 2015 Risk Factors Collaborators, 2016). The most commonly used exposure assessment method in health outcomes analysis has been land use regression (LUR) (Hoek et al., 2013). Since its introduction in Europe (Briggs et al., 1997), the approach has been extensively used over the last 20 years to estimate the spatial variability in a wide range of pollutants, mainly in high-income countries (HICs) (Beelen et al., 2013, 2014; Dirgawati et al., 2016; Eeftens et al., 2012; Henderson et al., 2007; Raaschou-Nielsen et al., 2013). However, there have also been some studies in low- and middle-income countries (LMICs) (Amini et al., 2014b, 2016; Gurung et al., 2017; Lee et al., 2017; Yang et al., 2017).

Generally, LUR models have been applied to map concentrations of particulate matter and nitrogen oxides and, to a lesser extent, other pollutants, such as volatile organic compounds (VOCs) (Hoek et al., 2008). There are hundreds of VOCs species in ambient air, but they are all characterized by a low boiling point and ready transformation to the gaseous phase (Monks et al., 2009). Important groups of VOCs include: aliphatic alkanes, such as hexane; aromatic alkylbenzenes, such as benzene, toluene, ethylbenzene, and xylenes (BTEX); halogenated hydrocarbons, such as tetrachloromethane; and terpenes, such as carene (Baldasano et al., 1998). To date, most LUR models of VOCs have focused on the aromatic alkylbenzenes, which are ubiquitous in fossil fuels and combustion products (Monks et al., 2009).

One of the largest studies to use LUR for long-term exposure assessment in research on the development of chronic disease is the European Study of Cohorts for Air Pollution Effects (ESCAPE) (Beelen et al., 2013; Eeftens et al., 2012). However, studies such as ESCAPE and the GBD have not used LUR to model VOCs, despite their carcinogenicity (International Agency for Research on Cancer (IARC), 2016; Lipfert, 2017). We see three possible reasons for this. First, most studies in HICs have reported very low concentrations of VOCs in the ambient air (Guerreiro et al., 2014). Second, both $PM_{2.5}$ and O_3 have been consistently useful for predicting the range of health outcomes included in large studies (Brauer et al., 2016; Cohen et al., 2017). Third, study of VOCs has not been a priority for funding agencies, likely due to the first and second points. However, some studies have reported that ambient VOC concentrations are very high within large LMICs cities where large numbers of people are exposed (Amini et al., 2017a; Hoque et al., 2008; Matysik et al., 2010).

There is no evidence of a safe threshold for carcinogenic VOCs (e.g., benzene), and they may contribute to a considerable burden of disease even at concentrations below the current standards (Beelen et al., 2014; Künzli et al., 2015; Kutlar Joss et al., 2017). As such, the exclusion of VOCs from burden of disease studies likely leads to underestimation of the deaths and DALYs attributable to a wide range of cancers, particularly in densely populated and highly exposed LMICs. Based on the evidence to date, one key difference between VOCs and pollutants such as $PM_{2.5}$ or O_3 is the distributions of their ambient concentrations in HICs and LMICs. The burden of disease associated with $PM_{2.5}$ and O_3 also tends to be high in LMICs, but the vast literature from HICs can be used to inform LMICs calculations because there is considerable overlap between the distributions across contexts (Brauer et al., 2016). When it comes to VOCs, however, there appears to be little overlap in the distributions, which is consistent with the nature of pollutants that disperse quickly to the atmosphere. This results in a dearth of literature from highly-studied areas that can be used to inform calculations for highly-exposed areas.

Given (1) the potential burden of disease attributable to VOCs and (2) the limited information about population exposures to VOCs, we have conducted a systematic review of the published LUR models. Many different components of LUR modeling, such as monitoring data, geographic predictors, model development, and validation have been reviewed elsewhere (Hoek et al., 2008; Jerrett et al., 2005; Ryan and LeMasters, 2007), but no other study has focused on VOCs. In this article, we aim to provide a systematic review of LUR models developed for VOCs over the last two decades to summarize different elements of this literature, including: the geographic distribution of published studies; the VOCs modeled; the number of measurement sites used for VOC modeling; air quality data collection methods; VOC pollutant-specific predictor variables; and model evaluation. Finally, we discuss the knowledge gaps and future directions of research in this area.

2. Materials and methods

We searched 12 databases in *The Web of Science*: *Web of Science™ Core Collection*; *Medline®*; *BIOSIS Citation Index℠*; *BIOSIS Previews®*; *Current Contents Connected®*; *Data Citation Index℠*; *Derwent Innovations Index℠*; *Inspect®*; *KCI-Korean Journal Database; Russian Science Citation Index; SciELO Citation Index; and Zoological Record®*. The search phrases and keywords were: Land use regression; LUR; volatile organic compound; VOC; BTEX; benzene; toluene; and xylene. There was no restriction on timespan or language, and the final search was done on August 25, 2017. Only original research articles were retained for the analyses. Studies were only included if they were related to air pollution and they had developed an LUR model for at least one VOC. Studies were excluded if they had only applied VOC estimates from an LUR model described in another publication, or if no full-text was available (e.g. a conference abstract). The references of identified LUR articles on VOCs were also checked to identify any relevant articles missed by the search.

The full-text of all identified articles was reviewed and the following data were extracted: the year of publication; citation; study location (country, city/area, and population size); modeled VOCs; years of

Table 1
Summary of 16 LUR studies published for VOCs up to August 25, 2017.

Country (citation)	City/Domain	Population (Million)	Modeled area (km^2)	# of measured sites	Cocheo's minimum required # of sites[a]	Measurement period	Data source: # of measurement campaigns	# of reference sites (measurement period)[b]	Modeled VOCs[c]	Median (min–max) measured benzene (μg/m^3)
Canada (Wheeler et al., 2008)	Windsor, Ontario	0.2	146	54	43	Feb, May, Aug, and Oct 2004	Passive sampling: four 2-week campaigns	N/A	B, T	0.9 (0.5–1.4)
Canada (Atari and Luginaah, 2009)	Sarnia	0.07	165	39	48	Oct 2005	Passive sampling: one 2-week campaign	N/A	B, T, E, *mp*-X, *o*-X, TBTEX	0.93 (0.3–3.4)
Canada (Su et al., 2010)	Toronto	2.7	630	50	183	Jul 25–Aug 9, 2006	Passive sampling: one 2-week campaign	N/A	B, *n*-H, TH	0.6 (0.4–1.3)
Canada (Hystad et al., 2011)	National	35	9 million	53	N/A	Annual averages for 2006	Fixed-site monitoring data	N/A	B, E, 1,3-B	N/A
Canada (Oiamo et al., 2015)	Ottawa	0.9	2790	42	809	Oct 7–21, 2008 and May 6–20, 2009	Passive sampling: two 2-week campaigns	N/A	B, T, *mp*-X	0.5 (0.3–0.8)
Canada (Poirier et al., 2015)	Halifax	0.3	70% of Halifax population	50	N/A	Oct 20–Nov 3, 2010 and Jan 5–Jan 19, 2011	Passive sampling: two 2-week campaigns	N/A	B, T	0.4 (0.3–2.6)
USA (Smith et al., 2006)	El Paso	0.6	664	22	193	Nov & Dec 1999	Passive sampling: two 1-week campaigns	N/A	B	2.5 (1.6–4.9)
USA (Mukerjee et al., 2009)	Detroit	0.7	370	25	107	Summer 2005	Passive sampling: one 5-week campaign	N/A	B, T, E, *mp*-X, *o*-X, TBTEX, S, 1,3-B	1.5 (1.1–2.2)
USA (Johnson et al., 2010)	New Haven	0.1	52	XX[e]	N/A	Jul–Aug 2001	Pseudo-observations: estimates of modeling based on CMAQ and AERMOD	N/A	B	1.1 (N/A)
USA (Smith et al., 2011)	Dallas	1.3	999	24	290	Aug 1–Sep 5, 2006	Passive sampling: one 5-week campaign	N/A	B, T, E, *o*-X, *mp*-X, 1,3-B	0.7 (0.3–1.3)
USA (Kheirbek et al., 2012)	New York	8.4	789	69[f]	229	March 22–Jun 01, 2011	Passive sampling: five 2-week campaigns	3 (∼2-months)	B, TBTEX, F	0.8 (0.3–2.3)
Spain (Aguilera et al., 2008)	Sabadell	0.2	38	55	11	Apr 2005–March 2006	Passive sampling: four 1-week campaigns	N/A	TBTEX	0.9 (0.4–3.1)
Spain (Fernandez-Somoano et al., 2011)	Asturias	0.1	483	67	140	Jun 2005 and Nov 2005	Passive sampling: two 1-week campaigns	N/A	B	2 (0.04–9.2)
Germany (Carr et al., 2002)	Munich	1.4	310	34	90	Dec 1996–Feb 1998	Passive sampling: twelve 4-week campaigns	N/A	B, T, E	N/A[g] (1.8–14.5)
Italy (Gaeta et al., 2016)	Rome[d]	N/A	64	43	19	May 31–Jun 14, 2011 and Jan 11–25, 2012	Passive sampling: two 2-week campaigns	1 (N/A)	B, T, A, F	2.2 (1.6–2.6)
Iran (Amini et al., 2017b)	Tehran	9	613	179	178	Apr 2015–May 2016	Passive sampling: three 2-week campaigns	5 (∼1-year)	B, T, E, *p*-X, *m*-X, *o*-X, TBTEX	7.8 (2.1–25.8)

[a] Cocheo's minimum required number of sites = 0.29 × study area (in km^2) (Cocheo et al., 2008).
[b] Reference sites are used for temporal variation adjustment in passive sampling campaigns.
[c] Abbreviations or letters denote: B (benzene), T (toluene), E (ethylbenzene), *p*-X (*p*-xylene), *m*-X (*m*-xylene), *o*-X (*o*-xylene), *mp*-X (*m*/*p*-xylene), TBTEX (total benzene, toluene, ethylbenzene, and xylenes), *n*-H (*n*-hexane), TH (total hydrocarbons), 1,3-b (1,3-butadiene), S (styrene), F (formaldehyde), and A (acrolein).
[d] This LUR study has been conducted in the Ciampino Airport area, Rome, Italy.
[e] This study used up to 285 sites for LUR modeling. However, there has been no real measurement and they were pseudo-observations from a hybrid modeling based on CMAQ and AERMOD (Isakov et al., 2012; Johnson et al., 2010).
[f] In this study 14 sites were measured at each campaign resulting in about 70 sites over five consecutive 2-week campaigns.
[g] Site-specific statistics are reported. Median (min-max) for benzene were at 18 traffic sites 8.7 (4.5–14.5) and at 16 school sites 2.6 (1.8–3.8).

Table 2
Details of 16 LUR studies published for VOCs up to August 25, 2017.

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m^3)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
Carr et al. (Carr et al., 2002) Munich (Germany) 34	Benzene	18 traffic sites: 8.7 (4.5–14.5) 16 school sites: 2.6 (1.8–3.8)	0.80/N/A	N/A	N/A	- Traffic counts within 0–50 m (N/A); (N/A) - Traffic counts within 0–300 m (N/A); (N/A) - Traffic counts with high traffic jam percentages (N/A); (N/A)
	Toluene	18 traffic sites: 28.5 (16.3–44.3) 16 school sites: 9.9 (6.0–14.5)	0.76/N/A	N/A	N/A	same as benzene (N/A); (N/A)
	Ethylbenzene	18 traffic sites: 5.6 (3.1–9.0) 16 school sites: 1.9 (1.2–2.7)	0.79/N/A	N/A	N/A	same as benzene (N/A); (N/A)
Smith et al. (Smith et al., 2006) And Mukerjee et al. (2012) (Mukerjee et al., 2012) El Paso (USA) 22 schools	Benzene	2.5 (1.6–4.9)	0.93/N/A	N/A	N/A	- Population density within census block group or set radii (positive); (N/A) - Point source (categorical or continuous) (negative if categorical/positive if continuous); (N/A) - Distance to nearest international border crossing (negative); (N/A)
Aguilera et al. (Aguilera et al., 2008) Sabadell (Spain) 55	Ln(Total BTEX)	17.5 (3.5–34.1)	0.74/N/A	- LOOCV[a] - Leave 15% out	No LOOCV validation R2 reported	- Altitude (negative); (N/A) - Distance to nearest major road (negative); (N/A) - Distance to nearest secondary road (negative); (N/A) - Distance to nearest parking lot (negative); (N/A)
Wheeler et al. (Wheeler et al., 2008) Windsor (Canada) 54	Benzene	0.9 (0.5–1.4)	0.73/N/A	-Leave five sites out from modeling	0.78	- Length of major roads within 100 m (positive); ($p < 0.001$) - Length of expressways and primary highways within 50 m (positive); ($p < 0.001$) - Detroit VOC emission point sources within 4,000 m (positive); ($p < 0.001$) - Windsor VOC emission point sources within 3,000 m (positive); ($p < 0.001$)
	Toluene	2.7 (1.3–6.3)	0.46/N/A	same	0.65	- Distance to Ambassador Bridge (negative); ($p < 0.001$) - Length of major roads within 200 m (positive); ($p = 0.055$) - Length of primary highways within 100 m (positive); ($p = 0.033$) - Windsor VOC emission point sources within 1,000 m (positive); ($p < 0.001$)
Atari et al. (Atari and Luginaah, 2009) Sarnia (Canada) 39	Benzene	0.93 (0.3–3.4)	0.78/0.76	-LOOCV -Leave 10%, 20%, and 50% out	0.75–0.81	- Industry 1,600 m (positive); (N/A) - Dwelling 1,200 m (positive); (N/A) - Highway 800 m (positive); (N/A)
	Toluene	2.6 (0.8–6.9)	0.81/0.79	same	0.77–0.86	- Industry 2,800 m (positive); (N/A) - Open 600 m (negative); (N/A) - Highway 800 m (positive); (N/A)
	Ethylbenzene	0.5 (0.1–1.1)	0.81/0.79	same	0.79–0.86	- Industry 2,600 m (positive); (N/A) - Dwelling 1,400 m (positive); (N/A) - Highway 800 m (positive); (N/A)
	(*m*/*p*) xylene	1.2 (0.4–2.8)	0.80/0.78	same	0.78–0.81	- Industry 1,600 m (positive); (N/A) - Dwelling 1,200 m (positive); (N/A) - Highway 800 m (positive); (N/A)
	o -xylene	0.5 (0.1–1.2)	0.80/0.78	same	0.77–0.79	- Industry 1,600 m (positive); (N/A) - Dwelling 1,200 m (positive); (N/A) - Highway 800 m (positive); (N/A)

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Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m³)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
	Total BTEX	5.7 (1.8–14.5)	0.81/0.79	same	0.80–0.84	- Industry 2,500 m (positive); (N/A) - Dwelling 1,400 m (positive); (N/A) - Highway 900 m (positive); (N/A)
Mukerjee et al. (2009) (Mukerjee et al., 2009) And Mukerjee at al. (2012) (Mukerjee et al., 2012) Detroit (USA) 25 schools	Ln(Benzene)	1.5 (1.1–2.2)	0.43/N/A	Leave two sites out from modeling	N/A	- Distance to nearest medium traffic road (negative); (N/A) - Traffic intensity within 1,000 m (negative); (N/A) - Population density within 500 m (positive); (N/A) - Distance(m) to nearest large Manganese emission source (negative); (N/A) - Distance to nearest international border crossing (positive); (N/A)
	Ln (Toluene)	6.10 (0.4–8.6)	0.31/N/A	same	N/A	- Distance(m) to nearest large Manganese emission source (negative); (N/A) - Distance to nearest international border crossing (positive); (N/A)
	Ln (Ethylbenzene)	0.8 (0.5–1.6)	0.63/N/A	same	N/A	- Log-distance to nearest medium traffic road (negative); (N/A) - Distance to nearest high traffic road (negative); (N/A) - Log-traffic intensity within 1,000 m of location (negative); (N/A) - Distance (m) to nearest large VOC emission source (negative); (N/A) - Log(distance to nearest large Manganese emission source) (negative); (N/A) - Distance to nearest border crossing (positive); (N/A)
	Ln (*m*/*p*-xylene)	2.7 (1.6–5.3)	0.55/N/A	same	N/A	- Distance to nearest medium traffic road (negative); (N/A) - Distance to nearest high traffic road (negative); (N/A) - Traffic intensity within 1,000 m of location (negative); (N/A) - Log(distance) to nearest large VOC emission source (negative); (N/A) - Distance to nearest large PM2.5 emission source (positive); (N/A) - Log(distance to nearest large Manganese emission source) (negative); (N/A) - Distance to nearest international border crossing (negative); (N/A)
	Ln (*o*-xylene =	0.90 (0.5–1.5)	0.60/N/A	same	N/A	- Log-distance to nearest medium traffic road (negative); (N/A) - Distance to nearest high traffic road (negative); (N/A) - Log-population density within 500 m (positive); (N/A) - Distance to nearest large VOC emission source (negative); (N/A) - Log-distance to nearest large PM2.5 emission source (positive); (N/A) - Log(distance to nearest large Manganese emission source) (negative); (N/A) - Distance to nearest international border crossing (positive); (N/A)
	Ln (Total BTEX)	2.81 (1.95–4.11) in ppb units	0.40/N/A	same	N/A	- Distance to nearest medium traffic road (negative); (N/A)

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Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m^3)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
						- Log(distance to nearest large Manganese emission source) (negative); (N/A)
	Ln (styrene)	0.1 (0.1–0.3)	0.43/N/A	same	N/A	- Distance to nearest moderate traffic road (positive); (N/A) - Distance to nearest high traffic road (negative); (N/A) - Traffic intensity within 1,000 m of location (positive); (N/A) - Population density within 500 m (positive); (N/A) - Distance(m) to nearest large Manganese emission source (negative); (N/A) - Distance to nearest international border crossing (negative); (N/A)
	Ln (1,3-butadiene)	3.5 (2.5–6.5)	0.43/N/A	same	N/A	- Log-distance to nearest moderate traffic road (negative); (N/A) - Traffic intensity within 1,000 m of location (positive); (N/A) - Population density within 500 m (positive); (N/A) - Log-distance to nearest large VOC emission source (positive); (N/A) - Log-distance to nearest large PM2.5 emission source (negative); (N/A) - Distance(m) to nearest large Manganese emission source (negative); (N/A) - Distance to nearest international border crossing (positive); (N/A)
Johnson et al. (Johnson et al., 2010) New Haven (USA) 25–285[b]	Benzene	1.1 (N/A – N/A)	N/A/ 0.67–0.89	-LOOCV -Hold out 33 to 293 sites	No LOOCV validation R2 reported; Hold-out R2 = 0.21–0.71	- Traffic intensity (N/A); (N/A) - Proximity to roadways (N/A); (N/A) - Proximity to ports of harbors (N/A); (N/A) - Proximity to industrial sources (N/A); (N/A)
Su et al. (Su et al., 2010) Toronto (Canada) 50	Ln(Benzene)	0.6 (0.4–1.3)	0.67/N/A	bootstrap (in total 18 bootstrap models applied)	No bimodal shape was presented for predictors coefficients	- Expressway in 100 m (positive); (N/A) - Major road in 50 m (positive); (N/A) - Commercial land use in 2,900 m (positive); (N/A) - Industrial in 1,200 m (positive); (N/A)
	Ln(*n*-hexane)	1.0 (0.7–3.3)	0.68/N/A	same	same	- Local road in 50 m (negative); (N/A) - Industrial in 1,200 m (positive); (N/A) - Open land use area in 50 m (negative); (N/A) - Number of chimneys in 2050 m (positive); (N/A) - Population Density in 1,150 m (positive); (N/A) - Soil brightness in 1,650 m (positive); (N/A)
	Ln(Total hydrocarbons)	25.6 (17.1–77.5)	0.66/N/A	same	same	- Industrial in 1,200 m (positive); (N/A) - Open land use area in 50 m (negative); (N/A) - Open land use area in 1,200 m (negative); (N/A) - Number of chimneys in 2050 m (positive); (N/A) - Soil brightness in 1,650 m (positive); (N/A)
Fernandez-Somoano et al. (Fernandez-Somoano et al., 2011) Asturias (Spain) 67	Ln(Benzene)	2 (0.04–9.2)	0.73/N/A	LOOCV	0.71	- Altitude (negative); (N/A) - Continuous urban land cover in 300 m (negative); (N/A) - Agriculture/forest land cover in 300 m (negative); (N/A) - Distance to nearest road (positive); (N/A) - Discontinuous urban land cover in 1,000 (positive); (N/A)
Hystad et al. (Hystad et al., 2011) National (Canada) 53	Benzene	N/A (N/A – N/A)	0.62/N/A	LOOCV Bootstrap	0.12; Normal distribution for predictors coefficients	- Major road length in 10 km (positive); ($p < 0.001$) - National Pollutant Release Inventory (NPRI) emissions in 10 km (positive); ($p < 0.001$)
	Ethylbenzene	N/A (N/A – N/A)	0.67/N/A	same		- Population in 10 km (positive); ($p < 0.001$)

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Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m^3)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
					Normal distribution for predictors coefficients	- NPRI emissions in 2 km (positive); ($p < 0.001$)
	1,3-Butadiene	N/A (N/A – N/A)	0.68/N/A	same	Normal distribution for predictors coefficients	- Road length in 750 m (positive); ($p < 0.001$) - Highway in 500 m (positive); ($p = 0.002$) - Commercial land use area in 10 km (positive); ($p = 0.01$)
Smith et al. (Smith et al., 2011) Dallas (USA) 24 fire stations (models are for summer and winter, respectively)	Benzene	0.7 (0.3–1.3)	0.72/N/A	N/A	N/A	- Distance to nearest road with 10,000 < traffic volume < 20,000 vehicles per day (negative); (N/A) - Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (positive); (N/A) - Traffic intensity within 1,000 m (positive); (N/A)
	Benzene	1.2 (0.8–1.7)	0.49/N/A	N/A	N/A	- Distance to nearest road with 10,000 < traffic volume < 20,000 vehicles per day (positive); (N/A) - Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Traffic intensity within 1,000 m (positive); (N/A)
	Ln (Toluene)	2 (0.6–4.3)	0.41/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Distance to source with NOx emissions > 570,000 lbs per year (negative); (N/A) - Distance to source with 21,000 < NOx emissions < 221,000 lbs per year (positive); (N/A)
	Ln (Toluene)	2.3 (0.9–6.6)	0.41/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Distance to source with NOx emissions > 570,000 lbs per year (negative); (N/A) - Distance to source with 21,000 < NOx emissions < 221,000 lbs per year (negative); (N/A)
	Ln (Ethylbenzene)	0.4 (0.1–0.8)	0.63/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Traffic intensity within 1,000 m (negative); (N/A) - Distance to source with benzene emissions > 270,000 lbs per year (negative); (N/A) - Distance to source with NOx emissions > 570,000 lbs per year (positive); (N/A) - Distance to source with 21,000 < NOx emissions < 221,000 lbs per year (negative); (N/A)
	Ln (Ethylbenzene)	0.4 (0.2–1.3)	0.40/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Traffic intensity within 1,000 m (positive); (N/A) - Distance to source with benzene emissions > 270,000 lbs per year (negative); (N/A) - Distance to source with NOx emissions > 570,000 lbs per year (positive); (N/A)

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Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m^3)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
						- Distance to source with 21,000 < NOx emissions < 221,000 lbs per year (negative); (N/A)
	Ln (*o*-xylene)	0.4 (0.1–0.9)	0.46/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Distance to source with benzene emissions > 270,000 lbs per year (negative); (N/A) - Distance to source with NOx emissions > 570 000 lbs per year (positive); (N/A)
	Ln (*o*-xylene)	0.4 (0.2–1.2)	0.37/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Distance to source with NOx emissions > 570,000 lbs per year (negative); (N/A)
	Ln(*m*/*p*-xylene)	1.1 (0.4–2.7)	0.71/N/A	N/A	N/A	- Distance to nearest road with 10,000 < traffic volume < 20,000 vehicles per day (positive); (N/A) - Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (positive); (N/A) - Traffic intensity within 1,000 m (positive); (N/A) - Distance to source with benzene emissions > 270 000 lbs per year (negative); (N/A) - Ln (Distance to source with ethylbenzene emissions > 4,400 lbs per year) (positive); (N/A) -Distance to source with NOx emissions > 570,000 lbs per year (positive); (N/A)
	Ln(*m*/*p*-xylene)	1.1 (0.4–3.9)	0.40/N/A	N/A	N/A	- Distance to nearest road with 10,000 < traffic volume < 20,000 vehicles per day (positive); (N/A) - Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (positive); (N/A) - Traffic intensity within 1,000 m (positive); (N/A) - Distance to source with benzene emissions > 270,000 lbs per year (negative); (N/A) - Ln (Distance to source with ethylbenzene emissions > 4,400 lbs per year) (positive); (N/A) - Distance to source with NOx emissions > 570,000 lbs per year (positive); (N/A)
	Ln(1,3-butadiene)	3.6 (1.9–7.5)	0.26/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A) - Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Distance to source with benzene emissions > 270,000 lbs per year (negative) - Distance to source with 21,000 < NOx emissions < 221,000 lbs per year (negative)
	Ln(1,3-butadiene)	5.8 (2.4–15.7)	0.40/N/A	N/A	N/A	- Distance to nearest road with 70,000 < traffic volume < 80,000 vehicles per day (negative); (N/A)

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Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m^3)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
						- Distance to nearest road with 100,000 < traffic volume < 120,000 vehicles per day (negative); (N/A) - Distance to source with benzene emissions > 270 000 lbs per year (negative); (N/A) - Distance to source with 21,000 < NOx emissions < 221,000 lbs per year (negative); (N/A)
Kheirbek et al. (Kheirbek et al., 2012) New York City (USA) 67–69 (14 sites at each campaign)	Benzene	0.8 (0.3–2.3)	0.65/N/A	Build model by 85% of observations and test the remaining 15% for validation	0.62	- Number of traffic signals within 400 m (positive); ($p < 0.001$) - Length of interstate, state, and county highways within 100 m (positive); ($p < 0.001$) - Reference site mean (positive); ($p = 0.022$)
	Total BTEX	4.7 (1.5–20.4)	0.70/N/A	same	0.65	- Number of signals within 450 m (positive); ($p < 0.001$) - Kernel-weighted smooth of solvent-based industry locations in 500 m (positive); ($p < 0.001$) - Reference site mean (positive); ($p = 0.01$)
	Formaldehyde	2.2 (1.2–3.7)	0.83/N/A	same	0.68	- Reference site mean (positive); ($p < 0.001$) - Number of signals within 400 m (positive); ($p < 0.001$) - Road length within 100 m (positive); ($p < 0.001$) - Built space within 100 m (positive); ($p = 0.001$)
Oiamo et al. (Oiamo et al., 2015) Ottawa (Canada) 41–42	Benzene	0.5 (0.3–0.8)	0.78/N/A	Bootstrap	Stable predictors coefficients	- Population in 2,500 m (positive); ($p < 0.001$) - Length of highway in 300 m (positive); ($p < 0.01$) - NPRI VOC facility count in 4 km (positive); ($p < 0.01$) - Distance to National Pollutant Release Inventory VOC facility (negative); ($p < 0.05$) - Intersection count in 100 m (positive); ($p < 0.01$)
	Toluene	1.8 (0.5–5.1)	0.79/N/A	same	One variable was unstable	- Area of parks/open space in 1,200 m (negative); ($p < 0.01$) - Length of highway in 350 m (positive); ($p < 0.01$) - National Pollutant Release Inventory VOC facility count in 4 km (positive); ($p < 0.01$) - National Pollutant Release Inventory toluene facility count in 8 km (positive); ($p < 0.05$) - Intersection count in 100 m (positive); ($p < 0.05$)
	m/p -xylene	0.7 (0.2–1.3)	0.75/N/A	same	One variable was unstable	- Area of parks/open space in 1,400 m (negative); ($p < 0.001$) - Length of highway in 350 m (positive); ($p < 0.01$) - Intersection count in 100 m (positive); ($p < 0.01$) - National Pollutant Release Inventory VOC facility count in 4 km (positive); (N/A)
Poirier et al. (2015) (Poirier et al., 2015) Halifax Regional Municipality (Canada) 50	Benzene	0.4 (0.3–2.6)	0.61/N/A	N/A	N/A	N/A
	Toluene	0.4 (0.2–1.1)	0.63/N/A	N/A	N/A	N/A
Gaeta et al. (Gaeta et al., 2016) The Ciampino Airport, Rome (Italy) 39–43	Benzene	2.2 (1.6–2.6)	0.57/0.53	LOOCV	0.50	- The North latitude (positive); ($p < 0.05$) - Product of traffic intensity of the nearest road and the inverse of distance to the nearest road (positive); ($p < 0.05$) - Number of inhabitants in a 100 m buffer (positive); ($p < 0.05$)
	Toluene	5.8 (3.4–7.3)	0.54/0.50	same	0.40	- The North latitude (positive); ($p < 0.05$)

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Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m³)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
						- Product of traffic intensity of the nearest road and the inverse of distance to the nearest road (positive); ($p < 0.05$) - Number of inhabitants in a 100 m buffer (positive); ($p < 0.05$)
	Acrolein	2.8 (2.6–4.1)	0.55/0.51	same	0.50	- Number of inhabitants in a 100 m buffer (positive); ($p < 0.05$) - Traffic intensity of the nearest major road (positive); ($p < 0.05$) - Traffic intensity of the nearest road (positive); ($p < 0.05$) - Aircraft contribution to HC concentration (positive); ($p < 0.05$)
	Formaldehyde	2.7 (2.4–2.9)	0.29/0.24	same	0.13	- The North latitude (negative); ($p < 0.05$) - Number of inhabitants in a 500 m buffer (positive); ($p < 0.05$) - Traffic intensity of the nearest major road (positive); ($p < 0.05$)
Amini et al. (Amini et al., 2017b) Tehran (Iran) 179	Ln (Benzene)	7.8 (2.1–25.8)	0.70/0.68	LOOCV	0.66	- All road (5,000) (positive); ($p < 0.02$) - Distance to sewage treatment plants (negative); ($p < 0.02$) - Ancillary roads (50) (positive); ($p < 0.02$) - Highways (50) (positive); ($p < 0.02$) - Taxi lines (25) (positive); ($p < 0.02$) - Log-distance to taxi lines (negative); ($p < 0.02$) - Distance to all bus terminals (negative); ($p < 0.02$) - Sensitive land use areas (700) (negative); ($p < 0.02$) - Official/commercial land use areas (2,500) (positive); ($p < 0.02$)
	Ln (Toluene)	23.2 (6.1–88.9)	0.65/0.64	same	0.60	- All road (50) (positive); ($p < 0.02$) - Log-distance to alleys (positive); ($p < 0.02$) - Log-distance to taxi lines (positive); ($p < 0.02$) - Log-distance to gas filling stores (positive); ($p < 0.02$) - Official/commercial land use areas (2000) (positive); ($p < 0.02$) - All road (5,000) (positive); ($p < 0.02$) - Product of green space areas in buffer 5,000 m/distance to green spaces (negative) - Distance to sewage treatment plants (negative); ($p < 0.02$) - Sensitive land use areas (2000) (negative); ($p < 0.02$)
	Ln (Ethylbenzene)	5.7 (1.4–9.8)	0.66/0.64	same	0.61	- Taxi lines (25) (positive); ($p < 0.05$) - Log-distance to taxi lines (negative); ($p < 0.05$) - Official/commercial land use areas (2000) (positive); ($p < 0.05$) - Residential land use areas (3,500) (positive); ($p < 0.05$) - All road (5,000) (positive); ($p < 0.05$) - Product of green space areas in buffer 5,000 m/distance to green spaces (negative); ($p < 0.05$) - Distance to sewage treatment plants (negative); ($p < 0.05$) - Industrial land use areas (5,000) (positive); ($p < 0.05$) - Sensitive land use areas (500); ($p < 0.05$) - Highways (50) (positive); ($p < 0.05$)

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Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m^3)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
						- All road (50); ($p < 0.05$)
	Ln (*p*-xylene)	5.6 (1.7–16.8)	0.64/0.62	same	0.59	- Taxi lines (50) (positive); ($p < 0.02$) - Ancillary roads (50) (positive); ($p < 0.02$) - Product of highways in buffer 50 m/distance to highways (positive); ($p < 0.02$) - Green space land use areas (5,000) (negative); ($p < 0.02$) - Official/commercial land use areas (2000) (positive); ($p < 0.02$) - Distance to all bus parking areas (negative); ($p < 0.02$) - All road (5,000) (positive); ($p < 0.02$) - Distance to sewage treatment plants (negative); ($p < 0.02$) - Product of green space areas in buffer 5,000 m/distance to green spaces (negative); ($p < 0.02$) - Distance to urban facilities land use areas (positive); ($p < 0.02$) - Arid or undeveloped land use areas (700) (negative); ($p < 0.02$) - Sensitive land use areas (400) (negative); ($p < 0.02$)
	Ln (*m*-xylene)	10.4 (2.6–34.7)	0.66/0.64	same	0.61	- Ancillary roads (50) (positive); ($p < 0.05$) - Highways (50) (positive); ($p < 0.05$) - Taxi lines (25) (positive); ($p < 0.05$) - Log-distance to taxi lines (negative); ($p < 0.05$) - Official/commercial land use areas (2000) (positive); ($p < 0.05$) - Distance to sewage treatment plants (negative); ($p < 0.05$) - All road (5,000) (positive); ($p < 0.05$) - Industrial land use areas (3,500) (positive); ($p < 0.05$) - Distance to all bus terminals (negative); ($p < 0.05$) - Urban facilities land use (3,500) (negative); ($p < 0.05$) - Sensitive land use areas (2000) (negative); ($p < 0.05$)
	Ln (*o*-xylene)	6.1 (2.1–17.8)	0.66/0.63	same	0.59	- Taxi lines (50) (positive); ($p < 0.05$) - Ancillary roads (50) (positive); ($p < 0.05$) - Blocks (250) (positive); ($p < 0.05$) -Transportation land use areas (5,000) (positive); ($p < 0.05$) - Official/commercial land use areas (3,500) (positive); ($p < 0.05$) - Green space land use areas (5,000) (negative); ($p < 0.05$) - Sensitive land use areas (200) (negative); ($p = 0.067$) - Product of green space areas in buffer 5,000 m/distance to green spaces (negative); ($p < 0.05$) - Distance to sewage treatment plants (negative); ($p < 0.05$) - Product of taxi lines in buffer 3,500 m/distance to taxi lines (positive); ($p = 0.066$) - Distance to agricultural land use areas (positive); ($p < 0.05$) - Product of alleys in buffer 5,000 m/distance to alleys (positive); ($p < 0.05$)

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measurements; measurement method; the number of distributed sites used to build the LUR; the number of reference sites; median measured concentrations (min – max); important model diagnostics including R^2, adjusted R^2, validation method, cross-validation R^2; and the predictive spatial variables included in the final LUR model, along with their buffer sizes (where applicable), direction of the effect, and p-values (if available).

3. Results and discussion

The initial search identified 39 records. One conference abstract that overlapped with one original research article was immediately removed. After further assessments of the remaining records, 23 more were excluded according to the study criteria. Checking the references of the remaining publications resulted in identification of an early VOCs model in Munich (Germany) where the authors did not use the term LUR despite using LUR methods (Carr et al., 2002).

Overall, we identified 16 LUR studies for VOCs published between 2002 and 2017. Of these, 11 were conducted in North America including six in Canada (Atari and Luginaah, 2009; Hystad et al., 2011; Oiamo et al., 2015; Poirier et al., 2015; Su et al., 2010; Wheeler et al., 2008) and five in the USA (Johnson et al., 2010; Kheirbek et al., 2012; Mukerjee et al., 2009, 2012; Smith et al., 2006; Smith et al., 2011). Of the remainder, two were conducted in Spain (Aguilera et al., 2008; Fernandez-Somoano et al., 2011), one in Germany (Carr et al., 2002), one in Italy (Gaeta et al., 2016), and one in Iran (Amini et al., 2017b). The populations of the cities covered by the VOC models ranged from ~70,000 in Sarnia (Canada) (Atari and Luginaah, 2009) to ~9 million in Tehran (Iran) (Amini et al., 2017b). A national model for Canada estimated VOCs for the whole population of the country, which is ~35 million people. The modeled areas also ranged widely, from 38 km^2 in Sabadell (Spain) (Aguilera et al., 2008) to 2,790 km^2 in Ottawa (Canada) (Oiamo et al., 2015) (Table 1).

The 16 studies developed LUR models for VOCs based on measurements ranging from 22 sites in El Paso (USA) (Smith et al., 2006) to 179 sites in Tehran (Iran) (Amini et al., 2017b). There was also one study in New Haven (USA) where benzene concentrations were simulated at 285 sites using a hybrid of two air quality modeling systems (CMAQ and AIRMOD), and the LUR models were built using the pseudo-observations (Johnson et al., 2010) (Table 2). Although there is no consensus in the LUR community about the number of sites needed to develop the spatial models (Amini et al., 2014b; Hoek et al., 2008), studies have shown that using a small number of sites may lead to overestimates of model performance. One study in Girona (Spain) found that > 80 sites were needed across 46 km^2 to adequately capture the range of NO_2 concentrations and to properly estimate long-term spatial variability (Basagaña et al., 2012). Authors further recommended that > 100 sites might be needed for LUR models of NO_2 in more complex urban settings (Basagaña et al., 2012). Beckerman et al. (2008) reported that NO_2 concentrations near an expressway were strongly correlated with benzene (0.85) and total hydrocarbons (0.74), but less correlated with toluene (0.63), ethylbenzene (0.51), *m/p*-xylene (0.46), and *o*-xylene(0.51) (Beckerman et al., 2008). Thus, we assume that a similar number of sites might be needed for VOCs as for NO_2. In a related study, Cocheo et al. (2008) evaluated how the number of passive BTEX samplers could be reduced in four European cities (Dublin, Madrid, Paris and Rome) while maintaining the quality of the results achieved with a larger number of sites. They found that each 3.4 km^2 in urban areas needed at least one passive sampler, and recommended that the number of sites needed can be calculated by $0.29 \times A$ where A denotes the study area in km^2 (Cocheo et al., 2008). Overall, 10 out of 16 studies in our review failed to meet this criterion, including those in Sarnia, Toronto, national model of Canada, Ottawa, El Paso, Detroit, Dallas, New York, Asturias, and Munich. However, the studies in Windsor, Sabadell, Rome, and Tehran well met this criterion (Table 1). The national Canadian study developed models based on 53 sites

Table 2 (*continued*)

Authors/citation City (Country) # of sites	Modeled VOC	Median (min – max) (μg/m³)	Model R^2/Adj. R^2	Validation method	Validation R^2	Predictors (direction of association (positive; negative; or N/A)); (p-value)
	Ln (Total BTEX)	58.6 (16.4–195.0)	0.66/0.64	same	0.61	- Distance to all bus parking areas (negative); ($p < 0.05$) - Highways (250) (positive); ($p < 0.05$) - Distance to educational areas (positive); ($p < 0.05$) - Taxi lines (50) (positive); ($p < 0.05$) - Product of highways in buffer 50 m/distance to highways (positive); ($p < 0.05$) - Log-distance to official/commercial land use areas (negative); ($p < 0.05$) - Log-distance to gas filling stores (negative); ($p < 0.05$) - Official/commercial land use areas (2000) (positive); ($p < 0.05$) - Urban facilities land use (200) (negative); ($p = 0.06$) - Distance to sewage treatment plants (negative); ($p < 0.05$) - Product of green space areas in buffer 5,000 m/distance to green spaces (negative); ($p < 0.05$) - All road (5,000) (positive); ($p < 0.05$) - Sensitive land use areas (2000) (negative); ($p < 0.05$) - Ancillary roads (50) (positive); ($p < 0.05$)

[a] LOOCV, leave one out cross-validation.
[b] Note that these sites were pseudo-observations not real measurements.

(Hystad et al., 2011) for a 9.9 million km^2 modeling domain. The study in Dallas (USA) used 22 sites in an area of 664 km^2 (Smith et al., 2006), and the study in New York City (USA) used 69 sites for an area of 789 km^2 (Kheirbek et al., 2012). Only the study in Tehran had > 100 measurement sites available, with 179 sites for an area of 613 km^2 (Amini et al., 2017b).

Three of the studies modeled only benzene, and four modeled all BTEX species. Others modeled a few different VOCs, such as *n*-hexane, 1,3-butadiene, styrene, formaldehyde, and acrolein (Table 1). Given that the BTEX species have been highly correlated (Amini et al., 2017a; Hoque et al., 2008), future studies might consider restricting measurements and models to benzene, given its well-established adverse health effects. However, studies have shown that modeling each VOC separately might help to identify pollutant-specific predictor variables and/or sources, which could inform air pollution control programs (Amini et al., 2017b). In addition, some VOCs such as acetaldehyde and acetone have shown low to moderate correlations with other VOCs because their sources can be different (Possanzini et al., 2007; von Schneidemesser et al., 2010), so separate models will be needed in some cases.

Passive sampling was used to collect data for 14 of the 16 studies (Table 1). The Canadian national study used routinely collected fixed-site monitoring data, and the aforementioned study in New Haven used pseudo-observations based on air quality simulations (Table 1). Most studies have used inexpensive passive samplers because regulatory networks (1) may not measure VOCs routinely and (2) are unlikely to capture the whole range and spatial variability of concentrations across the study area. These considerations are especially true for LMICs, where missing data, could be challenging to impute, making long-term averages nearly impossible to estimate for LUR (Amini et al., 2014b). Previous studies have demonstrated that passive samplers provide accurate data compared with other types of measurements (Marc et al., 2015; Stevenson et al., 2001). Furthermore, the hourly benzene pseudo-observations simulated by Johnson et al. (2010) were compared with measurements at one site, and the agreement was within a factor of two (Johnson et al., 2010). As such, the uncertainty of LUR models based on simulated data might be larger than the uncertainly of models based on true measurements.

The measurement periods for the passive sampling campaigns have been: (1) one 2-week campaign in two studies; (2) one 5-week campaign in two studies; (3) two 1-week campaigns in two studies; (4) four 1-week campaigns in one study; (5) two 2-week campaigns in three studies; (6) three 2-week campaigns in one study; (7) four 2-week campaigns in one study; (8) five 2-week campaigns in one study; and (9) twelve 4-week campaigns in one study. Finally, the national Canadian model used annual averages at 53 fixed regulatory monitoring over one entire year, and the study in New Haven simulated the benzene data over a single summer (Table 1). While data from regulatory networks can provide high temporal coverage, they cannot adequately capture spatial variability on air pollutant concentrations (Kanaroglou et al., 2005). Simulated data can capture both temporal and spatial trends with high resolution, but their accuracy is uncertain in the absence of a sufficient number of measurements for robust evaluation.

Although the ideal approach in passive sampling campaigns is to measure at all sites throughout the study period (e.g. annually), this might not be feasible due to budget and/or logistic constraints (Amini et al., 2017a). Therefore, the investigators usually measure at a small number of sites throughout the year, which we refer to as reference sites. The long-term means for the distributed sites are then adjusted based on their comparison with the reference site(s) using various approaches (Amini et al., 2017a; Eeftens et al., 2012). Again, there is no consensus in the LUR community about the number of reference sites that should be measured, the number of measurement periods, the length of those periods, the number of campaigns needed, or how measurements should be spaced in time. From review of the available literature, these choices often depend on the study domain, local meteorology, and geographic characteristics.

Previous studies have shown that measurements from reference sites are needed to obtain robust estimates of the long-term mean at the distributed sites (Amini et al., 2017a). However, only three of the 16 studies used reference sites in their analyses (Table 1). The study in New York City had three reference sites and the measurements were taken over five consecutive 2-week periods. This study used the raw concentrations from the distributed sites as the response variable for the LUR, and the reference site mean was used predictive covariate, along with the spatial variables (Kheirbek et al., 2012). The study in Rome had one reference site, but it was in 7 km removed from the distributed sites and it was not clear whether the site ran throughout the study or how the data were used to adjust the other measurements (Gaeta et al., 2016). The study in Tehran measured five reference sites for 25 2-week periods and adjusted the models by using the ratios of the measurements at distributed sites to concurrent levels at reference sites (Amini et al., 2017a, 2017b).

Fifteen of the 16 studies were conducted in areas where long-term benzene concentrations were lower than 5 μg/m^3, which is the standard value set by the European Union (Marco and Bo, 2013). Only one study in the highly polluted megacity of Tehran reported annual average concentrations above this threshold (Amini et al., 2017b). Otherwise, the maximum long-term mean concentrations of benzene was reported in El Paso, Texas, where one site had an annual average of 2.5 μg/m^3 (Mukerjee et al., 2012). The median long-term measured benzene concentrations at individual sites ranged from 0.5 μg/m^3 in Ottawa, which has a population of approximately 900,000 people, to 7.8 μg/m^3 in Tehran, which has a population of approximately 9 million people (Table 1). The low concentrations in North America are consistent with the fact that emissions of VOCs have been drastically reduced in HICs over the last two decades. One study reported reductions of −3% to −26% per year from 1998 to 2008 for some individual VOCs in London (von Schneidemesser et al., 2010). There are no long-term standards for ambient exposure to VOCs other than benzene, which made further comparison between studies more challenging. All in all, the available evidence suggests that VOCs have high concentrations in LMICs communities (Amini et al., 2017a; Hoque et al., 2008; Matysik et al., 2010) compared with HICs.

Overall, 15 out of the 16 studies modeled at least benzene. These models explained a range of variability in measured concentrations from 43% in Detroit to 93% in El Paso. The high value for El Paso was likely a function of the high number of model parameters (n = 16) relative to the small number of sites used in the analyses (n = 22) (Hoek et al., 2008). The average (standard deviation) R^2 across all 15 studies on benzene was 0.70 (0.12). In general the most important variables in the LUR models for benzene were indicators of traffic, such as population density, highway density, distance to major roads, and some distinct variables relevant to local conditions. Specifically, the common predictors were: (1) population density in six studies; (2) length of expressways and highways within a buffer in five studies; (3) distance to nearest major road in five studies; (4) industry within a buffer or distance to industries in three studies; (5) VOC emissions sources in three studies; (6) commercial land use in two studies; (7) altitude in two studies; (8) and distance to nearest international border in two studies. Many individual studies also included variables that did not appear or were not calculated for other studies, including: traffic counts within a buffer; intersection count within a buffer; number of traffic signals within a buffer; total length of roads within in buffer; taxi lines within a buffer; dwellings within a buffer; proximity to ports of harbor; northern latitudes; distance to sewage treatment plants; and distance to nearest bus terminals (Table 2).

Model evaluation was also varied across the studies and, once again, there is no consensus in the LUR community about the best methods. Leave one out cross-validation (LOOCV) has been the popular approach when the number of measurement sites is small (Amini et al., 2014b, 2016). However, one NO_2 study in the Netherlands reported that models based on a smaller number of sites (n = 24 in this case) performed poorly in hold-out external validation (Wang et al., 2012). The LUR validation methods used in the reviewed studies were: LOOCV in Asturias, Rome, and Tehran; leave two out in Detroit; leave five out in Windsor; leave out proportions ranging from 10% to 50% in Sarnia, Sabadell, New Haven, and New York City. Bootstrapping was used (sometimes in addition to LOOCV) for the national Canadian model, and the Canadian cities of Toronto and Ottawa (Table 2). No clear validation method was reported for the models in Munich (Carr et al., 2002), El Paso (Smith et al., 2006), Dallas (Smith et al., 2011), or Halifax (Poirier et al., 2015). The validation R^2 values ranged from 12% in national Canadian model (Hystad et al., 2011) to 81% in Sarnia (Atari and Luginaah, 2009) (Table 2). Overall, there is a critical need for studies that compare different LUR validation methods for all pollutants, and specifically for VOCs.

We identified nine LUR models for toluene, explaining a range of variability from 31% in Detroit to 81% in Sarina. The average (SD) R^2 of these nine models was 0.60 (0.18), and the predictor variables were similar to those for benzene. In addition to the general traffic surrogates, specific variables that described toluene concentrations were: (1) distance to the Ambassador Bridge in Windsor; (2) distance to nearest large Manganese emissions source in Detroit; (3) industrial land use in Sarnia; (4) northern latitude in Rome; (5) log-distance to gas filling stores in Tehran; and (6) distance to the nearest sewage treatment plant in Tehran. The cross-validation R^2 were 40% in Rome, 60% in Tehran, 65% in Windsor, and 77%–86% in Sarnia. The other five studies did not report cross-validation values. The validation method in Ottawa was bootstrapping, and one variable was identified as unstable in the model (Table 2).

Six of the 16 studies modeled ethylbenzene, with an average (SD) variability explained of 0.66 (0.13), ranging from 0.40 to 0.63 in Dallas to 81% in Sarnia. Once again, the predictors were similar to those used for modeling benzene and toluene. The cross-validation R^2 was 0.61 in Tehran, and ranged from 0.79 to 0.86 in seasonal models of Sarnia. No cross-validation R^2 was reported for the models in Munich, Detroit, Dallas, or national model of Canada (Table 2).

Five of the 16 studies modeled xylenes, including *m*-xylene, *p*-xylene, (*m*/*p*)-xylene, and *o*-xylene. The LUR models for (*m*/*p*)-xylene explained 0.40 to 0.70 of variability in the seasonal data for Dallas and up to 0.80 of the variability in Sarnia. The Tehran study modeled *m*- and *p*-xylene separately and explained 0.66 of variability in both pollutants. The average (SD) R^2 was 0.65 (0.14) for all studies on (*m*/*p*)-xylene, and the predictive variables were similar to those used for benzene. Only the study in Sarnia reported a validation R^2 for (*m*/*p*)-xylene, which ranged from 0.78 to 0.81. The validation R^2 in Tehran was 0.61 for *m*-xylene and 0.59 for *p*-xylene. The LUR models for *o*-xylene explained 0.37 to 0.60 of variability in the seasonal data for Dallas, and up to 0.80 in Sarnia with an average (SD) of 0.61 (0.15) for all studies. The validation R^2 for *o*-xylene was 0.59 in Tehran, and ranged from 0.77 to 0.79 in Sarnia (Table 2).

While different studies covered benzene, toluene, ethylbenzene, and xylenes separately, five of the studies summarized in the paragraphs above also modeled total BTEX. The average (SD) R^2 value for these models was 0.66 (0.16), ranging from 0.40 in Detroit to 0.81 in Sarnia. Once again, the spatial predictors of total BTEX were similar to those for the benzene models. The reported validation R^2 values were 0.61 in Tehran, 0.65 in New York City, and 0.80 to 0.84 in Sarnia (Table 2).

Beyond the BTEX species, three studies modeled 1,3-butadiene, explaining 26% of variability in Dallas, 43% in Detroit, and 68% in the national Canadian model. No validation R^2 has been reported for these models but the national Canadian model reported a normal distribution for predictors coefficients as they used bootstrap method for validation (Table 2). Two modeled formaldehyde with R^2 values of 0.29 in Rome and 0.83 in New York City. The validation R^2 was 0.13 in Rome and 0.68 in New York City (Table 2). One study modeled styrene in Detroit and could explain 43% of variability. One study in Rome modeled acrolein near an Italian airport with an R^2 value of 55%. In addition to traffic-related predictors, a variable called "aircraft contribution to hydrocarbon concentration" (spray estimates) was a significant predictor for acrolein (Table 2). Finally, one study modeled *n*-hexane and total hydrocarbons in Toronto, explaining 68% and 66% of variability, respectively. In addition to traffic-related variables, these models also included the number of chimneys and soil brightness. However, local road had a negative effect on *n*-hexane. The models were validated by bootstrap and reported no bimodal shape for predictor coefficients (Table 2).

In general, we observed discrepancy among studies regarding the direction of association for predictors. Although most of the studies reported logical directions (e.g., increasing benzene concentrations with increasing traffic intensity), some reported inconsistent results (Fernandez-Somoano et al., 2011; Mukerjee et al., 2012; Smith et al., 2011). The studies in Munich and Halifax were missing important information on variable direction, and could not be included in this assessment. Regarding the non-linear terms in the models, some studies included log-transformed predictors (Mukerjee et al., 2009; Smith et al., 2011) while others divided one variable by another variable (Amini et al., 2017b). Only 6 out of 16 studies provided the p-values of predictors for their models. Of those predictors, majority had p-value < 0.05 but all had < 0.1, which is acceptable in the LUR community (Amini et al., 2014b).

4. Conclusions

In this article we used a systematic approach to provide an overview of all LUR models that have been developed for VOCs. Generally, the important VOC predictors were traffic-related variables. However, other significant predictors included proximity to ports of harbor in USA, number of chimneys in Canada, altitude in Spain, northern latitudes in Italy, and proximity to sewage treatment plants, taxi lines, bus terminals, or gas filling stores in Iran. Many of the traffic-related and other variables used large buffers, up to 5,000 m, which may be important for describing ambient VOCs in large cities (Amini et al., 2017b). On the other hand, future studies may need to critically evaluate specific local characteristics and sources of each VOC to achieve the best possible models. They may consider the inclusion of satellite derived variables, incorporating meteorological variables, particularly for temperature, or may develop hybrid models. So far, only one LUR study for VOCs has incorporated the meteorological variables in the modeling process, but they were not selected for the final models (Amini et al., 2017b).

So far only one set of national models has been developed for VOCs in Canada, and the performance of the models was relatively good (Hystad et al., 2011). A recent study showed that LUR models can be developed globally when the authors built an NO_2 using 5220 air monitors in 58 countries and reported an R^2 of 0.54 (Larkin et al., 2017). Currently, there is no such model for VOCs, mainly due to scarce global measurements. It is possible that the simulation approach used by Johnson et al. (2010) or recent advancements in satellite observation of VOCs (Zhu et al., 2017), could provide one pillar needed for construction of VOC models at the national and global scales. The availability of such models would facilitate epidemiologic studies on VOCs even in areas where no measurements have been made.

As shown, the majority of LUR models have been developed in high income countries for the aromatic alkylbenzene group of VOCs where they include toxic pollutants. Further studies on VOCs from outside North America and Europe are critically needed to describe the wide range of exposures experienced by different populations and possible health effects in LMICs.

Conflicts of interest

Vahid Hosseini declares that he is affiliated to Tehran Air Quality Control Company (AQCC). The views expressed in this manuscript are those of the authors and do not necessarily reflect the views or policies of the Tehran AQCC. The rest of authors declare that they have no actual or potential financial competing interests.

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Discussion and conclusions

Air pollution in low- and middle-income countries is higher and from different sources than air pollution in high-income countries, where most exposure and epidemiologic research has been done. The burden of air pollution could be very large through acute and chronic effects. This two-part dissertation focused on these two key challenges of air pollution in Tehran, Iran. First in part I, research on short-term daily exposure and its effects, and second in part II, the assessment of long-term exposure spatial patterns, which in fact is needed for assessment of chronic health effects of air pollution.

In part I of this thesis, we observed positive associations for almost all lag-responses of daily non-accidental mortality and $PM_{2.5}$, NO_2, and AQI in Tehran. We further observed strong evidence of effect modification by sex, age, and season where the overall effect estimates were larger in females, older age groups, and cooler months. Another key finding of this study was that the short-term effects of air pollution in a Middle Eastern megacity remained significant for about a month or even a longer-term period, which has important implications for risk and health impact assessment.

The research on acute effects of air pollution in Iran has been mainly on hospital admissions due to respiratory diseases (Rezaei et al., 2015; Vahedian et al., 2017b), hospital admissions due to cardiovascular diseases (Hosseinpoor et al., 2005; Vahedian et al., 2017a), mortality due to accidents (Dastoorpoor et al., 2016), mortality due to cardiovascular diseases (Dadbakhsh et al., 2016), mortality due to respiratory diseases (Dadbakhsh et al., 2015; Khanjani et al., 2012) but to the best of our knowledge, no study so far evaluated the acute effects of air pollution on non-accidental mortality in Iran. A study in heavily polluted (mean PM_{10} = 237 $\mu g/m^3$) Ahvaz city in Iran found that traffic accidents did not increase by air pollution concentrations (measured by NO, CO, NO_2, NOx, PM_{10}, SO_2, and O_3) (Dastoorpoor et al., 2016). We, therefore, focused on non-accidental mortality as many other international studies also focused on and rationalized that accidents should not be associated with air pollution concentrations (Chen et al., 2011; Filleul et al., 2005; Gasparrini et al., 2012; Qian et al., 2007). Regarding the exposures, we chose $PM_{2.5}$ and NO_2 because these have been robust pollutants in predicting health effects elsewhere (Cohen et al., 2017; Filleul et al., 2005), and because they have been shown to have independent associations with mortality (Cesaroni et al., 2013; Filippini et al., 2015; Samoli et al., 2006; Thomas et al., 2014). On the other hand, we were interested in the validity of AQI in Tehran, as reported by Tehran AQCC, in predicting mortality. We found gender difference in the associations and the sources of this effect modification should be further investigated. Previous reviews on the role of gender in air pollution epidemiology have listed a number of possible sources, such as life stage, co-exposures, hormonal status, or other factors (Clougherty, 2010). Yin et al. (2017) conducted a time series analysis in 38 China's largest cities for the association of particulate matter and mortality, and found larger risks in females than males in their pooled estimate (Yin et al., 2017). All in all, it is currently unclear why the effects of air pollution in females are larger in various studies and why they are more susceptible to air pollution. The observed effect modification by season (cooler vs warmer months) in Tehran has been discussed in Article 1 but it seems this depends on local conditions and also sources of air pollution in the particular region. For example, studies in the US reported higher estimates in warm season for Detroit but vice versa for Seattle (Zhou et al., 2011). The role of age has been more investigated by the scientific community and it seems that elderly subjects are more susceptible to air pollution elsewhere (Li et al., 2015; Qin et al., 2017). Although we found positive associations between air pollution and mortality in Tehran for the age group <18, which are mainly driven by infants mortality, the associations were not significant. This also needs further investigation in Tehran. Although the previous research on PM with aerodynamic diameter $\leq$ 10 μm (PM_{10}) has shown that the short-term effects on mortality can persist up to 30-40 days (Zanobetti et al., 2002; Zanobetti et al., 2003), to the best of our knowledge, no study reported lag structures of acute effects up to 45 days for $PM_{2.5}$, NO_2, and AQI. We observed that the associations between mortality and $PM_{2.5}$, NO_2, and AQI in Tehran remain for a longer time (for about a month or even more). Perhaps this is because of local conditions (air pollution sources and other environmental conditions) and maybe due to the susceptibility of Tehran population. This could also be more investigated for other outcomes, such as hospital admissions, in Tehran or in the similar contexts in the Middle East or elsewhere.

In part II, in order to be able to study in future chronic health effects of ambient air pollution in Tehran, we aimed to assess the long-term exposure spatial patterns for important air pollution markers. In doing so, we first gathered the local measured data of NO, NO_2, and NO_x for 2010 from Tehran AQCC and also from the Department of Environment (DOE). These were measured by 23 regulatory monitoring stations in Tehran, 16 of which belonged to the Tehran AQCC and 7 to the DOE. We developed LUR models based on these data to estimate annual but also seasonal (cooler months vs warmer months) spatial variability of nitrogen oxides (Amini et al., 2016). We first found that the 2010 annual mean NO, NO_2, and NO_x concentrations were relatively high in Tehran, and for NO_2 the annual mean was almost 2.5 times higher than the recommended WHO guideline value. We further found that the concentrations were higher in the cooler season than in the warmer season. This could be due to the increase in emissions, especially from residential heating where people use natural gas (thus, chimney point sources), and in addition, due to the local meteorological conditions (inversion and low mixing height during cold season). We found significant seasonal differences in the spatial variation of nitrogen oxides in Tehran, especially for NO_2. The models performed better (in terms of R^2, adjusted R^2, and LOOCV R^2 values) in the cooler season for NO_2 and NO_x but not for NO where performance was better in warmer season.

Regardless, several of the cooler and warmer season models shared the same predictor variables. Overall, similar to other LUR studies elsewhere (Beelen et al., 2013; Henderson et al., 2007; Hoek et al., 2008), the nitrogen oxide concentrations were predicted by traffic related variables in Tehran. The development of LUR models based on fixed site monitoring network stations has pros and cons. On the one hand, readily-available data from validated instruments allows academics and government agencies to regularly model the spatial variability in air pollutants with minimal additional costs. However, on the other hand, the numbers and locations for the regulatory monitoring network sites are generally chosen by the criteria that may not optimize their ability to capture the variability necessary for spatial modelling. Therefore, although our models based on these data performed relatively well in Tehran, the small number of measurement sites and also their locations in our study might limit our findings.

To address the abovementioned limitations of spatial modeling based on regulatory network data, we designed and ran a large campaign in Tehran to measure and model important ambient air pollutants, in a study called "Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)" (Amini et al., 2017a). We measured O_3, NO_2, SO_2, and BTEX concentrations at 5 reference sites for 25 two-week periods using passive samplers and also at 174 distributed sites in summer, winter, and spring seasons.

Cocheo et al. (2008) evaluated how the number of passive BTEX samplers could be reduced in four European cities (Dublin, Madrid, Paris and Rome) while maintaining the quality of the results achieved with a larger number of sites. They found that each 3.4 km^2 in urban areas needed at least one passive sampler (Cocheo et al., 2008). Based on this criterion, our study in Tehran needed at least 178 sites to be monitored as the area of Tehran is about 613 km^2. Tehran SEPEHR well met this criterion for number of sampling sites by having 179 sites under study. The locations of Tehran SEPEHR, due to special circumstances of Tehran and to prevent risk of vandalism, were selected mostly from government and/or municipality buildings and/or from other appropriate places determined by local investigators. They were selected, however, out of 276 potential sampling locations using a cluster analytic method integrating prior knowledge about the spatial variability of air pollution in Tehran, as described above in Article 3 (Amini et al., 2017a).

The choice of air pollution markers to be monitored in Tehran SEPEHR was based on international studies where they have linked variety of health effects to these pollutants (Brunekreef and Holgate, 2002; Hoek et al., 2008; Katsouyanni et al., 2001). However, the budget was not allowing us to measure particles, such as PM_{10}, $PM_{2.5}$, ultrafine particles, and/or particle numbers, and this was one of the limitations of Tehran SEPEHR that could be addressed in future studies. Furthermore, recent studies suggest that oxidative potential (OP) of particles and/or particle constituents might predict health effects of air pollution (Brook, 2008; Delfino et al., 2013; Maier et al., 2008; Schwarze et al., 2006; Strak et al., 2012). Thus, several LUR models so far have been developed for OP elsewhere (Gulliver et al., 2018; Jedynska et al., 2017; Yang et al., 2015). These markers of air pollution could also be studied in Tehran in future.

Although we measured O_3, NO_2, SO_2, and BTEX in Tehran SEPEHR, in this thesis we focused on the analysis of benzene, toluene, ethylbenzene, *p*-xylene, *m*-xylene, *o*-xylene (BTEX), and Total BTEX due to better performance of the duplicate samplers.

The Tehran SEPEHR has been the largest effort, to date, to measure spatial and temporal variability of BTEX in a LMIC megacity and one of the largest of its kind in the world. We found that the annual concentrations of benzene consistently exceeded recommendations and standards set to protect public health. In light of its known carcinogenic effects, the related burden needs to be quantified in terms of morbidity, mortality, and their related costs. We found higher concentrations of BTEX around gas stations, and most of the hotspots were sites in areas with high traffic (Amini et al., 2017a). Evaporation from fueling stations and unburned gasoline in the carburetors of cars, trucks, and motorcycles are likely major contributing factors. Approximately 86% of VOCs are emitted from mobile sources in Tehran (Shahbazi et al., 2016), confirming the need for appropriate actions against vehicular traffic, such as applying state-of-the-art technologies to reduce emissions, and implementation of low emissions zones. In order to support implementation of such protective policies, epidemiologic research is needed. In doing so, we are required to estimate the long-term exposures of Tehran population and afterwards we will be able to study the effects of these pollutants on various health outcomes. Thus, in a later stage we developed high resolution LUR models of the abovementioned alkylbenzenes in Tehran (Amini et al., 2017b). We updated our modeling algorithm in Tehran SEPEHR, given the larger dataset we collected (compared to the data explained in Article 2 for nitrogen oxides measured by regulatory network), acquisition of new predictors' data (such as bus lines, taxi lines, meteorology, emission and various point sources as explained in Article 4 (Amini et al., 2017b)), and new updated data for previous predictors used in Article 2 (Amini et al., 2016), and also created larger pool of predictors having buffers up to 5,000 m for some variables. These advancements enabled us to reveal that sewage treatment plants, statistically, are a major source of alkylbenzenes in Tehran along with traffic predictors (Amini et al., 2017b). However, further investigation is needed in this regard in Tehran. We also found that 83% of Tehran's surface had estimated concentrations of benzene above the allowed annual mean standard of Iran and European Union, which is 5 $\mu g/m^3$. Given the carcinogenicity of these air toxics, the related burden needs to be quantified by rigorous methods and appropriate policy actions are needed to target emission control in Tehran. In this LUR practice, we also found that large buffers up to 5,000 m are needed to explain annual mean concentrations of alkylbenzenes in complex situations of a megacity. Furthermore, we found that toluene was the predominant alkylbenzene and the most polluted area was the city center. Our analyses on differences between wealthier and poorer areas also showed somewhat higher concentrations for the latter. These findings also have important implications for Tehran. Although we found that northern areas had somewhat lower concentrations compared to southern areas in Tehran, the maximum concentrations were observed in northern areas because there are many busy highways there and they are one of the major sources of alkylbenzenes in Tehran (Amini et al., 2017b).

We finally conducted a systematic review of all LUR models for VOCs (Amini et al., 2017c). We found that the Tehran SEPEHR, to date, has been globally the largest LUR study to predict all BTEX species in a megacity. Generally, the important VOC predictors have been traffic-related variables. However, other significant predictors included proximity to ports of harbor in USA, number of chimneys in Canada, altitude in Spain, northern latitudes in Italy, and proximity to sewage treatment plants, and to gas filling stores in Iran. We further found that large buffers, up to 5,000 m, are needed for traffic related variables in large cities.

Future studies on LUR modeling for VOCs may need to critically evaluate specific local characteristics and sources of each VOC to achieve the best possible models. They may consider the inclusion of satellite derived variables, incorporating meteorological variables, particularly temperature, or may develop hybrid models. So far, only one LUR study for VOCs has incorporated the meteorological variables in the modeling process (Amini et al., 2017b), but they were not selected for the final models. Thus far, only one set of national models has been developed for VOCs in Canada (Hystad et al., 2011), and the performance of the models has been relatively good. Currently, there is no global LUR model for VOCs, mainly due to scarce global measurements. It is possible that the simulation approaches or recent advancements in satellite observation of VOCs could provide one pillar needed for construction of VOC models at the national and global scales (Johnson et al., 2010; Zhu et al., 2017). The availability of such models would facilitate epidemiologic studies on VOCs even in areas where no measurements have been made. The majority of LUR models have been developed in high income countries for the aromatic alkylbenzene group of VOCs where they include toxic pollutants. Further studies on VOCs from outside North America and Europe are critically needed to describe the wide range of exposures experienced by different populations and possible health effects in LMICs (Amini et al., 2017c).

In this thesis, we first evaluated the acute health effects of air pollution in Tehran. In a next stage, we bridged to long-term exposure assessment needed for studying chronic health effects of air pollution in Tehran. In doing so, we first developed LUR models for nitrogen oxides measured by regulatory monitoring network. As these models had important limitations (discussed above and in Article 2 (Amini et al., 2016)), we designed and conducted one of the largest air pollution monitoring campaigns in a megacity, called Tehran SEPEHR (Amini et al., 2017a). We later conducted the largest LUR study to predict all BTEX species in a megacity (Amini et al., 2017b; Amini et al., 2017c). Examples of LUR models are rare in LMICs, and these estimates could be used for various health effects studies, urban planning, air quality management, and the monitoring of evidence-based policy making. In addition, this thesis established a benchmark for future air pollution monitoring and modeling in Tehran, and in general, in Iran.

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