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Assessing traffic and industrial contributions to ambient nitrogen dioxide and volatile organic compounds in a low pollution urban environment

Tor H. Oiamo [a,*], Markey Johnson [b], Kathy Tang [a], Isaac N. Luginaah [a]

[a] Department of Geography, Social Science Centre, The University of Western Ontario, 1151 Richmond Street, London, Ontario N6A 5C2, Canada
[b] Air Health Science Division, Health Canada, 269 Laurier Ave West, Room 3-024, Ottawa, Ontario K1A 0K9, Canada

HIGHLIGHTS

- Applied land use regression (LUR) modeling to generate spatially resolved air quality data
- Study supports national health studies on air pollution and advances LUR methodology.
- Shows industrial and traffic contributions to ambient NO_2 and VOCs in a low pollution urban area
- Demonstrated the utility of road intersections as surrogate for traffic data

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ABSTRACT

Land use regression (LUR) modeling is an effective method for estimating fine-scale distributions of ambient air pollutants. The objectives of this study are to advance the methodology for use in urban environments with relatively low levels of industrial activity and provide exposure assessments for research on health effects of air pollution. Intraurban distributions of nitrogen dioxide (NO_2) and the volatile organic compounds (VOCs) benzene, toluene and m- and p-xylene were characterized based on spatial monitoring and LUR modeling in Ottawa, Ontario, Canada. Passive samplers were deployed at 50 locations throughout Ottawa for two consecutive weeks in October 2008 and May 2009. Land use variables representing point, area and line sources were tested as predictors of pooled pollutant distributions. LUR models explained 96% of the spatial variability in NO_2 and 75–79% of the variability in the VOC species. Proximity to highways, green space, industrial and residential land uses were significant in the final models. More notably, proximity to industrial point sources and road network intersections were significant predictors for all pollutants. The strong contribution of industrial point sources to VOC distributions in Ottawa suggests that facility emission data should be considered whenever possible. The study also suggests that proximity to road network intersections may be an effective proxy in areas where reliable traffic data are not available.

1. Introduction

Air pollution has been unambiguously linked with cardiopulmonary morbidity and mortality (Brunekreef and Holgate, 2002; Health Effects Institute, 2010; Miller et al., 2007; Pope et al., 2002; Ryan et al., 2007). There is also emerging evidence that air pollution may be associated with a variety of adverse health effects including neurological, reproductive, and developmental outcomes (Peters et al., 2006; Lewtas, 2007; Freire et al., 2010). In order to accurately characterize potential risks associated with air pollution, epidemiological studies require accurate determination of ambient pollution concentrations.

Certain air pollutants such as NO_2 (nitrogen dioxide) and BTEX (benzene, toluene, ethylbenzene, m/p-xylene and o-xylene) may exhibit high spatial variability in urban areas (Parra et al., 2009; Kheirbek et al., 2012; Smith et al., 2006). These pollution gradients are attributable to local land-use patterns such as stationary (industrial and commercial) source locations and transportation infrastructure (Jerrett et al., 2005). Therefore, to accurately assess the health effects of air pollution, spatially resolved concentration surfaces are needed to estimate exposure. However, collection of household or personal monitoring data for each study participant is not feasible for large health cohorts. In the absence of subject-specific measurements, a variety of methods have been used to assign air pollution exposure in epidemiological health studies (Jerrett et al., 2005; Baxter et al., 2013; Ozkaynak et al., 2013).

Fixed air quality monitoring stations in regulatory or surveillance networks are widely used to represent the exposure of subjects residing within large geographic areas. Regulatory and surveillance monitoring provide finely resolved temporal variability, which can be used to

* Corresponding author.
E-mail address: thoiamo@uwo.ca (T.H. Oiamo).

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estimate short term and historic concentrations. However, fixed monitoring sites are too sparsely located to characterize intra-urban gradients. Spatial and statistical techniques, such as kriging, have also been used to interpolate from ambient monitoring data. However, interpolation methods are limited by the number of monitoring sites found in typical urban areas, and do not effectively represent small scale spatial variations associated with local land use patterns such as proximity to roadways (Jerrett et al., 2005).

Land use regression (LUR) modeling has emerged as a cost-effective alternative to household or individual monitoring for estimating exposure in epidemiological health studies (Atari et al., 2008; Beelen et al., 2013; Brauer et al., 2003; Briggs et al., 1997; Chen et al., 2012; Henderson et al., 2007; Luginaah et al., 2006; Oiamo et al., 2012; Poplawski et al., 2009; Sahsuvaroglu et al., 2006; Su et al., 2008; Wheeler et al., 2008). LUR models utilize ambient air quality measurements together with detailed land-use data from geographic information systems (GIS) to estimate concentrations throughout an area (Johnson et al., 2010). LUR modeling produces fine-scale spatial surfaces characterizing intra-urban concentrations, which provide more accurate exposure estimates for community health studies. This approach is particularly important for spatially heterogeneous pollutants such as NO_2 and BTEX. In a critical review on exposure and health effects, the Health Effects Institute panel recommended using LUR modeling as the preferred method for assessing exposure to traffic-related pollutants (Health Effects Institute, 2010).

Health Canada is collaborating with researchers across Canada to develop LUR models for Canadian cities to support air pollution health studies. LUR models have been developed for NO_2 and other pollutants in approximately thirteen urban areas across the country. Parenteau and Sawada (2012) developed an LUR model for NO_2 in Ottawa using spatial monitoring data from 30 sites sampled in fall 2007. The current study builds and expands on that work by developing LUR models for NO_2 and BTEX species that incorporate new predictors, including industrial point source emissions and alternative traffic proxies, and two seasonal sampling campaigns in Ottawa, Ontario, Canada. With respect to traffic proxies specifically, the study tests the utility of intersection densities in a study area where detailed and reliable traffic volume data was not available. These models provide information about ambient gradients, and demonstrate the impact of industrial sources, in smaller, post-industrial urban areas. These LUR surfaces will provide exposure estimates for multi-city health studies to assess population health risks associated with ambient air pollution.

2. Methods

The study conducted two-week passive air monitoring of NO_2 and BTEX during spring and fall in Ottawa, Ontario, Canada. These measurements were then used to develop LUR models for NO_2, benzene, toluene, and m/p-xylene.

2.1. Study area

Ottawa is the capital city of Canada and its 4th most populous Census Subdivision (CSD). The Ottawa CSD, 45°25′15″N 75°41′24″W, has a population of 883,391 and covers a 2790 km^2 area (Statistics Canada Focus on Geography Series, 2011). Ottawa is home to many legislative and administrative centers of government. Combined with the presence of several universities and colleges, Ottawa has a high proportion of governmental and institutional land-use compared with other Canadian cities (Fig. 1). As with most cities of its size, residential densities are mixed and a freeway system transects the downtown urban center. Lower density residential housing and rural areas are present to the east, south and west of the city center. Although Ottawa is not an industrial city, a number of point sources for both NO_2 and BTEX are present and their air releases are reported to Environment Canada and disseminated through the National Pollutant Release Inventory (NPRI) on a yearly basis. The Ottawa River provides the northern boundary of the CSD, and along with the Rideau River and Rideau Canal provides adjacent areas with parks and natural areas throughout the city. Uniquely, Ottawa's downtown core is surrounded on the south (from east to west) by the federally controlled greenbelt, a 200 km^2 crescent in which real estate development is limited. The greenbelt primarily includes forest, wetlands, and fields, with some recreational, agricultural, and government land-use.

2.2. Air pollution monitoring

Optimal locations for passive sampling were determined with a location–allocation model (LAM) in ArcGIS 9.2 (Esri, Redlands, CA) (Kanaroglou et al., 2005). The p-median (P-MP) approach was used, which minimizes the sum of the distance between all demand locations and chosen sampling locations. Demand locations where based on population densities weighted by road network data within 1000 × 1000 m grids. Centroids of these grids were used as “demands” and monitoring locations were chosen based on minimizing the distance between these centroids and evenly distributed sampler locations throughout the Ottawa CSD. Passive samplers were dispatched for monitoring campaigns during the fall season in 2008 (October 7–21) and the spring season in 2009 (May 6–20). The sampling dates were chosen based on previous research suggesting that fall and spring levels of air pollution were more representative of annual concentrations in Windsor, Ontario (Wheeler et al., 2008). Furthermore, the only previous monitoring campaign for NO_2 in Ottawa conducted by Parenteau and Sawada (2012) in 2007 took place in the fall, therefore the current study provided an opportunity to substantiate their results.

Sampling was carried out at 50 locations, but samples from 2 sites in fall and 4 sites in spring were invalidated due to improper installation or public interference with the samplers. Valid samples were obtained at 48 locations during the fall of 2008 and 46 locations during the spring of 2009 with 3M Model 3500 Organic Vapor Passive Samplers (Guillevan, Montreal) for the BTEX species and Ogawa Passive Samplers (Ogawa & Company USA, Inc., Pompano Beach, FL) for nitrogen dioxide. The samplers were placed at a height of 2.5 m on utility poles and the exact spatial coordinates of the monitoring locations were recorded using the global positioning system (Magellan GPS315).

To provide a more robust estimate of long-term spatial distributions, LUR models were developed based on pooled data from the two sampling seasons. The pooled analyses were limited to sites with valid sampling data for both seasons. In total, 42 sites for benzene, *m*-/*p*-xylene and toluene and 38 sites for NO_2 provided the pooled data. However, an extreme outlier (5 + SD from mean) was observed for toluene during the fall monitoring (12.21 μg/m^3) at a residential sampling location, and this observation was consequently removed from the analysis.

Duplicate samples were collected at 5 sites in each sampling season to estimate precision and field blanks were collocated with 5 badges and sent for analysis to provide mass correction coefficients. Two of the monitoring sites for each season were also collocated with permanent Environment Canada monitoring stations that are part of the National Air Pollution Surveillance (NAPS) network, and these were used to estimate sampling bias. See Oiamo et al. (2012) for a detailed description of the quality control procedure and bias estimation. Nitrogen dioxide concentrations were measured and reported hourly for both the central and downtown NAPS stations, while VOCs were reported weekly from the downtown station only (Fig. 1).

2.3. Land-use and spatial data

Potential predictors for LUR model estimation were created to represent all major emission sources, including point sources (*e.g.*, power plants), area sources (*e.g.*, residential areas) and line sources (*e.g.*, highways). Predictor variables were derived from several data sets (described further below) and included measures of land use, the