Evaluation of land use regression models for NO_2 in El Paso, Texas, USA

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Abstract

Developing suitable exposure estimates for air pollution health studies is problematic due to spatial and temporal variation in concentrations and often limited monitoring data. Though land use regression models (LURs) are often used for this purpose, their applicability to later periods of time, larger geographic areas, and seasonal variation is largely untested. We evaluate a series of mixed model LURs to describe the spatial-temporal gradients of NO_2 across El Paso County, Texas based on measurements collected during cool and warm seasons in 2006-2007 (2006-7). We also evaluated performance of a general additive model (GAM) developed for central El Paso in 1999 to assess spatial gradients across the County in 2006-7. Five LURs were developed iteratively from the study data and their predictions were averaged to provide robust nitrogen dioxide (NO_2) concentration gradients across the county.

Despite differences in sampling time frame, model covariates and model estimation methods, predicted NO_2 concentration gradients were similar in the current study as compared to the 1999 study. Through a comprehensive LUR modeling campaign, it was shown that the nature of the most influential predictive variables remained the same for El Paso between the 1999 and 2006-7. The similar LUR results obtained here demonstrate that, at least for El Paso, LURs developed from prior years may still be applicable to assess exposure conditions in subsequent years and in different seasons when seasonal variation is taken into consideration.

Key Words: Nitrogen dioxide, land use regression, Exposure models, Exposure variability, Monitoring

1. Introduction

In urban areas, emissions from motor vehicles are a major source of air pollution and contributor to chronic and acute respiratory illness (Health Effects Institute, 2010). Accurate exposure estimates are a crucial component of environmental epidemiology studies of air pollution. However, developing suitable exposure metrics for traffic-related air pollutants is problematic due to spatial and temporal variation in concentrations and often limited monitoring data. Land use regression models (LURs) have gained acceptance as a valid, cost-effective method of modeling the intra-urban spatial variability in air pollution for health effect studies. LURs combine land use characteristics such as distance to roads, traffic intensity and elevation from geographic information systems (GIS) and air pollution monitoring data to estimate exposures at unmonitored locations. LURs have performed well when validated against direct measurements, reporting correlation coefficients ranging from 0.36-0.82 (Hoek et al. 2008). However, only a limited number of studies have assessed the stability of LURs to predict ambient exposures across larger geographic areas, during different seasons and in later years (Poplawski et al., 2009; Eeftens et al., 2011).

Exhaust from motor vehicle traffic is a significant source of oxides of nitrogen (NOx), carbon monoxide, non-methane volatile organic compounds and particulate emissions. Nitrogen dioxide (NO_2) is a US EPA criteria air pollutant commonly used indicator for air pollution generated by mobile and stationary sourcesFour international ports of entry are located in El Paso county. A fifth, in Santa Teresa, New Mexico is located 35 miles west of downtown El Paso. These border crossings represent the second highest rates of international passenger and commercial traffic between the United States and Mexico (Rajbhandari et al. 2009).

Previous studies of NO_2 and other air toxics in the U.S.-Mexico border community of El Paso, TX identified significant spatial variation of NO_2 via direct measurements and LUR modeling (Gonzales et al., 2005; Smith et al., 2006). Most of the spatial variation in NO_2 in El Paso was explained in the LURs by traffic patterns and density, elevation, population density, distances to major nitrogen oxide (NOx) emissions sources, and international border crossings (Gonzales et al. 2005; Smith et al. 2006; Funk et al. 2001). These initial studies were conducted in central El Paso during cool weather conditions when thermal inversions impacted pollutant concentrations. Since these studies were initially conducted, El Paso has experienced significant population growth both within and beyond the city limits into the surrounding area. In 2009, an estimated 750,000 people lived in the county, an increase of 10% from 2000 (U.S. Census Bureau, 2010). A component of the University of New Mexico-University of Texas at El Paso Advanced Research Cooperation in Environmental Health (ARCH) Program on Border Asthma measured year-round passive NO_2 monitoring across the entirety of El Paso County between 2006 and 2007. The ARCH study provided an opportunity to evaluate the earlier LUR models with NO_2 measurements collected seven to eight years later, across larger geographic areas, and during different seasons.

We had two objectives for this study. The first was to develop LURs for the County of El Paso, TX based on NO_2 concentrations measured in 2006-7, contemporaneous land use characteristics, and the impact of seasonal variation. The second was to evaluate how well the LUR model developed for El Paso in 1999 estimated NO_2 concentrations compared to the 2006-7 measurements.

2. Methods

2.1 Air monitoring

Ambient NO_2 was measured during the cool season months of December and March (temperature range 1-21 °C) and the warm season months of May and August (temperature range 16-34 1 °C) in 2006 and 2007 (2006-7). Average ambient NO_2 concentrations were determined on a weekly basis during the year 2007 for 7 weeks between May and August, 4 weeks between December and March, and 3 weeks between May and July. Weeklong integrated sampling was chosen to represent chronic ambient exposures. Samples were collected at least seven days apart, except in two cases. Ogawa Model 3300 passive samplers were used for NO_2 monitoring (Ogawa & Co., Pompano Beach, FL, USA). Samplers were placed in shelters and suspended at breathing zone height of 1.5-2 m. Samplers were analyzed by ion exchange chromatography at the Carlsbad Environmental Monitoring & Research Center (Carlsbad, NM). Ion exchange chromatography was also used to quantify NO_2 in the 1999 study conducted by Smith et al. (2006). Field quality control included the field blanks, and collocated replicate samples.

2.2 Selection of air monitoring sites

Our NO2 monitoring sites were selected to capture large-scale spatial gradients in NO2 exposures across the entire El Paso ARCH health study area. The selected monitoring sites were located within infrastructure property owned by the El Paso Water Utilities (EPWU) and continuous ambient monitoring stations (CAMS) operated by State of Texas Commission on Environmental Quality (TCEQ) as shown in Fig. 1. Spatially-representative sites were selected based on traffic and other urban land-use variables from available GIS databases. During the first year of the study, NO_2 measurements were made at 12 locations. Sites were selected to represent approximate uniform distribution of NO_2 concentration gradients previously described by Gonzales et al. (2005) and Smith et al. (2006). Site I was replaced with a nearby location (Site Ia) when the property was sold after the first year of monitoring. The monitoring network was augmented during the second year by selecting an additional 8 water facility locations. The additional locations were selected by applying two optimal design criteria to the candidate LUR variables used in prior El Paso spatial studies: road density, distance to freeway, distance to border crossing, distance to major petroleum facility, and population density. Two design criteria were applied to evaluate the suitability of candidate locations to inform an LUR model based on these variables. The first minimized the confidence interval for the LUR model coefficients (D-criteria), which ensured that sites near the extremes of the variable space were not under-represented (OPTEX procedure in SAS v9.2,). The second, a space-filling criterion, ensured uniform coverage of intermediate values within the design (U-criteria).

During both years, passive NO_2 samplers were collocated at four TCEQ sites (sites D, F, H, and J) to assess potential bias in NO_2 measurements relative to corresponding reference method measurements reported in the EPA AQS database. Hourly results from TCEQ sites were downloaded from the US EPA Air Quality System (AQS) and averaged over passive monitor sampling periods to create comparison values. AQS data were required to exhibit a data completeness level of at least 75% (i.e. 75% of valid hourly data) within each of the sampling periods.

2.3 GIS variables

GIS variables were generated using ArcView v3.2 and ArcMap v9.3 & 10 (ESRI 2010) with statistical analyses implemented in SAS version 9.2 (SAS, 2008). Data sources for variables were: 1) water utility site location from the El Paso municipal government; 2) 2005 traffic volume data estimates for El Paso County (El Paso Metropolitan Planning Organization); 3) U.S. Census data (US Census Bureau, 2010); 4) point source location and emissions data from the EPA 2002 National Emission Inventory database; 5) elevation (Gesch et al., 2002); and 6) vehicle border crossing locations (Paso del Norte Mapa). It should be noted that traffic volume estimates from 2005 and point source emissions data from 2002 were used as surrogates for 2006-7 conditions. Although some traffic information was available for 2006-7, evaluating and converting these limited data into a suitable format for modeling was not feasible within the study's time constraints. The 2002 point source emissions were the most recent publicly available data at the time.

Based on previous results, source locations for NOx or volatile organic compounds (VOC) that totaled more than 10,000 kg per year were also included in analyses (Smith et al. 2006). Traffic intensity was calculated for different distances from measurement and prediction locations following Smith et al (2006) and using their Arcview programming. The traffic intensity measure was calculated by multiplying traffic volume estimates (vehicles day^{-1}) within a distance buffer times their respective segment lengths (km), summing these products over all segments in the buffer, and then dividing the sum by the total buffer area (km^2). Comparisons of monitoring information and LUR variables in this study versus the 1999 El Paso study (Smith et al., 2006) are presented in Table1.

2.4 LURs

Our model-building strategy began with a LUR model that incorporated the variables used by Smith et al. (2006) and Gonzales et al. (2005) with subsequent modifications to account for the expanded spatial and temporal domain of this study. Gonzales et al. (2005) used log-log regression and Smith et al. (2006) used general additive models (GAM) to assess spatial gradients across El Paso. We used mixed model regression analysis with random site and week effects and temporally correlated within-site residual errors (SAS v9.2 proc MIXED) to estimate land use regression model coefficients. Within-site temporal autocorrelation was modeled with a Gaussian covariance function in which the decline in correlation was proportional to the squared temporal difference between measurements. LURs were assessed by examining Akaike Information Criterion (AIC) corrected for small sample size. By convention, models that have AIC values that differ by no more than 2.0 are considered equivalent, and those differing between 2.0 to 10.0 also have substantial empirical support (Burnham and Anderson, 2002). Collinearity between land use variables was evaluated in each model by examining the variance inflation factor (VIF). VIF statistics for all LURs developed were < 4.1, suggesting that the model variables were not encumbered by collinearity (O'Brien, 2007). We allowed variables to enter the model if a) their role as a measure of source intensity or dispersion process could be pre-defined, and b) the sign of the regression coefficient accorded with this expectation (Briggs et al., 1997; 2000). Given the relatively small data set, the criterion of a p-value of 5% or less was relaxed, accepting the possibility of overfitting the model. To offset the risk of overfitting, AIC was used to intentionally penalize models with too many parameters.

Model A was intended to be the closest match to the Smith et al. (2006) model, given that the current study expanded the range of VOC point sources and introduced seasonality. Model A included elevation, traffic intensity within a 1000 m buffer, population density, distance to border crossing, distance to a major VOC source, distance to a NO_2 source, and a binary indicator for cool/warm season differences in average concentrations. Model B tested one-way interactions between season, elevation, and distance to NO_2 sources. An interaction between season and LUR variables was necessary because the NO_2 concentrations in outlying areas did not increase as much as centrally located sites during high NO_2 periods during the cool season. The interaction term allowed slopes to be different to accommodate a different concentration surface by season. In Model C the traffic intensity variable buffer distance was changed to 1500 m, and an interaction between traffic intensity and distance to NO_2 sources was added. Model D added a term for population density to Model C. In Model E traffic intensity was replaced with distance to a major highway, which varies by season (distance-season interaction), distances to VOC sources and to the border, elevation, and population density. LUR model performance was evaluated based on variance component estimates which are detailed in the Supplementary Information.

3. Results

3.1 NO_2 measurements

Table 2 shows summary statistics of the air pollutants collected at the study sites for each season. NO_2 concentrations averaged 5 to 6 ppb lower than cool season samples in the prior El Paso study. As in the previous study, concentrations were highest in central El Paso with lower values in the east and west. In general, pollutant levels were higher in winter than summer. The exception to this pattern was Site M, which was higher in the warm season (27 ppb) than in the cool season (10 ppb). Weekly NO_2 concentrations at site O were greater than 20 ppb in both seasons. Countywide, the geometric mean of NO_2 was 14.7 ppb (95% CI = 10.3 – 21.1) in the cool season and 7.1 ppb (95% CI = 6.6 – 8.9) during the warm season. The NO_2 concentrations measured by the passive monitors averaged 1.0 ppb (average error ±3.7 ppb) higher than NO_2 measured at co-located TCEQ monitors ($R^2 = 0.89$).

3.2 LURs

Summary statistics for land use variables used in the 2006-7 and 1999 El Paso NO_2 LURs are shown in Table 3. Several land use variables had similar distributions across the two studies: distances to the international border crossings and to freeways, elevation, and census tract population density. The minimum and median traffic intensities at buffer distances ≤1000 m, were higher in the 1999 study. No differences were noted at larger buffer distances. Differences in traffic intensities at smaller buffer distances were caused by a different approach to developing the traffic intensity data layer. Smith et al. smoothed the raw traffic intensity data layer and we did not, which produced areas of zero traffic intensity because locations were not close enough to streets with traffic data. Because a larger geographic area was used in the 2006-7 study, more VOC sources were included in the 2006-7 models than in the 1999 models. In addition, the 2006-7 LURs used log-transformed NO_2 as the dependent variable.

NO_2 concentrations predicted in Model A were inversely associated with elevation, distance to border crossing in central El Paso, and population density, but increased significantly with increasing traffic intensity within 1000 m (Table 4). The slopes for elevation and distance to major NOx sources were significantly steeper for the warmer season measurements than for cooler season measurements when NO_2 concentrations decreased rapidly with increasing distance from areas of higher concentration (Model B).

We compared LURs that used traffic intensity, similar to the 1999 LUR model in Smith et al. (2006), with models that used distance to different road classes (Table 4). All five models (A-E) performed well in terms of explaining spatial variation in NO_2 concentration across the County (see text and Table S1 in Supplemental Information). AIC values for models A-E differed by < 9 units. Rather than arbitrarily choose one of these five models as "best," the approach taken here was to utilize the average of the different predictions from Models A-E. Given that the five models used same or similar variables and were not radically different, averaging had the advantage of incorporating as much information as possible from all the various predictors into the final estimate. Hence, the resulting predicted value was considered to be reasonably robust with respect to model misspecification. (Burnham and Anderson (2002) provide further details on averaging model estimates.)

3.3 2006-7 LUR model performance

LUR--predicted NO_2 concentrations for each ARCH study strata, and averaged over the five LURs, are shown in Figure 2. These figures show generally higher predicted NO_2 levels in the central section of El Paso where traffic intensity is greatest.

There were no apparent spatial trends in the prediction errors based on examination of leave-one-out cross-validation measures and studentized residuals. The largest, although the largest absolute errors tended to be near the study area boundaries. For example, sites M and L were the westernmost and easternmost sites, respectively and had the largest likelihood displacement statistics (13.2 and 28.4, respectively) and the largest Cook's D (5.2 and 1.4, respectively). Although these locations were influential, their presence in the dataset did not drastically change the estimated slopes or predicted values. We also examined sensitivity of predictions from Model D to a relatively high NO_2 measurement at site M in July 2007. When this measurement was omitted, the predicted value at M was 4.5 ppb lower in the warm season and 3.8 ppb lower in the cool season relative to predictions based on the full data set. Predictions for all other sites in the warm season were within ±0.6 ppb and were ±1.7 ppb in the cool season predictions. (See supplementary information on further discussion of the predictions of the separate LURs.)

3.4 Performance of 1999 model

When the 1999 EPA GAM model was updated using land use regression variables from 2006-7 the predictions tended to have a positive bias that varied in magnitude by season and location (Figure 3). (The 1999 study was based only on cool season measurements that averaged 3–5 ppb higher than cool season measurements from this study.) The 1999 model had a smaller bias in the cool season samples than during the warm season samples. Locations with the largest positive bias were J, L, and R that are in the eastern and southeastern part of the study area. The westernmost site M was located in the far northwestern part of the study area and had measured NO_2 values that were greater than predicted by the

1999 model. All four sampling sites identified above were outside the 1999 spatial sampling domain.

Although the 1999 model predictions did not always agree well with the magnitude of our measurements, they were correlated over the spatial distribution (i. e., generally, areas which were relatively high (or low) in the 1999 predictions were relatively high (or low) based on the latter measurements). Correlations (Pearson's ρ) between 1999 model predictions and cool season measurements by week were between 0.39 and 0.65 and between 0.10 and 0.62 for warm season weeks. The spatial correlation between the average of cool season measurements with 1999 model predictions was equal to 0.65 ($P = 0.002$), but the correlation with average warm season concentrations was only 0.20 ($P = 0.4$). When sample locations outside the 1999 spatial sampling frame were excluded from the analysis, cool season correlation increased to 0.91 ($P < 0.001$) and warm season correlation increased to 0.78 ($P = 0.001$).

Discussion and conclusion

Five LURs were initially considered for generating predictions of large-scale spatial gradients of ambient NO_2 in El Paso County. Model performance suggested that no one model was clearly superior to the others; thus, model estimates were averaged to mitigate possible effect(s) of model misspecification on the final prediction (REF). Averaging was considered to be relatively more robust compared to arbitrary selection of one of the five LUR estimates.

Most LUR studies typically choose one model to develop predictions. For example, it is possible to simply choose the most parsimonious model, i.e. that with the fewest parameters. However, model averaging employed here weighted the model predictions based on the models' AIC values, thus incorporating parsimony since the AIC penalizes models as the parameter count increases. As noted above, the averaging procedure mitigates the possible effect(s) of model misspecification on the final prediction. Averaging the models does necessitate running all the models to generate separate predictions. Though running five LUR models instead of one may seem laborious, the major effort in predicting exposures entails the assembly of model variables and collection of new ambient monitoring data. Against this required effort, the running of five models versus one represents relatively little extra work for the trade off of reduced exposure misclassification.

Despite differences in sampling time frame, model covariates and model estimation methods, the predicted NO_2 concentration gradients were similar in the current study as compared to the 1999 El Paso study conducted by Smith et al. (2006). Model-based estimation of chronic NO_2 concentration gradients using land use variables was not sensitive to changing environments or analysis methodology. The current work shows that a LUR model for ambient NO_2 concentrations in El Paso was applicable after a period of 7-years. The similar LUR results obtained here demonstrate that for El Paso, LURs developed from prior years may still be applicable to assess ambient exposure conditions for subsequent years. Through a comprehensive LUR modeling campaign, it was shown that the nature of the most influential predictive variables remained the same for El Paso between 1999 and 2006-7. The various LURs evaluated in this study provide flexibility in assessing predictor variable influences for future spatial studies in El Paso.

As expected, NO_2 measurements indicated seasonal differences in NO_2 concentrations with higher levels measured in winter versus summer. Higher NO_2 wintertime concentrations have also been found in other LUR studies in Dallas and Cleveland during winter and summer seasons using the same sampling methods (Smith et al., 2011, Mukerjee et al., 2011). Both the 2006-7 and 1999 LURs were developed using NO_2 concentrations measured during the cool season months and their NO_2 predictions were most highly correlated for these months ($\rho = 0.91$). During other seasons, the LUR model developed in 1999 over predicted ambient NO_2 levels measured in 2006, but captured the similar spatial gradients as was indicated by the statistically significant correlation with warm season measurements (ρ

= 0.78). The over prediction could be partially explained by overall lower regional NO_2 ambient levels in 2006, as reported by the EPA National Air Trends website. Nonetheless, explicit distinction between warm and cool seasons in the LURs developed here has also been found to be significant in LURs developed in Cleveland (Mukerjee et al., 2011). If the health issue being studied has a seasonal aspect, it would be beneficial for the corresponding LURs to account for this distinction.

Although in numerous LUR models population density has a positive coefficient reflecting its role as a surrogate for pollution sources, a negative coefficient is observed in the current LUR models. In Smith et al. (2006), population density in El Paso was estimated with the loess portion of the semi-parametric model, and indeed higher population was associated with higher NO_2 concentrations. However, a negative association was observed in preliminary LUR models for particulate matter in 2006-7 El Paso ARCH study, though not included in the final published models. A possible explanation for this association is the location of commercial and industrial corridors with high motor vehicle traffic densities in areas of relatively low population density. The current result for population density may also be a reflection of 1) the use of block groups instead of census tracts as in Smith et al. (2006) to calculate population density; 2) the expansion to include more point sources than Smith et al. (2006); and 3) the geographic extension from within the El Paso city limits to the entirety of El Paso County. Though median population is roughly similar, the present study encompasses a broader range of population densities than did the earlier study (Table 3). Further, the occurrence of point sources in the more sparsely populated areas of the county may have led to this somewhat curious result, although the overall relationship may not have been strong enough to show up in the collinearity check. For small buffer sizes (<500m), monitoring sites in commercial and industrial areas could have also contributed to the observed inverse association.

As encountered during the 1999 study, the spatial distribution of NO_2 concentrations measured in

2006-7 varied similarly by city section with the central El Paso exhibiting higher NO_2 levels than the outlying north and east areas. Though the slope of some 2006 LUR variables were steeper for warm season data to account for higher NO_2 concentrations close to major sources and less variable concentrations near the edge of the study area far from sources, overall spatial gradients were reproducible across seasons. There were no apparent spatial trends in the 2006-7 prediction errors based on examination of studentized residuals, although the largest absolute errors tended to be near the study area boundaries (sites L and M). Spatial variability in the measured and modeled NO_2 concentrations across El Paso County indicate that NO_2 data from monitoring sites should not be extrapolated to surrounding areas, since concentrations varied by sources, land cover and topography.

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Supplementary information

Text, table and figures on evaluation of LUR model performance based on variance components and predictions based on the separate LURs in supplemental material and are available via the Internet at http://www.sciencedirect.com.

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Figure 1. Locations of 2006-7 NO_2 monitoring sites (A), and the locations of 1999 Smith et al. (2006) NO_2 monitoring sites (B). Sites A through L were established in 2006. Sites M through T were added in 2007.

Figure 2. Predicted NO_2 for child asthma study strata in El Paso County, TX for warm (A) and cool (B) seasons. Estimates are weighted averages over LUR models A – E.

Figure 3. Comparison of measured NO_2 with values predicted by the 1999 EPA GAM model (Smith et al. 2006) using updated land use variable inputs. Boxplots show the distribution of differences between measured and predicted values by start of sample week (A) and by sampling location (B).

Table 1
Summary of land use regression model parameters in the 2006-7 [a] and the 1999 [b] El Paso studies

NO_2 measurement	2006-7 El Paso County Study [a]	1999 El Paso Study [b]
Samplers and duration	7-day passive samples (Ogawa)	7-day passive samples (Ogawa)
Temporal sampling	Cool Season: 4 weeks, November-March 2006 and 2007 Warm Season: 14 weeks, May - August 2006 and 2007	Cool Season: 2 weeks, November - December 1999
Spatial sampling	21 sites throughout El Paso County: Water utility locations and regulatory air monitoring stations operated by TCEQ sites	22 schools in El Paso city limits used for LUR development; 2 regulatory air monitoring stations operated by TCEQ used for validation
Modeling Methods		
Estimation Models	Linear Mixed Model (log-transformed pollutants)	General Additive Model
GIS-derived Covariates	Elevation, Traffic Intensity, Population Density, Distance to the international border crossing Distance to Freeways Distance to major VOC and/or NOx source (>10,000 kg/year) Season	Elevation, Traffic Intensity, Population Density, Distance to the international border crossing Distance to oil facilities

[a] Seven weeks of NO2 monitoring conducted May-August 2006, four weeks December 2006-March 2007, and three weeks May-July 2007; [b] Smith et al. (2006)

Table 2

Comparison of measured NO_2 concentrations collected during the 2006-7 and the 1999 [b] El Paso studies by sector.

El Paso Sectors	Season	Measured NO_2 Concentrations	
		2006-7 Study [a] Mean (Range), ppb	1999 Study [b] Mean (Range), ppb
Central [c]	Cool Warm	22 (5, 37) 13 (2, 45)	28 (18, 37) -
Eastern [d]	Cool Warm	14 (4, 35) 8 (1,34)	19 (11, 28) -
Western [e]	Cool Warm	15 (8, 24) 10 (4, 41)	21 (12, 27) -
Entire study area	Cool Warm	17 (4, 37) 10 (1, 45)	22 (11, 37) -

[a] Cool Season: 4 weeks, November- March 2006 and 2007 ; Warm Season: 14 weeks, May -August 2006 and 2007

[b] Smith et al. (2006) 2 weeks cool season monitoring in November and December 1999, all sites located at elementary schools within the El Paso city limits and within the El Paso sectors listed.

[c] Corresponds to 2007-7 monitoring sites C, H, I, Ia and O

[d] Corresponds to 2007-7 monitoring sites D, E, J, K, L, P, Q, R, S and T

[e] Corresponds to 2007-7 monitoring sites A, B, M and N

Table 3

Independent variables for the NO_2 monitoring locations used in the 2006-7 and the 1999 El Paso land use regression models.

Variable	2006-7 El Paso Study (n=21)[a]			1999 El Paso Study (n=22)[b]		
	Minimum	Median	Maximum	Minimum	Median	Maximum
125 m traffic intensity (vehicles day^{-1} km^{-1})	0	28,872	331,888	5,320	18,322	289,492
250 m traffic intensity (vehicles day^{-1} km^{-1})	0	36,698	388,788	3,216	18,639	217,280
500 m traffic intensity (vehicles day^{-1} km^{-1})	0	29,206	254,901	4,466	25,107	210,213
1000 m traffic intensity (vehicles day^{-1} km^{-1})	0	33,152	154,834	1,882	35,035	190,830
1500 m traffic intensity (vehicles day^{-1} km^{-1})	4,128	39,736	143,358	2,717	45,267	164,307
2000 m traffic intensity (vehicles day^{-1} km^{-1})	6,470	37,333	153,037	1,978	45,924	146,086
Meters to NOx [c]	1,345	5,666	12,453			
jMeters to VOC [d]	178	4,235	8,939	2,138	10,104	20,735
Meters to border crossing	420	9,999	21,953	943	9,664	22,344
Meters to freeway [d]	1,878	8,274	24,940	1,206	9,513	20,375
Elevation (m)	1,093	1,162	1,256	1,127	1,202	1,256
Block group population (#/km^2) [c]	46	1,413	6,080			
Tract population (#/km^2)	45	1,471	5,574	74	1,511	3,622

Table 4

Regression coefficients for five NO_2 LURs developed for the 2006-7 study in El Paso County, TX.

	Regression coefficients for 2006-7 LURs predicting log(NO_2) measurements				
Variable[a]	Model A	Model B	Model C	Model D	Model E
log(Elevation, m)	-4.68 ***				
log(traffic intensity 1000 m)	0.11 ***	0.10 ***			
log(Population density, km^{-2})	-0.15 *	-0.13 +		-0.09 +	
log(Distance to Border Crossing, m)	-0.12 *	-0.15 **			
log(Distance to VOC source, m)	-0.09 +++				-0.16 *
log(Distance to NO_x source, m)	-0.17 +				
Warm season log(Elevation, m)		-5.65 ***			
Cool season log(Elevation, m)		-2.95 *			
Warm season log(Distance to NO_x source		-0.32 **	-2.70 **	-2.87 ***	
Cool season log(Distance to NO_x source		-0.004	-2.40 **	-2.57 **	
Warm season elevation (m)			-0.51 ***	-0.46 ***	
Cool season elevation (m)			-0.27 *	-0.22 *	
log(Traffic intensity 1500 m)			-1.89 *	-2.01 **	
log(Traffic intensity) x log(Distance to NOx source, m) interaction			0.24 **	0.25 **	
Distance to border crossing (km)			-0.02 +	-0.03 **	-0.02 *
Elevation ([meters –1170]*0.01)					-0.49 ***
Warm season distance to major highway (m)					-0.04 ***
Cool season distance to major highway (m)					-0.01
Population density (km^{-1})					-0.10 *
Warm Season Intercept	38.17 ***	45.85 ***	23.83 **	25.84 ***	3.97 ***
Cool Season Intercept	38.97 ***	24.80 *	22.01 **	24.00 ***	4.44 ***

[a] Traffic intensity variable units are vehicles day^{-1} km^{-1}.

+++ P<0.20; ++ P<0.15; + P<0.10; * P<0.05; ** P<0.01; *** P<0.001

[a] Included the entirety of El Paso County, TX.

[b] Smith et al. (2006). Included elementary schools within the El Paso, TX city limits.

[c] These LUV covariates have been left missing for 1999 study, as there were no equivalent measurements.

[d] For the EPA El Paso study, these LUV covariates have been replaced by the following similar measurements: meters to VOC, meters to a petroleum facility

Figure

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Figure 1a

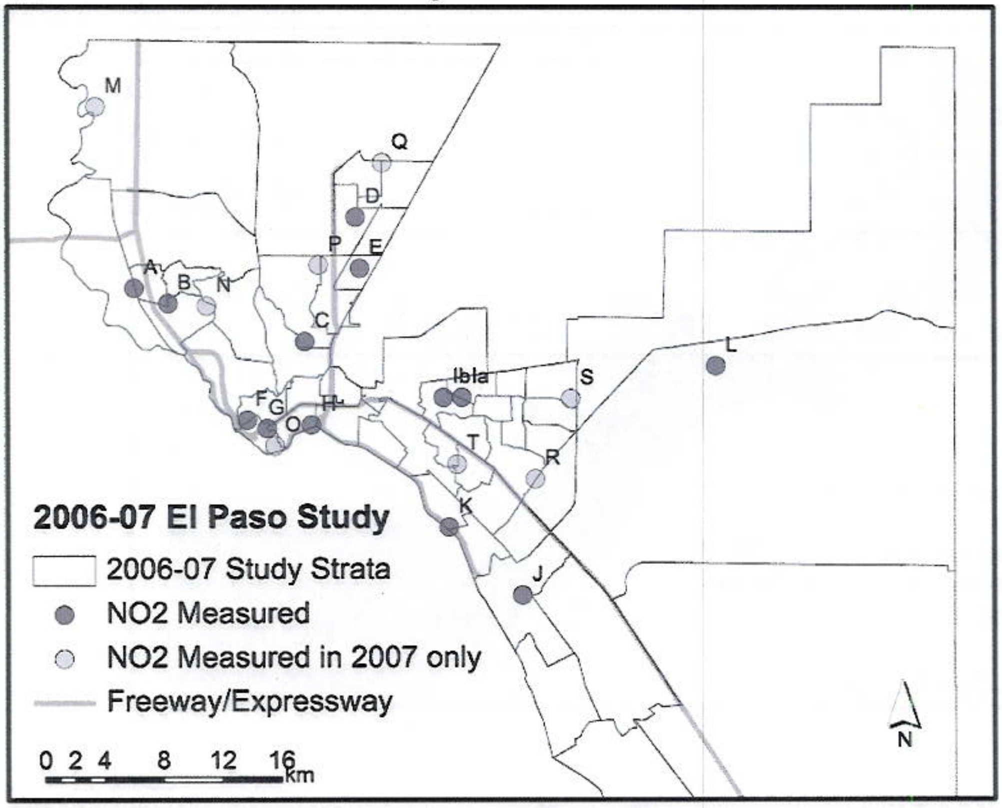
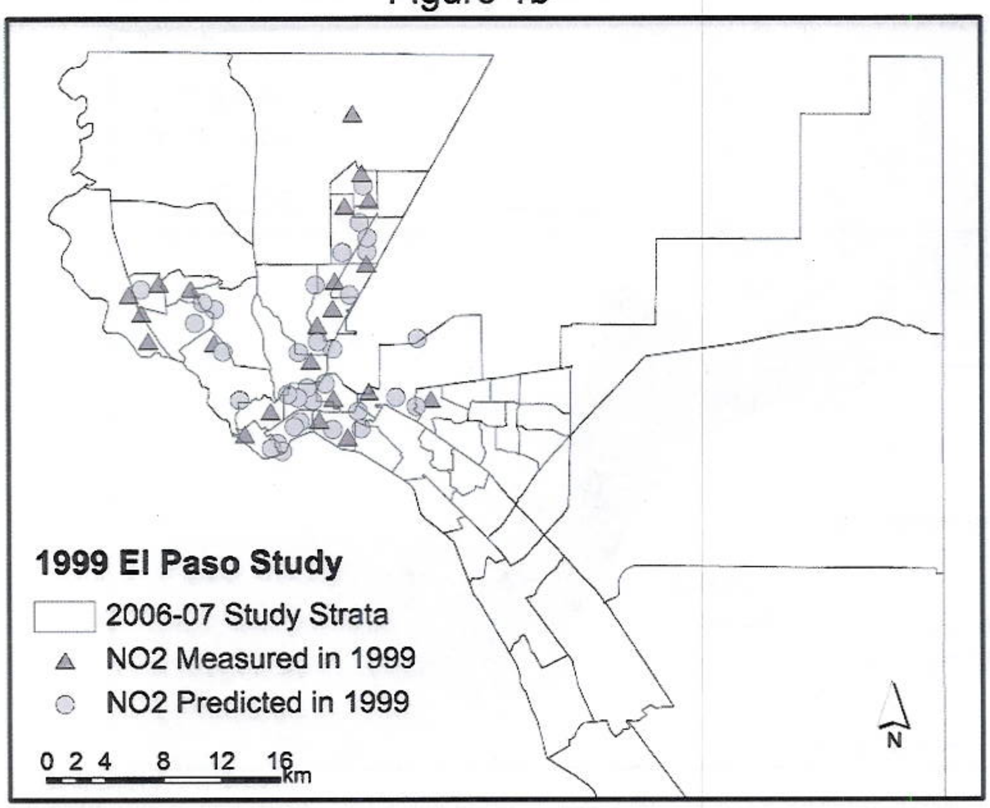


Figure 1b



Figure
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Figure 2a

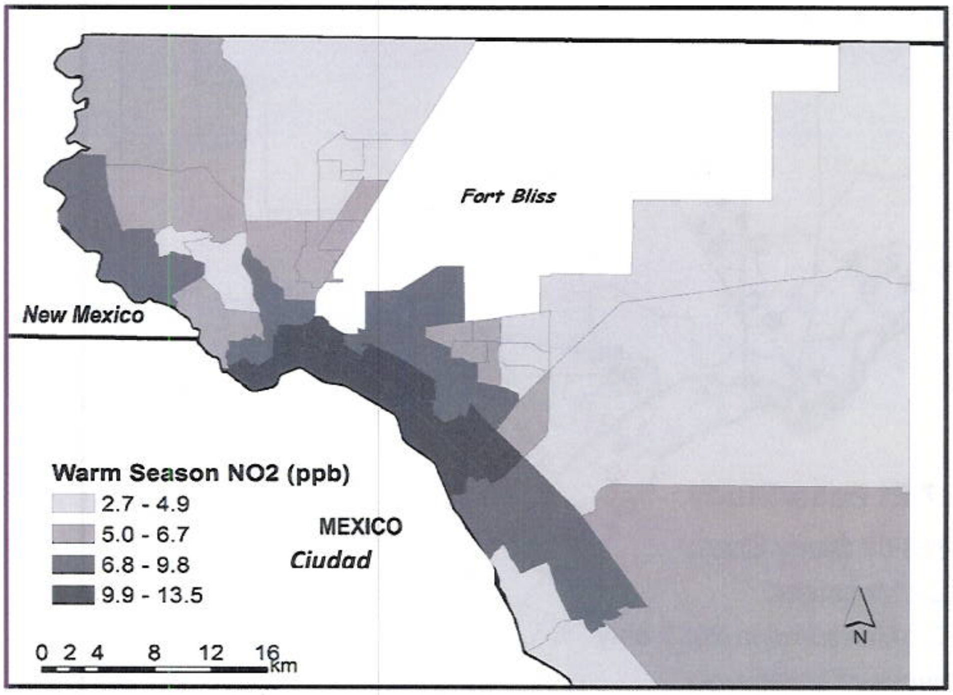
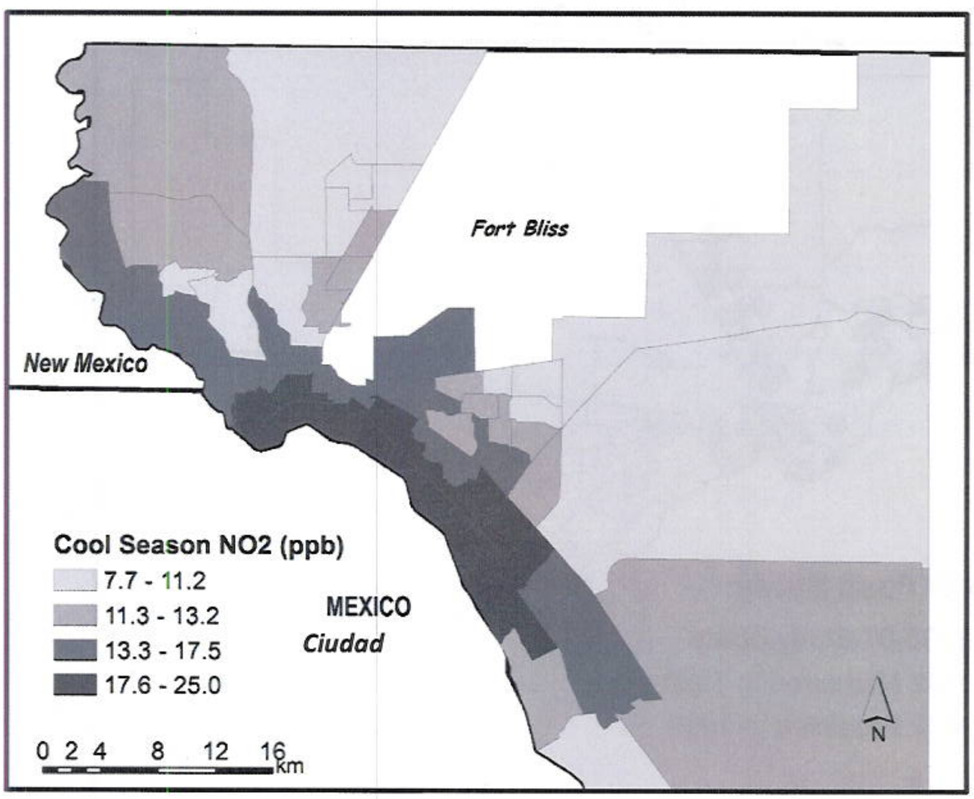


Figure 2b



Figure
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Figure 3a

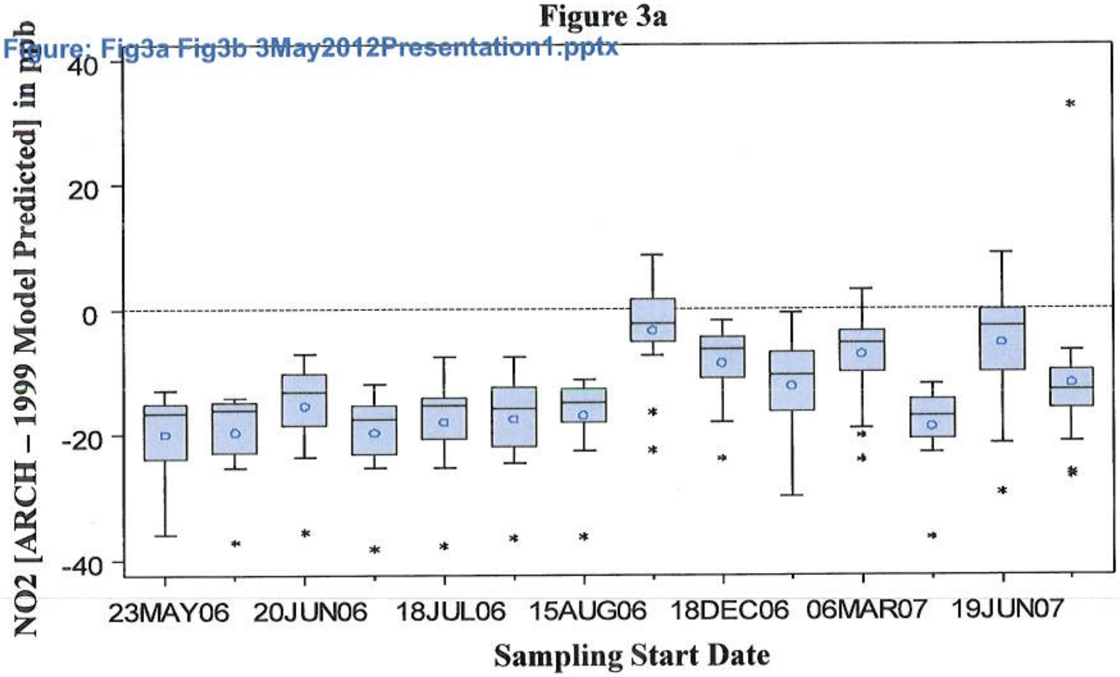
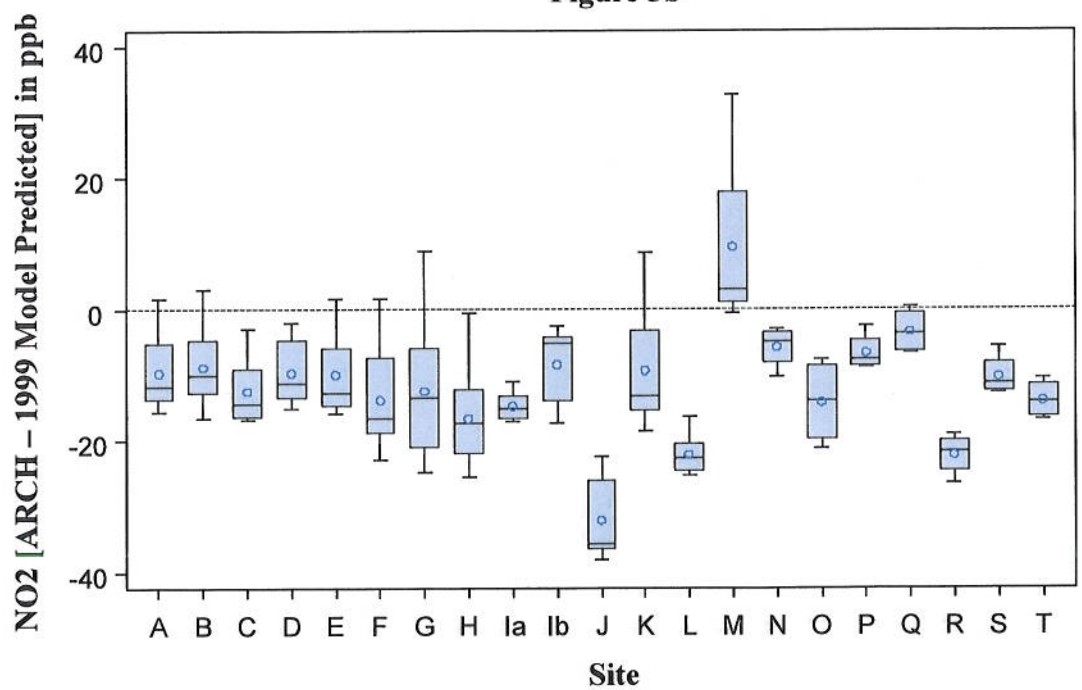


Figure 3b



Supplementary information for "Longitudinal evaluation of land use regression models for NO_2 in El Paso, Texas, USA"

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Evaluation of LUR model performance based on variance components

LUR model performance was assessed by examining the estimated variance components for sample weeks (σ^2_t), locations (σ^2_s), and residual error (σ^2_e) (Snijders and Bosker, 1999). The variance explained is comparable to the coefficient of determination (R^2) in linear regression analyses. An assessment of the maximum explained variance was based only on the spatial variance component (σ^2_s) from fitted models. Temporal variation explained by the LUR models was also assessed.

All five LURs (A-E) performed well in terms of explaining spatial variation in NO_2 concentration across El Paso County (see Table S1). Although model fit improved in Model C compared to Model B, modifications to the model did not substantially increase the amount of spatial or temporal variation explained by the model. Adding population density produced a small improvement in the AIC score for Model D. In Model E, distance to major highway was substituted for traffic intensity with different slopes for warm and cool seasons to obtain a model that fit almost as well as Model D. AIC values for Models C-E differed by <1.0 units, and therefore are approximately equivalent. Model D had the smallest AIC values.

Variance components from the mean model showed that NO_2 spatial variation and temporal variation had the same magnitude. Minimum and maximum amounts of explained variation were also calculated. The minimum spatial variance accounted for by the LURs was between 67% and 71% of the total spatial variation, and the maximum spatial variation explained was between 93% and 96% of the total spatial variation. The models explained 38% to 52% of the temporal variation by accounting for mean differences between seasons. The close equivalence of the LURs is also shown by the residual variance components and by the sum of spatial, temporal, and residual variance components for the models that are all within 0.01 variance units.

Predictions based on the separate LURs

Supplemental Figures S1A and S1B display geometric mean NO_2 measurements (labeled as Multi) and LUR predictions for the warm and cool seasons for each model and for the averaged model result. For the cool season all models under-predicted at site G and over-predicted at H and M. Warm season predictions and measurements were within 5 ppb at all sites except sites M and O, which were under-predicted. Sites G and T also were under-predicted in the warm season but by a smaller amount. Site O is located in an area with high population density. Model-averaged NO2 predictions were intermediate and had slightly larger prediction variances because they account for uncertainty in model selection (Figures S1C-2D).

References

Snijders TAB, Bosker RJ. Multilevel analysis: an introduction to basic and advanced multilevel modeling. Sage Publications, Newbury Park, CA. 1999. 266 pp.

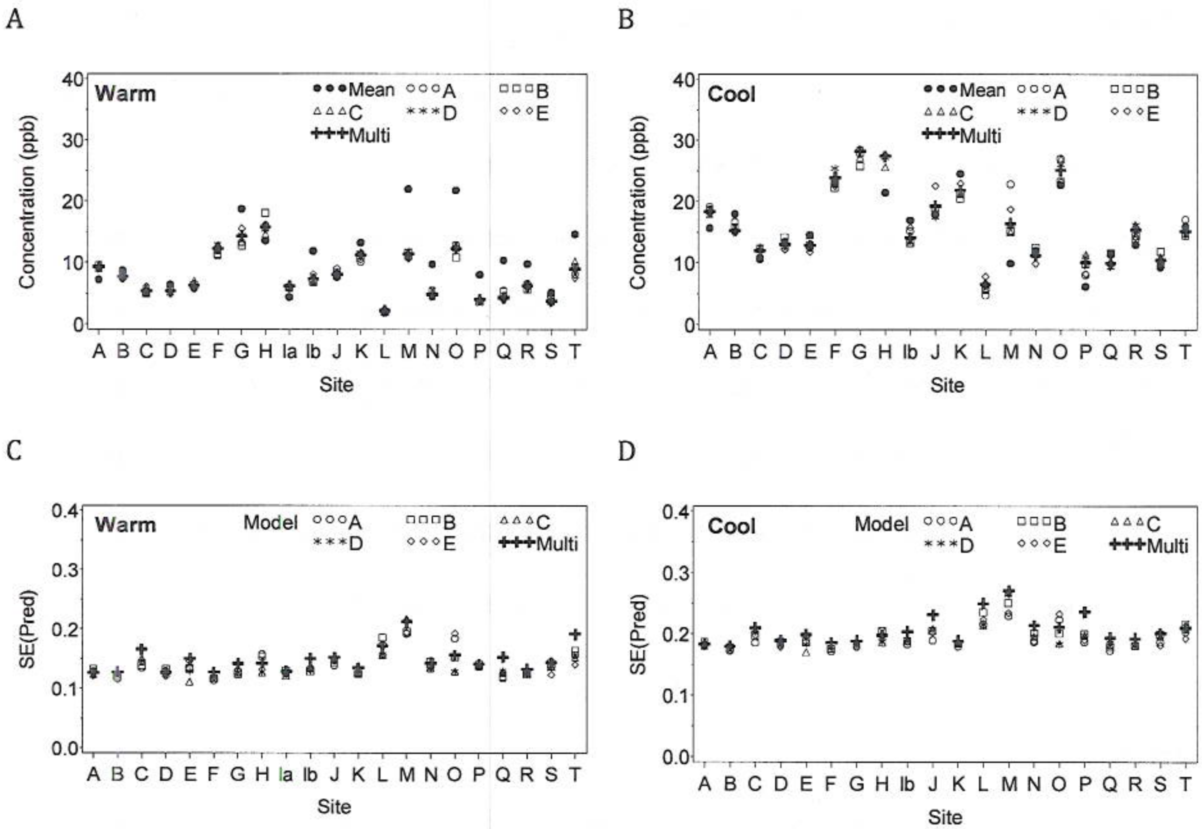

Figure S1. Comparison of average measured and predicted NO2 concentrations at measurement locations for warm (May – August , A) and cool seasons (December – March, B) from five LUR models and from the model-averaged estimate (Multi). Standard errors of predicted values at each measurement location for warm (C) and cool (D) seasons are also compared.

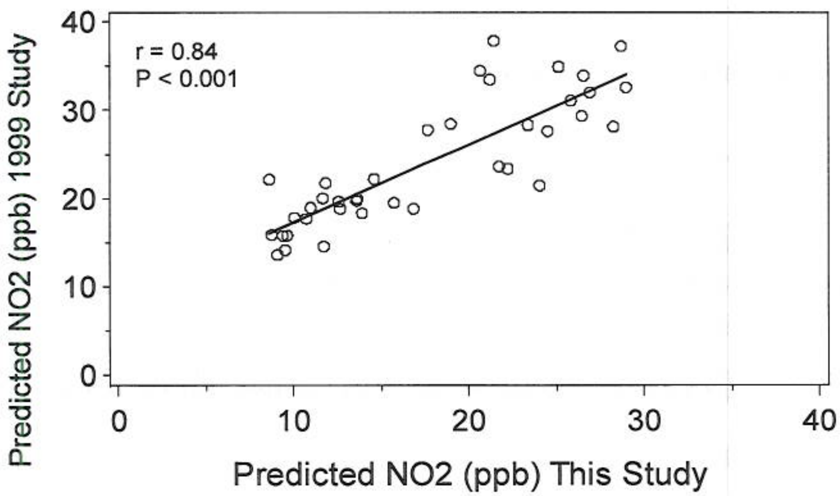

Figure S2. Predicted cool season NO_2 at school locations from 2006-7 study and from the Smith et al. (2006) 1999 study.

Table S1

LUR model performance based on variance components estimates for sample weeks (σ^2_t), locations (σ^2_s), residual error(σ^2_e), and AIC.

Components	20067 LURs				
	Model A Variance (SE)	Model B Variance(SE)	Model C Variance (SE)	Model D Variance (SE)	Model E Variance(SE)
Weeks (σ_w)	0.10 (0.01)	0.10 (0.04)	0.10 (0.04)	0.11 (0.04)	0.11 (0.04)
Sites (σ_s)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)
Residual (σ_e)	0.09 (0.01)	0.08 (0.01)	0.08 (0.08)	0.08 (0.01)	0.08 (0.01)
Total (σ_w+σ_s+σ_e)	0.20	0.19	0.20	0.19	0.20
Temporal autocorrelation (ρ)	1.85 (0.20)	1.70 (0.22)	1.70 (1.70)	1.72 (0.22)	1.72 (0.22)
Model evaluation					
# Fixed parameters	8	9	9	10	8
AIC	134.0	128.2	126.4	125.5	125.9
Variance explained					
Minimum temporal	0.37	0.39	0.39	0.39	0.38
Maximum temporal	0.52	0.51	0.51	0.51	0.50
Minimum spatial	0.67	0.70	0.70	0.71	0.69
Maximum spatial	0.94	0.95	0.94	0.96	0.93