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Does exposure to air pollution in urban parks have socioeconomic, racial or ethnic gradients? ☆

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ABSTRACT

Little is known about the levels of air pollution at public parks where regular exercise takes place or in park-adjacent neighborhoods where people have easy access to parks. In this study we investigated the ambient concentrations of criteria pollutants nitrogen dioxide (NO_2), fine particulate ($PM_{2.5}$) and ozone (O_3) at public parks and in park-adjacent neighborhoods for metropolitan Los Angeles. Socioeconomic and racial-ethnic inequalities in exposure to the three criteria pollutants were also investigated using multiple linear regression models. In addition, differences in inhalation doses from breathing the three + criteria pollutants were investigated for the top and bottom quartile racial composition in the parks and neighborhoods. Our research showed that although public parks had on average the lowest pollutant concentrations of NO_2 and $PM_{2.5}$, they had relatively high O_3 concentrations. Park-adjacent neighborhoods, by contrast, had the highest NO_2 and $PM_{2.5}$ concentrations, but the lowest O_3 concentrations. Higher exposures to NO_2 and $PM_{2.5}$ were systematically identified for the lower socioeconomic position or higher minority population neighborhoods. For children and adolescents aged 6–15 engaging in high and moderate intensity activities in and around public parks, those from the top quartile of primarily Hispanic neighborhoods had much higher (63%) inhaled doses of NO_2 compared to the bottom quartile counterpart. $PM_{2.5}$ showed a similar but less pronounced pattern of inhalation doses. Evidence of socioeconomic and racial-ethnic gradients was found in air pollution exposure and inhalation doses in and around the urban parks in Los Angeles. This suggests that patterns of exposure inequality found in other environmental justice research are present in exposures in and around urban parks.

1. Introduction

Public parks and green spaces play a decisive role in defining ecological functions of urban environments (Gilbert, 1989). They support biodiversity and provide important ecosystem services (Bolund and Hunhammar, 1999; Crane and Kinzig, 2005; Gaston et al., 2005; Smith et al., 2005). Parks and green spaces also provide many environmental, social and psychological services that are of significance for the livability of modern cities and the well being of urban dwellers (Fang and Ling, 2003; Yang et al., 2005). Trees in urban areas may reduce air pollution by absorbing gaseous pollutants and storing them, thereby removing them from the atmosphere (Nowak, 1994; Nowak et al., 2006). Urban trees also moderate temperatures by providing shade and cooling an area, thus helping reduce the risk of heat-related illnesses for city dwellers (Blum et al., 1998; Cummins and Jackson, 2001; Nowak and Dwyer, 1997; Nowak et al., 1998). A park experience may also reduce stress (Hull and Michael, 1995; Ulrich, 1981; Woo et al., 2009), enhance contemplation, rejuvenate the city dweller and provide a sense of peace and tranquility (Kaplan, 1985; Song et al., 2007). Open spaces such as public parks, natural areas and golf courses may also increase the sale price of nearby homes (Conway et al., 2008; del Saz Salazar and García Menéndez, 2007; Jim and Chen, 2006; Kong et al., 2007).

Additionally, parks often serve as sites of physical activity. Regular physical activity is associated with enhanced health and reduced risk for all-cause mortality, heart disease, diabetes, hypertension, mental illness, cancer and musculoskeletal problems (Anon, 1996; Barton and Pretty, 2010; Bush et al., 2007; Casey et al., 2008; Woodcock et al., 2009). Recent research indicates that proximity to parks and green space may also modify the well-established relationship between socioeconomic position (SEP) and mortality from cardiovascular disease. Across England, for example, persons living in areas with low levels of green space had higher levels of income-related disparities in

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cardiovascular outcomes than did persons living in areas with higher green space levels (Hartig, 2008).

Some researchers, however, have cautioned that people may experience increased health risks from exposure to air contaminants during exercise because ambient air pollution affects health (Atkinson et al., 2001; Gent et al., 2003; Nel, 2005) and exercise may amplify respiratory uptake and deposition of air pollutants in the lungs (Campbell et al., 2005; de Nazelle and Rodriguez, 2009; Sharman, 2005). McCurdy (1997) found that activities with an hourly breathing rate between 25 and 45 L/min (e.g. walking, cycling) could lead to high intake doses of ozone (O_3) for children and adolescents aged 6–13 years in the Los Angeles Metropolitan Area. Hollenbach et al. (2006) found that presence of PM_1 (particulate matter with diameter less than 1 μm) at athletic fields near major traffic areas might pose significant health risks to exercising athletes since the deposition fraction (ratio of number of particles inhaled to particles deposited in a given region) nearly doubled from rest to intense exercise. A case–control study on children showed that regular physical activity had a beneficial effect on cardiopulmonary fitness in terms of maximal oxygen uptake in low-pollution areas but not in high-pollution areas (Yu et al., 2004). A cohort study also showed that new onset asthma in children aged 10–18 years was associated with increased participation in team sports in communities with high concentrations of O_3 but not in communities with low O_3 levels (McConnell et al., 2002). Exercising in a park with high air pollution or in proximity to sources of air pollution may therefore induce adverse rather than beneficial health effects.

Environmental justice researchers have demonstrated that low income communities and communities of color face a disproportionately high frequency and magnitude of impacts from environmental degradation and hazards. To our knowledge, there has been little investigation on whether disadvantaged populations face higher pollution levels at public parks (during daily exercise or social activities) and around those public parks (when engaging in outdoor and indoor activities in their neighborhoods). In this paper we investigated ambient pollutant concentrations of nitrogen dioxide (NO_2), fine particulate matter ($PM_{2.5}$, particles with aerodynamic diameter less than or equal to 2.5 μm) and O_3 at public parks and park-adjacent neighborhoods, and modeled corresponding inequalities in exposure to these three air pollutants. Inequality in inhalation doses to the three pollutants was also investigated for children and adolescents aged 6–15 years performing moderate physical activity in park-adjacent neighborhoods and high intensity physical activity at public parks.

2. Materials and methods

2.1. Study area

Los Angeles is a megacity that influences global social, environmental and economic trends (O'Connor, 2010). With a metropolitan population of 17.7 million, Los Angeles is the largest metropolitan area in the state of California and the second-largest in the United States (U.S.) (Fig. 1). The link between the ports of Los Angeles–Long Beach and logistics facilities in the eastern part of the metropolitan area generates high volumes of truck traffic in the region (Hricko, 2008; Mortimer, 2008). The region is also highly dependent on automobiles for transportation, further increasing emissions of air pollutants. Pollution levels are made worse by consistent onshore breezes that push pollution inland toward steep mountain ranges. Because of this, temperature inversions occur regularly (Moore et al., 2007) and air pollution is kept near the ground. Los Angeles still ranks as the most polluted city in the United States (Sciences Daily, 2007), even though its pollution levels have declined over the past three decades.

This study focuses on an area of over 5.5 million acres that spans five Los Angeles area watersheds: the Los Angeles River, Calleguas Creek, Santa Clara River, San Gabriel River and a series of smaller streams that drain into the Santa Monica Bay. This region includes most of Los Angeles County, a large part of Ventura County and the northwest portion of Orange County. Data on parks were collected for this study area as part of the Green Visions Plan for 21st Century Southern California (www.greenvisionsplan.net), hereafter referred to as GVP. The spatial distribution of the GVP parks is displayed in Fig. 1.

2.2. Methodological overview

Several methods were used to estimated ambient air pollution levels and to identify socioeconomic or racial-ethnic inequalities in exposure to ambient air pollution in and around public parks (see Fig. 2 for a flow diagram). Criteria pollutants NO_2, $PM_{2.5}$ and O_3 were measured separately and then modeled using land use regression or kriging techniques to create pollution surfaces for the Los Angeles region. The pollutant concentrations were then overlaid with the GVP public parks layer to estimate pollutant concentrations at those parks. A quarter-mile ($\sim$0.4 km) buffer distance to the GVP parks was used to define park-adjacent neighborhoods. The reason for using a quarter-mile distance was because this distance affords easy access (10–15 min of travel time) for children going to a park on foot or bike and is widely utilized in the urban parks literature to define park catchment areas, based on behavioral studies. In addition, this buffer is often codified in municipal policy and used to assess adequacy of park space provisions (Dill, 2004; Sister et al., 2009; Wolch et al., 2005). Within park-adjacent neighborhoods (the area 1/4 mile away from a park, along the road network), we employed a continuous measure of exposure to assign likely average exposures. Some change in this average would occur if we expanded the buffers to cover larger areas, and we recognize this as one limitation of not having precise travel information on park users in adjacent neighborhoods. Socioeconomic and racial-ethnic characteristics in park-adjacent neighborhoods were then estimated using a proportion algorithm by intersecting the corresponding census tract level statistics. The socioeconomic and racial-ethnic characteristics were modeled against air pollution estimates to identify inequalities in exposure to the three criteria air pollutants at the parks. In addition, the pollutant concentrations of the three pollutants in park-adjacent neighborhoods were estimated by overlaying the pollutant concentrations estimated at the regional level with the neighborhood boundaries. The socioeconomic and racial-ethnic characteristics of park-adjacent neighborhoods were then used to regress against the three pollutant concentrations separately to model their inequalities in exposure to air pollution. Specifically, we captured inequalities in terms of socioeconomic status or race-ethnicity with the model prediction coefficients. The difference in inequality (either in socioeconomic status or racial-ethnic representation) between any two geographic domains (e.g., parks vs park neighborhoods) was estimated by comparing the regression coefficients of the characteristics from two models through a random effect *Q*-test (Cochran, 1954). The *Q*-test requires that the two models for comparison have the same prediction covariates. We compared inequalities in the three pollutants between three geographic domains: public parks, park-adjacent neighborhoods and the entire region. Lastly, inequalities in total inhalation doses were compared between the top and bottom quartiles of racial-ethnic composition through the U.S. Environmental Protection Agency (EPA) recommended ventilation rates and time activity patterns.

2.3. Parks in the Los Angeles region

The GVP parks layer used in this study was created by pooling together data from the following sources: ESRI's Business Analyst (ESRI, Redlands, CA), land use/land cover data from the Southern California Association of Governments (SCAG, Los Angeles, CA), coastal access information from the California Coastal Commission (Long Beach, CA) and Thomas Brothers Maps (Rand McNally, Irvine, CA), with the latter used mainly for cross-referencing and verification (Sister et al., 2009). From these sources, a total of over 1800 park polygons were identified. To restrict our analysis to urban areas, we excluded Angeles National Forest Los Padres National Forest and Santa Monica Mountains National Recreation Area. We assumed a walking distance of less than 10 min (or 1/4 mile) was reasonable for children and adolescents, the most likely park users (Wolch et al., 2005). Hence, quarter-mile network buffers (i.e., reflecting actual walking distance on streets) were created using TeleAtlas Dynamap 2000 (Lebanon, NH) to define park-adjacent neighborhoods.

2.4. Pollution sampling and modeling

2.4.1. Nitrogen dioxide

Modeling NO_2 for Los Angeles has been described elsewhere (Su et al., 2009a). Briefly, 201 monitors were deployed at the same locations over the winter and summer of 2006. Neighborhood NO_2 measurements were then used to develop a land use regression (LUR) model for the Los Angeles metropolitan area. LUR treats the pollutant of interest as the dependent variable and seeks to predict concentrations of the pollutant at a given site based on surrounding land use and traffic characteristics. Typically, land-use regression models use land use classification (e.g., commercial, industrial, institutional), road network, traffic, population distribution and physical properties (Jerrett et al., 2005). These variables were also applied in our modeling process. In addition, we used new sources of land use information such as remote sensing-derived greenness and soil brightness. The resulting model explained 86% of the variance in measured NO_2. Cross validation analysis based on 16 locations left out of the original modeling procedure had 87% prediction accuracy. The calibrated model was then used to predict pollution levels in and around public parks in the GVP.

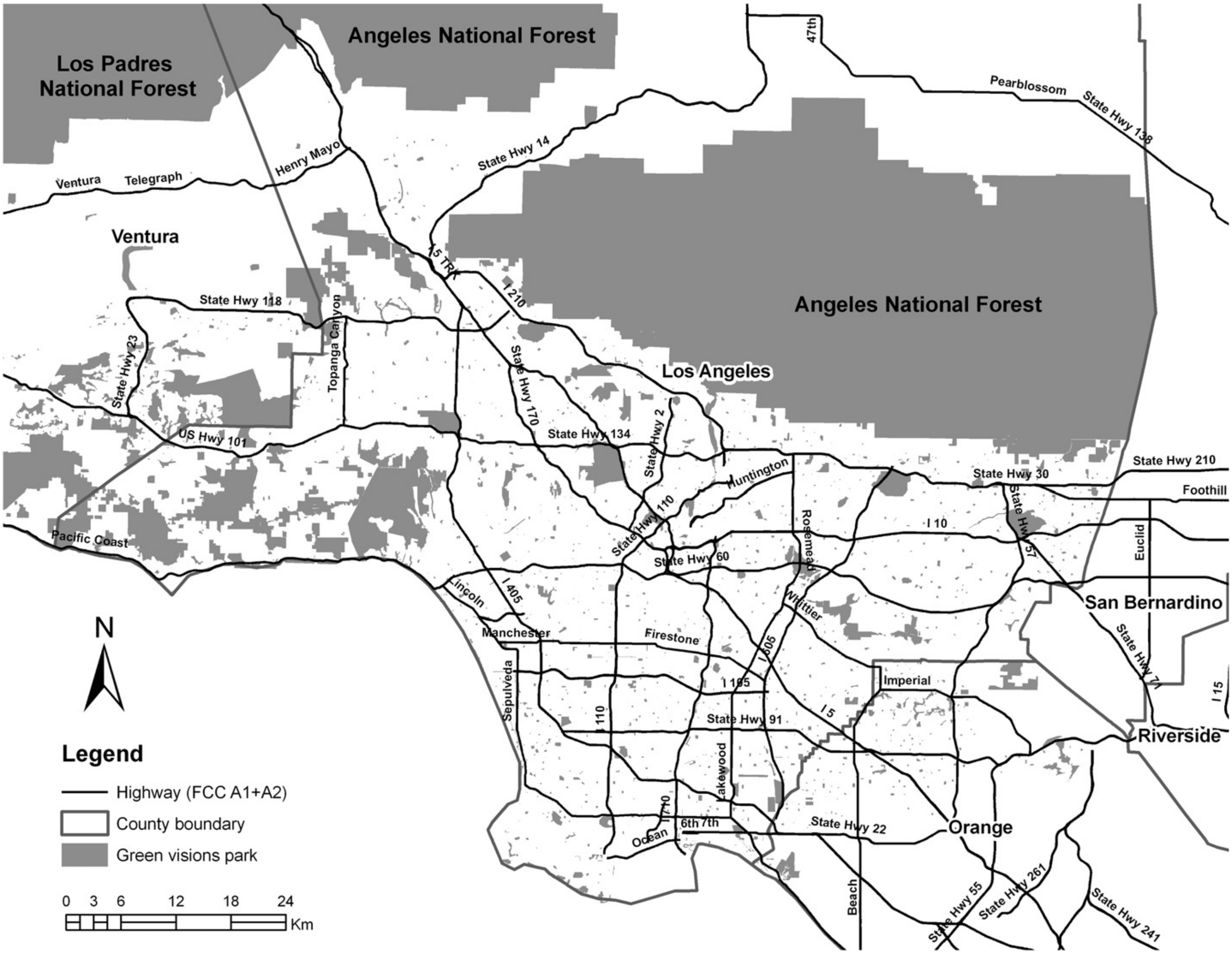

Fig. 1. Green visions parks in the Los Angeles region.

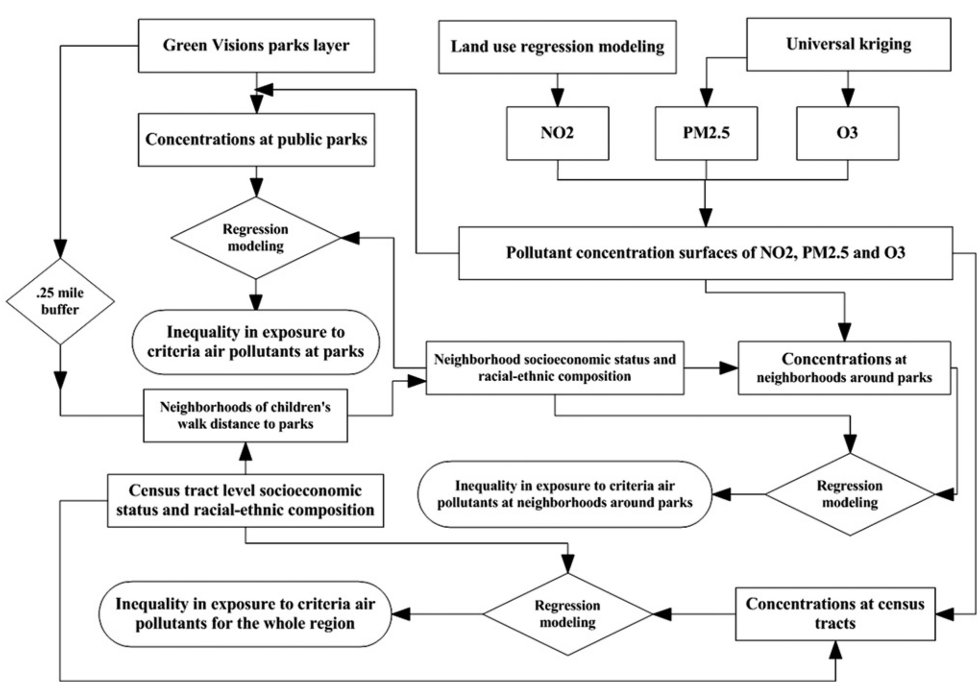

Fig. 2. Diagram of modeling inequality in exposure to criteria pollutants NO_2, $PM_{2.5}$ and O_3 at public parks, park-adjacent neighborhoods and the entire region.

2.4.2. Fine particles

To estimate exposure, we interpolated $PM_{2.5}$ data from 23 state and local district monitoring stations in the Los Angeles basin for year 2000 with a kriging model. We used a universal kriging algorithm. Further detail is given elsewhere (Jerrett et al., 2005).

2.4.3. Ozone

For O_3, we obtained data for 42 sites in and around the Los Angeles basin from the California Air Resources Board database. We interpolated a pollution surface using a universal kriging algorithm based on the average of the four highest 8-h concentrations over year 2000.

2.5. Inequality in exposure to air pollution in three geographic domains

The socioeconomic and racial-ethnic characteristics of park-adjacent neighborhoods were treated as independent variables and were derived from census tract data (from the U.S. Census Bureau for 2000) based on the proportion algorithm by intersecting the quarter-mile network buffers with the census tract boundaries. The socioeconomic and racial-ethnic variables included percent Hispanic, percent non-Hispanic African American, percent non-Hispanic Asian, median household income, per capita income, median family income, percent population over 25 with education attainment less than grade 9 and percent population over 16 in manufacturing occupations. The pollutant concentrations of NO_2, $PM_{2.5}$ and O_3 at public parks were treated as dependent variables and the arithmetic mean concentration of a pollutant at a park was treated as the concentration for that park. Neighborhood socioeconomic and racial-ethnic characteristics were modeled against each of the three pollutant concentrations at public parks. Regression coefficients were used to identify the degree of inequality in exposure to air pollution. Models were checked with standard diagnostics for outliers and heteroscedasticity.

We hypothesized that because of high dependency on motor vehicles for transportation in Los Angeles, parks are destinations that may have high traffic volumes in the nearby neighborhoods. The added traffic around public parks may therefore increase air pollution in those neighborhoods. Similar to the estimates for pollutant concentrations at public parks, the arithmetic mean concentration for a park-adjacent neighborhood was treated as the concentration of that neighborhood. Socioeconomic and racial-ethnic inequalities in park-adjacent neighborhoods were investigated using the same techniques as for identifying inequalities at public parks.

Separate models were run not only for parks and park-adjacent neighborhoods, but also for the entire region to test for socioeconomic and racial-ethnic inequalities in air pollution exposure across the three geographic domains. These regression models are displayed as

$$Y_{i,j} = b_0 + b_1 X_{1,i,j} + b_2 X_{2,i,j} + b_3 X_{3,i,j} + \varepsilon_{i,j} \quad (1)$$

For NO_2, $Y_{i,j}$ is the modeled pollutant concentration of NO_2 at domain i ($i=1$ for public parks, $i=2$ for park neighborhood and $i=3$ for the entire region) in neighborhood j; $X_{1,i,j}$ and $X_{2,i,j}$ are percent Hispanic and percent non-Hispanic Asian at domain i in neighborhood j; $X_{3,i,j}$ is the residual from modeling household income against percent Hispanic at domain i in neighborhood j. $\varepsilon_{i,j}$ is the prediction residual at domain i in neighborhood j. Because of collinearity between percent Hispanic and median household income, these two variables were not maintained in the model at the same time. The bivariate model residual from predicting percent Hispanic using median household income was used for NO_2 prediction because of its significance in the model at the 0.05 level. For $PM_{2.5}$, the model is the same as Eq. (1) but with $Y_{i,j}$ as the modeled pollutant concentration of $PM_{2.5}$ at domain i in neighborhood j; $X_{1,i,j}$, $X_{2,i,j}$ and $X_{3,i,j}$ are, respectively, the percent Hispanic, percent non-Hispanic Asian and percent non-Hispanic African American at domain i in neighborhood j. For O_3, the model is the same as Eq. (1) but with $Y_{i,j}$ as the modeled pollutant concentration of O_3 at domain i in neighborhood j; $X_{1,i,j}$, $X_{2,i,j}$ and $X_{3,i,j}$ are, respectively, the percent non-Hispanic African American, percent population in manufacturing and number of households at domain i in neighborhood j. The models shown above were selected from a larger array of variables through a manual forward selection process.

The inequalities in the entire region were used as a baseline against which to assess whether inequalities in and around the parks reflected broader patterns of social inequity that have been documented in Los Angeles (Marshall, 2008; Morello-Frosch et al., 2002; Su et al., 2009b) or were following different patterns of inequality than the entire region (e.g. parks with higher proportion of racial-ethnic minority composition or lower socioeconomic position had steeper gradients of exposure inequality than the entire region). In modeling inequalities for the entire region, the concentrations of NO_2, $PM_{2.5}$ and O_3 for each census tract were extracted from the above modeled pollution surfaces and then modeled separately against the above mentioned socioeconomic and racial-ethnic factors, also at the census tract level. In the modeling process, we restricted the spatial variables maintained in models of a pollutant prediction to be the same across the three domains—models for public parks, park-adjacent neighborhoods and the entire region—to identify differences of inequality. A random effects Q-test, a statistical test defined by Cochran (1954), was applied to identify such differences in the coefficients for different social groups across the three models. The Q-test for a variable of interest was defined as

$$Q = \sum w_i (T_i - \overline{T})^2$$
$$\text{where } \overline{T} = \frac{\sum_i w_i T_i}{\sum_i w_i} \text{ and } w_i = \frac{1}{s_i^2} \quad (2)$$

where T_i is the effect size (i.e., the regression coefficient) of the variable of interest in model i; s_i is the standard error of the variable of interest in model i. The comparison was made on a variable of interest between two domain models of a pollutant, so $i=1$ or 2. The Q-test determines whether, for example, the regression coefficient is different for the park-adjacent neighborhoods compared to the entire region. Comparisons between any two prediction models of a pollutant were conducted variable by variable for each individual predictor maintained in the models, and the significance of difference in inequality from that pollutant was examined. In addition, we tested models across the three geographic domains and the three pollutants using all the spatial covariates identified as significant in the bivariate model, to test the degree of inequality of all those predictor variables.

2.6. Inhalation dose inequality between neighborhoods by race-ethnicity

The U.S. EPA classifies daily activities as sedentary and passive, light, moderate and high intensity categories (U.S. Environmental Protection Agency, 2006). The total time spent in a day for moderate and high intensity activities based on the U.S. EPA statistics is around 3 h for children and adolescents aged 6–15 years. Hofferth (2009) investigated children and adolescents' change of time spent in physical activities from 1997 to 2003 and also found that on average a child aged 6–12 spent around 3 h with outdoor play, sports and other physical activities. Because our research interests were to model inequalities in inhalation doses of outdoor air pollution, we adopted a scenario assuming those moderate and high intensity activities performed by children and adolescents took place outdoors. We recognize that some of these activities could occur indoors, which would reduce the inhalation doses assuming infiltration factors of less than 1 and similar activity levels. We estimated annual average daily inhaled doses (AADID) of a pollutant for a typical U.S. child or adolescent aged 6–15 playing at a location using ventilation rates recommended by the U.S. EPA (Table 1). Recent studies from England combining objective measures of physical activity and geographic location indicate that time spent outdoors is usually more active than time spent indoors (Cooper et al., 2010). We surmised, therefore, that children and adolescents play high intensity activities in places with more space available and moderate intensity activities with less spaces required. Specifically, to illustrate maximal exposure differences we used the worst-case scenario to assume that children and adolescents engaged in high intensity activities at public parks and moderate intensity activities in their own outdoor neighborhood environments (i.e., park-adjacent neighborhoods, including back yards). The AADID calculated thus included only inhalation doses from moderate and high intensity activities in these two environments. For illustration, we restricted the analysis to children and adolescents living in park-adjacent neighborhoods. The AADID of a pollutant was derived from de Nazelle et al. (2009) and represented as

$$AADID_{i,j} = \sum_{k=1}^{2} (t_{i,k} * v_k) * P_{i,j} \quad (3)$$

where $AADID_{i,j}$ is the daily inhaled dose (μg per day) of pollutant j in environment i; $t_{i,k}$ is the time spent at activity level k ($k=1$ for moderate and $k=2$ for high intensity activities) in environment i; v_k is the ventilation rate of a child or adolescent when having activity level k, and $P_{i,j}$ is the ambient concentration of pollutant j in environment i. Based on the United States EPA recommendations (Table 1), a typical child or adolescent in the United States aged 6–15 years spent 2.4 h performing moderate activities and 0.31 h doing high intensity activities in a day with respective ventilation rates of 23.31 and 45.10 L/min. The corresponding total daily air intakes were 3353 and 839 L/day for moderate and high intensity activities.

Table 1
The U.S. EPA suggested durations of moderate and high intensity activities and ventilation rates for children and adolescents aged 6–15 years.

	Age	Moderate intensity		High intensity	
		Male	Female	Male	Female
Activity duration (h/day)	6–10	2.66	2.57	0.32	0.24
	11–15	2.35	2.01	0.38	0.30
	Mean	2.40		0.31	
Ventilation rate (L/min)	6–10	22.28	21.00	43.62	39.39
	11–15	26.40	23.55	50.82	46.56
	Mean	23.31		45.10	
Ventilation (L/day)	Mean	3353		839	

3. Results

3.1. Pollutant concentrations across geographic domains

Comparison between the mean pollutant concentrations for public parks, park-adjacent neighborhoods and the entire region (Table 2) showed that public parks had the lowest NO_2 (12.76 ppb) and $PM_{2.5}$ (18.30 μg m^{-3}) concentrations (compared to 19.33 ppb and 19.76 μg m^{-3} in the region, respectively). There were relatively higher O_3 (83.08 ppb) concentrations at the parks compared to park-adjacent neighborhoods (80.21 ppb). Park-adjacent neighborhoods had the highest NO_2 (21.01 ppb) and $PM_{2.5}$ (20.27 μg m^{-3}) concentrations compared to both the parks and the entire region, but the lowest O_3 (80.21 ppb) concentrations. The above descriptive statistics were size adjusted (e.g., the mean pollutant concentration at all public parks = Σ (area of a park*concentration at that park)/(total area of all the parks) to avoid attenuating the importance of high concentrations at smaller parks. Public parks showed higher variation of pollutant concentrations compared to the entire region, especially for NO_2 (Table 3).

3.2. Inequality in exposure to air pollution

3.2.1. Nitrogen dioxide

NO_2 concentrations were positively associated with Hispanic ($p < 0.05$) and non-Hispanic Asian (< 0.05) demographic characteristics in public parks, park-adjacent neighborhoods and the entire region. As expected, NO_2 was negatively associated with median household income (< 0.05) in the three geographic domains (Table 3). In agreement with model predictions, public parks and park-adjacent neighborhoods had higher absolute coefficients compared to the regional model, demonstrating higher NO_2 exposure inequality in park-adjacent neighborhoods characterized by Hispanic, Non-Hispanic Asian and low median household income populations. The prediction power decreased from park neighborhood to public park and then to the whole region (R^2 = 0.55, 0.53 and 0.46). Based on comparison of the same parameter between any two geographic domains, all the socio-economic/racial-ethnic variables were significantly different (< 0.05) from variables presented in the regional model, with non-Hispanic Asians being at the borderline level (Table 4). The differences, however, between public parks and park-adjacent neighborhoods in exposure to NO_2 were not significant for each of the racial-ethnic and socioeconomic measures (all the p-values > 0.8, Table 4).

3.2.2. Fine particles

$PM_{2.5}$ concentrations were positively associated with Hispanic ($p < 0.05$), non-Hispanic Asian (< 0.05) and non-Hispanic African American (< 0.05) characteristics for all three domains (Table 3). Similar to NO_2 modeling results, public parks and park-adjacent

Table 2
Air pollution concentrations at public parks, park-adjacent neighborhoods and the entire region.

Scope of comparison	NO_2 (ppb)[a]				$PM_{2.5}$ (μg m^{-3})[a]				O_3 (ppb)[a]			
	Mean	Min	Max	Var.	Mean	Min	Max	Var.	Mean	Min	Max	Var.
Public parks[b]	12.76	5.22	49.97	33.16	18.30	11.68	24.52	5.01	83.08	42	134	381
Park-adjacent neighborhoods[b]	21.01	5.31	50.07	32.01	20.27	11.73	24.31	5.02	80.21	42	134	382
The entire region[c]	19.33	6.26	47.73	23.40	19.73	12.19	24.25	4.07	86.70	44	134	379

[a] NO_2 was measured and then modeled using a land use regression model from 201 sampling sites which were measured from two sampling campaigns of two weeks each in 2006. Sampling was conducted at times of the year when concentrations were most correlated with the seasonal averages for the cold and warm seasons. Our analysis of interclass correlations suggested that two rounds of measurement had the capacity to replicate the pattern of spatial variation well (see Su et al., 2009a, 2009b for more details). $PM_{2.5}$ and O_3 were derived through kriging algorithms from 23 and 42 sites, respectively, both measured in year 2000; all the estimates were for annual averages. The national ambient air quality for NO_2, $PM_{2.5}$ and O_3 are 53 ppb (annual), 15.0 μg m^{-3} (annual) and 75 ppb (8-h), respectively.

[b] Excludes the two largest parks and corresponding network buffers.

[c] Includes all the census tracts in Los Angeles County.

Table 3
Modeling inequalities in exposure to ambient pollutants using socioeconomic/racial-ethnic variables at public parks, park-adjacent neighborhoods and the entire region.

Pollutant	Variable	Public park			Park neighborhood			The entire region		
		Coefficient	Std. error	p-value	Coefficient	Std. error	p-value	Coefficient	Std. error	p-value
NO_2	Intercept	1.53E+01	2.32E−01	0.000	1.54E+01	2.19E−01	0.000	1.69E+01	1.85E−01	0.000
	Percent Hispanic	1.32E−01	4.11E−03	0.000	1.33E−01	3.89E−03	0.000	1.05E−01	2.87E−03	0.000
	Percent non-Hispanic Asian	1.02E−01	7.91E−03	0.000	1.01E−01	7.47E−03	0.000	8.23E−02	6.07E−03	0.000
	Resid. from median household income[a]	−1.02E−04	5.83E−06	0.000	−9.96E−05	5.51E−06	0.000	−6.86E−05	4.12E−06	0.000
	Coefficient of Determination (R^2)		0.53			0.55			0.46	
$PM_{2.5}$	Intercept	1.81E+01	1.29E−01	0.000	1.82E+01	1.19E−01	0.000	1.84E+01	1.04E−01	0.000
	Percent Hispanic	3.89E−02	2.13E−03	0.000	3.90E−02	1.97E−03	0.000	3.29E−02	1.46E−03	0.000
	Percent non-Hispanic Asian	4.76E−02	4.15E−03	0.000	4.64E−02	3.83E−03	0.000	4.29E−02	3.16E−03	0.000
	Percent non-Hispanic African American	2.40E−02	4.14E−03	0.000	2.32E−02	3.83E−03	0.000	2.32E−02	2.67E−03	0.000
	Coefficient of Determination (R^2)		0.23			0.26			0.22	
O_3	Intercept	9.14E−02	1.27E−03	0.000	9.15E−02	1.25E−03	0.000	9.85E−02	1.52E−03	0.000
	Percent non-Hispanic African American	−3.26E−04	3.67E−05	0.000	−3.26E−04	3.62E−05	0.000	−4.00E−04	2.56E−05	0.000
	Percent population in manufacturing	−5.17E−04	7.24E−05	0.000	−5.17E−04	7.15E−05	0.000	−6.73E−04	4.94E−05	0.000
	# households	−4.58E−06	1.13E−06	0.000	−4.71E−06	1.11E−06	0.000	−2.36E−06	6.06E−07	0.000
	Coefficient of Determination (R^2)		0.10			0.11			0.16	

[a] Refers to the residual from modeling median household income against percent Hispanic. Because of collinearity between percent Hispanic and median household income, these two variables were not maintained in the model at the same time. The bivariate model residual from predicting percent Hispanic using median household income was used for NO_2 prediction because of its significance in the model at the 0.05 level.

Table 4
Q-test of significance in difference between public parks, park-adjacent neighborhoods and the entire region for modeling socioeconomic/racial-ethnic variables.

Pollutant	Variable	Park vs Park-adjacent		Park-adjacent vs Region		Park vs Region	
		Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
NO_2	Percent Hispanic	1.33E−01	0.947	1.15E−01	0.000	1.14E−01	0.000
	Percent non-Hispanic Asian	1.02E−01	0.959	8.98E−02	0.049	8.95E−02	0.051
	Resid. from median household income[a]	−1.01E−04	0.811	−7.97E−05	0.000	−7.96E−05	0.000
$PM_{2.5}$	Percent Hispanic	3.90E−02	0.962	3.51E−02	0.012	3.48E−02	0.019
	Percent non-Hispanic Asian	4.69E−02	0.838	4.43E−02	0.485	4.46E−02	0.376
	Percent non-Hispanic African American	2.36E−02	0.882	2.32E−02	0.999	2.34E−02	0.864
O_3	Percent non-Hispanic African American	−3.26E−04	0.994	−3.75E−04	0.095	−3.76E−04	0.100
	Percent population in manufacturing	−5.17E−04	0.997	−6.23E−04	0.071	−6.24E−04	0.074
	# households	−4.65E−06	0.934	−2.90E−06	0.064	−2.86E−06	0.083

[a] The same definition as in Table 3.

Table 5
Comparison of the total daily inhalation doses for children and adolescents aged 6–15 years while pursuing moderate intensity physical activities in their own neighborhoods and high intensity activities at public parks.

Pollutant	Top quartile			Bottom quartile			Difference					
	Hispanic	NHAM[a]	NHA[b]	Hispanic	NHAM[a]	NHA[b]	Hispanic		NHAM[a]		NHA[b]	
NO_2 (μg /day)[c]	206,074	187,276	181,087	126,279	172,023	176,128	79,795	63.19%	15,254	8.90%	4,959	2.82%
$PM_{2.5}$ (μg/day)	90,489	86,915	87,122	79,402	86,656	86,644	11,088	13.96%	259	0.30%	479	0.55%
O_3 (μg /day)[c]	663,684	606,164	668,282	647,420	669,637	617,502	16,264	2.51%	−63,473	−9.50%	50,780	8.22%

[a] NHAM=Non-Hispanic African American.
[b] NHA=Non-Hispanic Asian.
[c] To be consistent with inhalation dose measures, gaseous pollutant concentrations of NO_2 and O_3 were converted from ppb to $\mu g m^{-3}$. Assuming a temperature of 20 °C, for NO_2 1 ppb=1.913 $\mu g m^{-3}$ and for O_3 1 ppb=2.00 $\mu g m^{-3}$.

neighborhoods had higher prediction coefficients for Hispanic and non-Hispanic Asian measures, but they were not higher for African American composition compared to the regional model, demonstrating higher $PM_{2.5}$ exposure inequality for Hispanics and non-Hispanic Asians around the parks. Though the prediction powers showed a similar pattern to NO_2 (i.e., decreased from park neighborhood to park and to region), the overall prediction power for $PM_{2.5}$ was much smaller than for NO_2 with the highest prediction power being 0.26 (R^2). Comparing between the modeled coefficients, these differences were not significant (>0.3) except for Hispanic composition (<0.05) (Table 4). Between public parks and park-adjacent neighborhoods, none of the racial-ethnic or socioeconomic measures were found to be significantly different (all *p*-values >0.8, Table 4).

3.2.3. Ozone

O_3 concentrations were negatively associated with African American population composition ($p<0.05$), populations employed in manufacturing industries (<0.05) and the number of households in the neighborhood (<0.05) (Table 3). Based on the model prediction coefficients, public parks and park-adjacent neighborhoods had lower absolute values for African Americans and populations employed in manufacturing but not for the number of households compared to the regional model, demonstrating lower O_3 exposure inequalities for African Americans and manufacturing industry workers in and around the parks. The prediction power for O_3 in the three geographic domains was the smallest with the highest R^2 being 0.16. Comparing between the model prediction parameters, all these differences were shown to be insignificant ($p>0.05$), although they were borderline significant with *p*-values less than 0.1. These findings suggest the inequality in exposure to O_3 in the three geographic domains might follow a relatively weak but positive social gradient, rather than the negative association observed with NO_2 and $PM_{2.5}$.

Overall, the prediction power (measured by R^2) decreased from NO_2, to $PM_{2.5}$ and to O_3. As a sensitivity analysis, we tested exposure inequality with all the available significant socioeconomic and racial-ethnic factors in the same model, including: percent Hispanic, percent non-Hispanic Asians, percent non-Hispanic African Americans, percent population employed in manufacturing, percent population under two times federally defined poverty level, median household income and percent of population with low educational attainment (less than grade 9). This model showed little improvement over the parsimonious models (based on R^2). Consistently, the Hispanic population had higher exposures to NO_2, $PM_{2.5}$ and O_3. Asian and African American populations had higher exposure to NO_2 and $PM_{2.5}$ compared to regional averages but not for O_3. By contrast, higher median household income neighborhoods were consistently associated with lower exposure to NO_2, $PM_{2.5}$ but higher O_3. Neighborhoods with higher proportions of manufacturing workers were associated with lower exposure to O_3.

3.3. Inhalation dose inequality across racial-ethnic groups

We assessed inhalation inequalities for children and adolescents aged 6–15 years residing in park-adjacent neighborhoods. The comparison was made between the top and bottom quartiles of racial-ethnic composition. We assumed that children and adolescents from both top and bottom quartile groups had the same ventilation rate when engaging in the same level of activity. Using Eq. (1) we found that children and adolescents residing in primarily Hispanic-dominated neighborhoods had an AADID of 206,074 μg/day from inhalation of NO_2 during their outdoor activity, or 63.2% greater than those living in the least Hispanic quartile neighborhoods (Table 5). These differences were 11,088 μg/day (or 14% increase) and 16,264 μg /day (2.5%) for inhalation from $PM_{2.5}$ and O_3. The inequalities in inhalation doses decreased from NO_2, to $PM_{2.5}$ and to O_3 for the Hispanic population.

For residents in neighborhoods falling into the top quartile of the non-Hispanic African American population, the AADID from high and moderate intensity activities was 187,276 μg/day, 8.9% greater than the lowest quartile counterpart for NO_2. These differences were 259 μg/day, 0.3% higher for $PM_{2.5}$ but 63,473 μg/day (9.5%) lower for O_3. The degree of inhalation dose inequality for the non-Hispanic African Americans decreased from NO_2 to $PM_{2.5}$ but had an inverse relationship with O_3. The overall inhalation dose inequality, though, was less than that for the Hispanic population.

For the non-Hispanic Asian population, these inhalation dose differences were generally lower compared to the Hispanic and non-Hispanic African American populations, but the top quartile neighborhoods always had higher exposures compared to the bottom quartile counterpart for NO_2, $PM_{2.5}$ and O_3.

4. Discussion and conclusion

Children and adolescents frequent recreational opportunities close to home (Gordon-Larsen et al., 2006; Grow et al., 2008), especially those offering unstructured activity space, such as parks and walking/running tracks (Grow et al., 2008). Parks may play a role in purifying the environment either by removal of the pollutants by plants or by buffering from emission sources (Bedimo-Rung et al., 2005; Crompton, 1999; Nowak et al., 2006); however, parks and adjacent neighborhoods may also be places of heightened physical activity that may increase air pollution inhalation doses and have negative health effects. NO_2, $PM_{2.5}$ and O_3 have all been linked to adverse effects on human health (Chen et al., 2008; Jerrett et al., 2009a, 2009b; Pope and Dockery, 2006). For these reasons, we investigated inequalities in exposure to NO_2, $PM_{2.5}$ and O_3 for people living in proximity to public parks. A quarter-mile buffer distance to public parks was used as a proxy for park-adjacent neighborhoods. We also investigated inhalation doses for children and adolescents aged 6–15 years playing at their neighborhood parks and in park-adjacent neighborhoods in Los Angeles. In our study, levels of $PM_{2.5}$ and NO_2 concentrations were lower at public parks than the entire region. O_3 followed the opposite pattern. Probably because of atmospheric chemical reactions and the "scavenging" of O_3 by nitric oxide (NO) emissions, O_3 concentrations were lower in roadways and in the park-adjacent neighborhoods where traffic was high. By contrast, O_3 was comparatively higher in public parks.

In our calculation of average pollutant concentrations for public parks in Los Angeles, the statistics were size adjusted. When no size adjustment was made, our results showed that pollutant concentrations at the parks were similar to the entire region. This is because the majority of the parks in the Los Angeles region are small (see Fig. 1), and they are not far away from major highways. In examining the distance of a public park to the nearest freeway, we found that more than 50% of parks in the study region were located within 1 km of freeways and 30% were within 500 m (Fig. 3). Those parks within 1 km of freeways had higher annual ambient concentrations of NO_2 (23 ppb) and fine particles (21 $\mu g/m^3$) than the other parks. They were also higher in concentration than the other parks and the regional averages (19 ppb and 20 $\mu g/m^3$, respectively). NO_2 and $PM_{2.5}$ concentrations in the parks decreased significantly when they were further away from freeways (correlation coefficient $r = -0.50$ for NO_2 and -0.32 for $PM_{2.5}$), but there was a slight increase for O_3 ($r = 0.06$). Because regular physical exercise might have an adverse effect on cardiopulmonary health in terms of pollutant uptake in the high-pollution areas, further investigation of potential exposures for children and adolescents playing in parks with high pollutant concentrations appears warranted. Personal air sampling equipment could be used to measure individual personal air pollution exposures and accelerometers could be used to measure energy expenditure and allow more precise inhalation rate calculations. Intermediary health indicators such as fitness, markers of inflammation and oxidative stress could also be measured before, after or during a physical activity. Air pollution exposures and inhalation doses could then be linked to those intermediary biomarkers to identify possible associations in a more complete way.

Park-adjacent neighborhoods had the highest levels of pollution such as NO_2 and $PM_{2.5}$ when compared to the parks themselves or the entire region. The higher air pollution in part resulted from high traffic volumes in park-adjacent neighborhoods because parks are major destinations, have been sited near arterials to enhance park access or take advantage of lower land costs. We found that park-adjacent neighborhoods had on average 1519.9 vehicle kilometers traveled (VKT) per hectare, which was more than twice that of the Los Angeles region (573.1 VKT per ha, calculated using data imputed from TeleAtlas traffic count data). In addition, because a high proportion of public parks are sited near freeways in Los Angeles, higher concentrations of traffic pollution could have damaging effects on child and adolescent health if they play in those park-adjacent neighborhoods or travel to the parks by bicycle or on foot because their inhalation rate would be heightened. Similar to inequalities identified for levels of air pollution (Su et al., 2009b), our study also revealed that children and adolescents living in low-income or minority neighborhoods and playing in the park-adjacent neighborhoods bore a disproportionate inequality in exposure to ambient air pollution (e.g., NO_2 and $PM_{2.5}$). When inequality in air pollution exposure at public parks and in park-adjacent neighborhoods was compared to the entire region, *Q*-tests still showed some significant differences, especially for the Hispanic population.

The inhalation dose characteristics for children and adolescents playing at public parks and in park-adjacent neighborhoods might be different from the entire region. Children and adolescents of color, especially Hispanics, are exposed to worse air quality and have much higher inhalation doses of pollutants compared to other counterparts. These inhalation dose inequalities decreased from exposure to NO_2 than the more spatially homogeneous fine particles; however, the pattern still existed, with parks in predominantly Hispanic neighborhoods having higher levels of inhalation doses for children and adolescents playing there. Though the inhaled dose of O_3 was found to be slightly lower for children and adolescents in the communities of high African American population composition, the higher inhalation doses of NO_2 and fine particles made the neighborhood less healthy for outdoor activities. Asian Americans were seemingly in a better position than Hispanic and non-Hispanic African American counterparts in air pollution exposure; however, they were still exposed to higher air pollution and thus higher inhaled doses compared to the population of non-Hispanic Whites.

Because of limited monitoring stations for $PM_{2.5}$ and O_3, and in the case of $PM_{2.5}$ lower inherent spatial variation (Gilliland et al., 2005), the pollutant concentration surfaces and corresponding modeled exposure inequalities and inhalation dose differences lacked the fine-scale resolution available for NO_2. The lower prediction powers from the inequality models for $PM_{2.5}$ and O_3 were partly due to their more homogeneous spatial nature, but could have been because of the lack of a dense monitoring

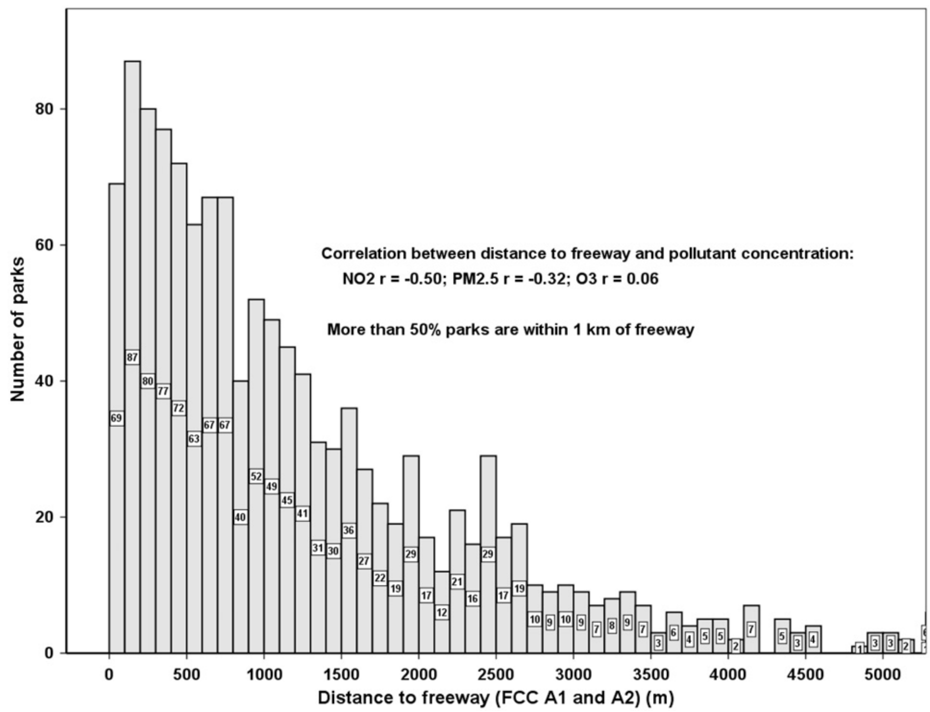

Fig. 3. The distribution of parks as a function of distance to the highways in the Los Angeles Study Area.

network. Future work is required to design sampling strategies to identify the small area variations of such pollutants near and in parks.

In this research, we assumed that the demographic characteristics of park users were the same as those of near-park residents; however, some park facilities might attract children from beyond a quarter-mile distance (for example, participants in team sports that require large playing fields such as soccer or baseball may travel from farther distances than a 1/4 mile). The level of air pollution and inhalation doses estimated for a minority or lower socioeconomic status child might be overestimated if the demographics near the park are different from the actual users. However, a majority of children spend time outdoors in close proximity (10–15 min walking distance) to home (Dill, 2004; Sister et al., 2009; Wolch et al., 2005). Thus this assumption is generally supportable. We assumed that children and adolescents played moderate and high intensity activities outdoors; however, some of these activities might take place indoors. If indoor air was not polluted and no infiltration and ventilation existed, the total inhalation doses from air pollution might be less than estimated.

We focused our inhalation dose analysis on children and adolescents aged 6–15 years to illustrate the potential impact of exposure inequalities on the inhaled dose; however, these differences could also be applied to other age groups. Similar inequalities could be found for those disadvantaged groups (i.e., low income communities and communities of color) with respect to park and park-adjacent neighborhood pollution using the U.S. EPA recommended age-specific activity patterns, ventilation rates and body weights. We used inhalation doses rather than exposure concentrations because inhalation doses allowed us to calculate the total amount when exposed at multiple locations. By contrast, it is difficult to estimate total concentrations in such situations. Another motivation was that socioeconomic status and racial-ethnic composition might affect activity patterns (amount, intensity and location of physical activity), and might affect body weight which in turn affects inhalation rates. Although no formal analysis was performed in this paper, it can be applied when such data are available. Our illustrative scenario indicates that substantial differences in the inhaled dose may exist, particularly for traffic-related pollutants such as NO_2 for Hispanic children and adolescents. The potential exposure inequalities identified in this initial research suggest more comprehensive Monte Carlo simulations may be worthwhile to assess the impacts of likely activity patterns, body weight, socioeconomic and racial-ethnic status on inhaled doses (see for example, de Nazelle et al., 2009). Further studies using global positioning systems and accelerometers should also lead to more realistic assumptions about variations in activity levels, body sizes, and inhaled dose (see e.g., (Jones et al., 2009).

In sum, public parks in Los Angeles had lower traffic-related air pollution and fine particles than the entire region. More than 50% of these public parks, however, were within 1 km of freeways, and the air pollutant concentrations in those near freeway parks were significantly higher than the entire region. Higher air pollution of NO_2 and $PM_{2.5}$ characterized public parks in low-income neighborhoods and communities of color, especially in Hispanic areas. These exposure and inhalation dose inequalities also extended to the park-adjacent neighborhoods. Los Angeles has relatively high levels of air pollution compared to other metropolitan areas in the U.S. and in the case of $PM_{2.5}$ has more within-region variations. This raises questions of the generalizability of our results to other cities in the U.S. and elsewhere. Other research into environmental exposures in other U.S. cities revealed a similar pattern of exposure inequalities with low-income communities and communities of color facing a higher frequency and magnitude of impact from environmental hazards (Morello-Frosch and Jesdale, 2006; Morello-Frosch and Shenassa, 2006; O'Neill et al., 2003). Evidence from Canada (Jerrett et al., 2001), France (Havard et al., 2009), Sweden (Chaix et al., 2006), and England (Brainard et al., 2002) found similar patterns of inequality in a wide range of environmental exposures. To our knowledge, this is the first study to investigate exposure and inhalation inequalities at and around parks; thus it is difficult to assess the generalizability of the findings. The presence, however, of inequalities in air pollution exposure in other US cities and in other countries suggests a high probability for similar exposure inequalities in other locales. From a policy perspective, these findings underscore problems of persistent urban environmental injustice, and suggest the importance of building new parks away from highways, increasing park greenness to further reduce and buffer against some forms of pollution and implementing policies that encourage non-motorized transport in and around parks, especially around parks in low income and minority communities.

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