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Inverse Relationship between Urban Green Space and Childhood Autism in California Elementary School Districts

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Abstract

Green space has a variety of health benefits. However, little is known about its impact on autism, the fastest-growing neurodevelopmental disorder in children. This study examined the relationship between green space and childhood autism prevalence. Autism count data in 2010 were obtained for 543 of ~ 560 public elementary school districts in California. Multiple types of green space were measured in each school district, including percentages of forest, grassland, and average tree canopy and near-road tree canopy. Their associations with autism prevalence were evaluated with negative binomial regression models and spatial regression models. We observed inverse associations between several green space metrics and autism prevalence in school districts with high road density, the highly urbanized areas, but not in others. According to negative binomial regression models, adjusted rate ratios (RR) for the relationships in these school districts between autism prevalence and green space metrics in 10% increments were as follows: for forest, RR = 0.90 (95% confidence interval [CI]: 0.84–0.95); for grassland, RR = 0.90 (95% CI: 0.83–0.97); for average tree canopy, RR=0.89 (95% CI: 0.83–0.95), and for near-road tree canopy, RR=0.81 (95% CI: 0.73–0.91). These results suggest that increases of 10% in forest, grassland, average tree canopy and near-road tree canopy are associated with a decrease in autism prevalence of 10%, 10% 11% and 19%, respectively. In contrast, urban land and road density were positively associated with autism prevalence. The results of spatial regression models were consistent with those obtained by negative binomial models, except for grassland. Our study suggests that green space, specifically tree cover in areas with high road density, may influence autism prevalence in elementary school children. Further studies are needed to investigate a potential causal relationship, and the major mechanisms that may underlie the beneficial associations with green space, such as buffering traffic-related air pollution and noise.

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Keywords

autism spectrum disorder; greenness; near-road tree canopy; air pollution; school children

Introduction

Autism spectrum disorders (ASD), commonly known as autism, are a group of complex neurodevelopmental abnormalities typically identified in early childhood (American Psychiatric Association 2013). Children with ASD exhibit abnormal behaviors including deficits in social interaction and communication, and repetitive patterns of behavior (Geschwind 2009; Newschaffer et al., 2007; Ozand et al., 2003). Over the past 3 decades, the rate of autism has increased dramatically. It was estimated to be approximately four to five cases per 10,000 children in the 1980s, to as high as 1 case per 68 children in 2014 (Christensen et al., 2016; Nevison 2014). Currently, autism affects more than 3 million people in the US and tens of millions in the world (Buescher et al., 2014). Since there is no cure, children with autism and their families can face a lifetime of adverse consequences related to impaired behavioral functioning (Newschaffer et al., 2007). The economic burden of autism in the US was estimated to be $268 billion in 2015 (Leigh and Du 2015); the cost may exceed $2 million for individual lifelong care (Buescher et al., 2014).

It is believed that autism results from a combination of genetic and environmental factors (Chaste and Leboyer 2012; Hallmayer et al., 2011; Newschaffer et al., 2007). Early studies focused on understanding genetic risk factors because high heritability was found in patients with autism (Bailey et al., 1995; Chaste and Leboyer 2012). The rapid increase in autism prevalence has spurred researchers to explore environmental factors (Chaste and Leboyer 2012; Dietert et al., 2011; Landrigan 2010; London 2000; McDonald and Paul 2010; Nevison 2014). Studies have linked autism to many of these, including pesticides, phthalates, polychlorinated biphenyls (PCBs), solvents, toxic waste, air pollutants and heavy metals (e.g., mercury, lead) (Becerra et al., 2013; Kalkbrenner et al., 2010; Kalkbrenner et al., 2014; Palmer et al., 2006; Raz et al., 2015; Roberts et al., 2007; Rossignol and Frye 2014; Volk et al., 2013; Windham et al., 2006). However, no single environmental factor can explain the increased prevalence of autism (Dietert et al., 2011).

Green space is land partly or completely covered with grass, trees, shrubs or other vegetation (e.g., parks, forests, green roofs, and community gardens). It has positive influences on human health through direct and indirect pathways, such as encouraging physical activity and social contact (Maas et al., 2009; Mitchell and Popham 2008; Wolch et al., 2014), and mitigating noise and traffic-related air pollution (Gidlof-Gunnarsson and Ohrstrom 2007; Mitchell and Popham 2008; Wolch et al., 2014). These influences promote physical fitness and maternal health (e.g., beneficial effects on pregnancy outcomes), and reduce the prevalence of some chronic illnesses such as obesity and cardiovascular disease (Coombes et al., 2010; Gidlof-Gunnarsson and Ohrstrom 2007; Hystad et al., 2014; Lee and Maheswaran 2011; van den Berg et al., 2015). Exposure to green space has been associated specifically with mental health (Beyer et al., 2014; Gascon et al., 2015). Access to gardens or other green space, and use of parks and playgrounds may reduce conduct and hyperactivity

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problems and improve attention and behavioral development in children, especially those with attention-deficit hyperactivity disorder (ADHD) (Amoly et al., 2014; Flouri et al., 2014; Kuo and Taylor 2004; Li and Sullivan 2016; Markevych et al., 2014; Taylor and Kuo 2009). Additionally, exposure to green space may have a long-term influence on children's cognitive development (Dadvand et al., 2015; de Keijzer et al., 2016).

In this exploratory analysis, we hypothesized that neighborhoods with more green space would have lower autism prevalence. In California, autism prevalence has increased continuously in the past 20 years (Autism Society of California 2012; Croen et al., 2002). Given its large population, California is expected to have a large number of autism cases (Autism Society of California 2012). In recent years, urbanized area has also gradually increased and vegetation cover (e.g., farmland, forest) has decreased, according to studies on land cover change in South Coast areas in California (Chen et al., 2010; Fischer et al., 2007). This study examined the association of green space (e.g., forest, grassland, tree canopy and near-road tree canopy) and autism prevalence in California elementary school districts. It presumes that children were born and raised in the school districts where they matriculated at the time of the autism data collection. This work is the first attempt to examine whether green space could help mitigate childhood autism prevalence.

Methods

Study setting

This study was carried out in California—the most populous US state, with the largest number of public school students (Keaton 2013). In California, there are about 560 public elementary school districts and 330 united school districts which include both elementary and high schools. According to statistics from the California Department of Education (http://www.cde.ca.gov/ds/sd/cb/cefenrollgradetype.asp), about 3 million children were enrolled in public elementary schools in the 2014–15 school year.

Childhood autism data

The number of children with autism in all public elementary school districts (kindergarten – grade 5, ages from 5 to 12 years) in 2010 was collected by the California special education management information system (CASEMIS) under the California Department of Education. The data are publicly accessible through the website of the Los Angeles Times (http://spreadsheets.latimes.com). The case definition of childhood autism is listed under the California Special Education Reference, Code of Federal regulations (CFR), 34 CFR Section 300.8(c)(1). Because the united school districts also include high schools, we excluded them from the analysis. We obtained autism count data and the number of students for 543 public elementary school districts, and matched these data with the location of each school district using ArcGIS 10.3 (ESRI, CA). Autism prevalence or prevalence rate was calculated using the number of autism cases divided by the number of students in these school districts.

Demographic and socioeconomic status data

Demographic and socioeconomic status (SES) data for the total population within each elementary school district were originally collected by the 2009 American Community

Survey, US Census Bureau. From these datasets, we generated 10 indicators, including the percentages of males and females, the percentages of children (age <=19) and older adults (age >=65), the percentages of white, Asian, and black populations, the percentage of households without a vehicle, the percentage of unemployed population, and median annual household income. These variables were selected because many of them were considered in other studies (Becerra et al., 2013; Volk et al., 2013) as potentially associated with autism. The percentage of households without a vehicle was selected as a potential proxy for income; it also suggests a greater likelihood of local versus more distant environmental influences during non-work hours.

2.4. Exposure to green space

We assessed exposure to green space using publicly available remotely-sensed data on general land cover composition, and both average and near-road tree canopy in each school district. The first two types of measures estimate overall outdoor greenness that may support healthful lifestyles and buffer environmental hazards in the residential vicinity. Near-road tree canopy reflects the potential buffering effect of tree cover on exposure to traffic-related noise and air pollution; the latter in particular has been suggested as a possible maternal risk factor for autism (Volk et al., 2013).

2.4.1. Calculating land cover components—Land cover data were obtained from the National Land Cover Dataset (NLCD) 2011, created by classifying Landsat images to a spatial resolution of 30 meters. Based on the NLCD classification system, land cover in each school district comprised 9 major categories: water, open land (developed open space, e.g., campus grounds, golf courses), urban land (>= 20% impervious surface, e.g., moderate density residential, commercial), barren land, forest, shrubland, grassland, agriculture and wetland. We were particularly interested in forest, grassland, and urban land; the first two represent common green spaces in and around developed settings (Maas et al., 2006), and the last one may be an important promoting factor for autism, as studies have suggested increased autism risk from urbanicity (Becker 2010; Lauritsen et al., 2014). The land cover image was first clipped by the 2010 school district boundary layer obtained from the US Census Bureau; then the percentages of these land cover classes in each school district were calculated using ArcGIS 10.3.

2.4.2. Calculating average tree canopy—The tree canopy data were obtained from the NLCD 2011 Cartographic Canopy dataset (http://www.mrlc.gov/nlcd11_data.php) created by the United States Forest Service (USFS). This dataset consists of a single raster layer of percent tree canopy, with a pixel size of 30 meters. Each pixel has a value ranging from 0 to 100 percent, indicating the proportion of the pixel covered by tree canopy. These data are key to estimating tree cover in areas with >=20% impervious surface, where no vegetation is captured by the NLCD classified land cover product. We clipped the tree canopy layer to each school district and averaged the pixel values for each school district using ArcGIS 10.3.

2.4.3. Calculating percent near-road tree canopy—A GIS layer containing major roadways in California was obtained from NavTEQ™ (Chicago, IL), a leading provider of data on the North American road network. Major roads refer to interstate highways, state highways, and major arterials (Volk et al., 2011). To calculate percent near-road tree canopy, we created 50 m buffers around road centerlines. We then calculated the average percent tree canopy in the buffers for each school district. Additionally, we calculated the road length and road density for each school district. Road density is equal to the total road length in a school district divided by the total area of that school district.

2.5. Statistical analysis

Exploratory data analysis was conducted at the school district level for each individual green space variable, and for selected demographic and socioeconomic metrics. Pearson correlation analysis and scatter plots were used to preliminarily examine the relationship between these variables and autism prevalence. Spatial autocorrelation of individual variables was measured with ArcGIS 10.3.

Negative binomial (NB) regression models were selected to examine the statistical association between autism prevalence and each of the green space metrics (Wu et al., 2016). The general equation for the NB regression model is:

$$\log(\mu_i) = \log(N_i) + \beta_0 + \beta_1 x_{1i} + \ldots + \beta_n x_{ni}$$

where μ is the expected number of autism cases, log is the natural logarithm transformation, and i is the index of an individual school district. N is the number of elementary school students in a school district, which is used as the offset term; $\beta_1, \ldots, \beta_n$ are the regression coefficients of the exploratory variables, and $x_1, \ldots, x_n$ are the exploratory variables. Multicollinearity among exploratory variables was examined with a correlation matrix generated by Pearson correlation analysis and variance inflation factors (VIF). If multicollinearity was found (e.g. $r > 0.6$ or $VIF > 5$), only one of the highly-correlated variables was considered (Wu et al., 2016). The rate ratio (RR, the ratio of autism prevalence between two exposure groups,) was calculated to characterize the change in autism prevalence, given a 1 unit change in the exploratory variable. Originally, the unit change in green space metrics was defined as 1%; this led to very tight RR values (close to 1). To strengthen the effect of the change in green space, and to reflect more reasonable potential interventions, we changed the green space unit definition to 10% by dividing the values of these metrics by 10. A positive association was assumed if the RR was above 1.00, while a negative or inverse association was assumed if the RR was below 1.00. The significance level was selected at 0.05.

The models were adjusted for potential confounders (Becerra et al., 2013) including race (the percentage of white population), gender (the percentage of male population) and socioeconomic status (the median annual household income). Because of high correlation, only one variable was selected as a confounder from each category (e.g., race, gender and socioeconomic status). To control for the potential confounding effects of road density and urban land, we stratified models by road density. Road density is highly correlated with urban land, which our preliminary analyses showed also to be associated with autism prevalence. Road density can also be used as a proxy for traffic-related air pollution, which has been associated with autism in previous studies (Raz et al., 2015; Volk et al., 2013). We controlled for road density by stratifying elementary school districts into 4 quartiles, following evaluation of interactive effects between road density and green space metrics using NB models. Model fit was assessed based on Pearson residual plots. The model fitting and residual diagnostics were carried out with SAS 9.3 (SAS Institute, Inc., Cary, NC, US).

To test the robustness of associations between autism prevalence and green space metrics, sensitivity analyses were conducted as described in the literature (Dadvand et al., 2015). Autism prevalence was again evaluated with negative binomial models; the near-road canopy variable was chosen as the exploratory variable because it showed a strong association with autism prevalence. Models were adjusted for the percentage of children in the population, one at a time to examine if notable changes occurred. This control variable was selected because it was not highly correlated with the variables (e.g., the percentage of male population and the median household income) in the main models. To test whether buffer distance affected the relationship between near-road tree canopy and autism prevalence, we also calculated percent near-road tree canopy within a buffer of 100 meters and examined its association with autism prevalence using models with both the original and test control variables. To test the effect of outliers (e.g., district with a particularly high autism rate) on the model results, we identified three districts with the highest autism rates, and ran the model after removing these districts one by one to examine any changes in the associations between green space metrics and autism prevalence. In addition, we examined the association between autism prevalence and several land cover classes (urban, forest and grassland) measured from the NLCD 2006 dataset, considering the effect of green space on children with autism in their early development.

To consider spatial dependence in the variables, we applied a spatial regression model, specifically, a spatial lag (SL) model (Wu et al., 2015). In this model, dependent variables for school district i are assumed to be affected by neighbors of the school district i. A general equation for the spatial lag model is:

$$\log(y_i) = \rho W * \log(y_i) + \log(N_i) + \quad \beta_0 + \beta_1 x_{1i} + \dots + \quad \beta_n x_{ni}$$

where the dependent variable ($\log(y_i)$) is the natural logarithm of autism cases, i is the index of the school district, W is the spatial weight matrix (queen-based contiguity), and ρ is the spatial autoregressive coefficient. N, $\beta_1,\dots,\beta n$ and $x_1, \dots, x_n$ are the same as in the negative binomial model. After fitting the model, the normality and spatial autocorrelation of model residuals were assessed using the Jarque-Bera test and Morans' I, respectively. The model fitting and residual diagnostics were carried out with GeoDa 1.6.6 package (Anselin et al., 2010).

Results

3.1. Description of childhood autism prevalence and green space metrics

In the 543 elementary school districts, autism prevalence ranged from 0 to 79 cases per 1000 children, with an average prevalence of 6.8 cases per 1000 children. Districts with high autism prevalence (43–79/1000 children) were located mainly in central and northern California, but were spatially dispersed (Figure 1). The major land cover classes in 543 school districts were agriculture (21.89%), forest (20.86%), grassland (16.44%) and urban land (16.16%). The average tree canopy coverage in these school districts was 18.38%. The average near-road tree canopy coverage within 50 m of major roads was 11.59% (Table S1). Pearson correlation analysis indicated that autism prevalence was positively correlated ($r>0.00$, $p<0.01$) with the percentages of open land and urban land, but negatively correlated ($r<0.00$, $p<0.01$) with the percentages of forest, grassland, agricultural area, average tree canopy and near-road tree canopy (Table S2).

3.2. Unstratified association of childhood autism and green space metrics

The unadjusted NB models showed that autism prevalence was positively associated with both urban land (RR=1.08, 95% CI: 1.06 – 1.10) and road density (RR = 1.21, 95% CI: 1.14 −1.27), but inversely associated with grassland (RR = 0.94, 95% CI: 0.91–0.97). Similar results were obtained from unadjusted SL models. In addition, these SL models showed autism prevalence had inverse associations with forest (RR=0.96, 95% CI: 0.93 – 0.99) and average tree canopy (RR=0.96, 95% CI: 0.92 – 0.99). Both types of models showed that autism prevalence and near-road tree canopy were not significantly associated (Table S3).

When the models were adjusted for race, gender and socioeconomic status (SES), both NB and SL models continued to show that autism prevalence had positive associations with the percentage of urban land and road density. The NB model also showed that autism prevalence and the percentage of grassland were inversely associated (Table 1). Analysis of interactions between road density and green space metrics showed that interaction terms were not significant (Table S4).

3.3. Stratified association of childhood autism and green space metrics

In districts with the highest road density (4th quartile), autism prevalence was significantly inversely associated with forest (RR = 0.90, 95% CI=0.84 – 0.95), grassland (RR =0.90, 95% CI = 0.83 –0.97), average tree canopy (RR =0.89, 95% CI=0.83 – 0.95) and near-road tree canopy (RR =0.81, 95% CI=0.73 – 0.91). All four green space metrics explored in NB models were adjusted for race, gender and SES (Table 2). For this highest road-density quartile, autism prevalence retained a positive association with the percentage of urban land (RR=1.08, 95% CI: 1.05 –1.10) in the same adjusted NB models. However, in the districts with the lowest road density (1st quartile), no significant associations were found between autism prevalence and green space variables using the same modeling methods (Table 2).

Results from SL models for the districts with the highest road density showed that autism prevalence was similarly inversely associated with all of the tree cover variables (e.g., RR=0.87, 95% CI: 0.78 – 0.96 for the percentage of forest), but not with the percentage of grassland when the models were adjusted for race, gender and SES. Autism prevalence continued to show a positive association with the percentage of urban land (RR=1.10, 95% CI: 1.06–1.15). In the districts with the lowest road density, autism prevalence had no significant associations with the green space metrics, but retained a positive association with the percentage of urban land (Table 3).

For the districts with intermediate road density (2nd and 3rd quartiles), autism prevalence had a positive association only with the percentage of urban land, and no significant associations with green space metrics in either type of model adjusted for race, gender and SES (Table S5).

3.4. Sensitivity analysis and model diagnostics

Sensitivity analysis of the association between autism prevalence and near-road tree canopy showed that results were consistent when the models were adjusted for an alternate variable, the percentage of children in the population (Table S6). In addition, near-road tree canopy within 100 m was found to have a similar association with autism prevalence as near-road tree canopy within 50 m (Table S6). The results also showed that a single district with a particular high autism rate had no significant influence on the model results (Table S7). The analysis of the association between autism prevalence and land cover in 2006 with NB models showed the autism prevalence still had a positive association with the percentage of urban land and negative associations with the percentages of forest and grassland (Table S8). Pearson residual plots showed that the main models fit the data well, given that the values of the residuals centered to zero and most of them ranged between −2 and 2 (Figure S1).

Discussion

We observed significant inverse associations between autism prevalence and all three tree-cover metrics in elementary school districts with high road density. The rate ratios associated with forest, average tree canopy, and near-road tree canopy within 50 m were approximately 0.90, 0.89 and 0.81, respectively, indicating that the risks for autism in these districts would be 10%, 11% and 19% lower, respectively, per 10% increase in these tree-cover metrics. However, associations between these metrics and autism prevalence were not significant when the models were not stratified by road density. Since road density is highly correlated with the percentage of urban land, the inverse relationship between autism prevalence and these green space metrics in districts with the highest road density suggests that urban tree cover, especially near-road tree canopy, may have protective effects on autism prevalence in highly urbanized areas. To date, little is known about the impact of green space on childhood autism; we are not aware of any studies examining the association between near-road tree canopy and autism in school children. Therefore, our findings provide new information about potentially beneficial environmental factors for autism.

In California, hazardous air pollutants derive mainly from motor vehicles (Gunier et al., 2003). Higher road density likely indicates more traffic-related air pollution. Our finding of positive associations between road density and childhood autism prevalence might be a result of an association between traffic-related air pollution and autism. Previous studies have shown that childhood autism was positively associated with exposure to traffic-related air pollution, especially prenatal exposure to particular matter (Kalkbrenner et al., 2015; Lam et al., 2016; Raz et al., 2015; Volk et al., 2011; Volk et al., 2013). Traffic-related air pollution induces oxidative stress and inflammation, which are also involved in the pathogenesis of autism (Volk et al., 2011). However, due to the lack of data on exposure time periods, our results cannot confirm a causal relationship between autism and road density.

Though derived using different methods, the NLCD forest class and the percent tree canopy measure are highly correlated based on Pearson correlation analysis ($r=0.96$, $p<0.001$). Trees improve air quality by intercepting particulate matter on their surfaces and absorbing gaseous pollutants through the leaf stomata (Nowak et al., 2006; Nowak et al., 2014). Though the amounts of air pollutants removed by green space is debatable (Grundstrom and Pleijel 2014; Pugh et al., 2012; Steffens et al., 2012), Nowak et al. (2014) estimated that forests and trees in the conterminous United States removed 17,400 million kg of air pollutants in 2010, with considerable beneficial effects on public health. Because near-road tree canopy can serve as a physical barrier to traffic-related air pollution (Brantley et al., 2014), its impact on childhood autism may be stronger than other types of tree cover, as shown by our results.

Reducing maternal stress is another possible mechanism to explain the inverse relationship between urban green space and autism prevalence. Urban green space has been shown previously to have beneficial effects on maternal stress (McEachan et al., 2015), one of the factors associated with autism observed in early childhood (Ronald et al., 2010). One pathway to reducing stress is noise reduction. Near-road tree cover may reduce traffic-related noise, which negatively affects mental health and cognitive function in both children and adults (Gidlof-Gunnarsson and Ohrstrom 2007; McEachan et al., 2015; Ronald et al., 2010).

It is estimated that millions of children have autism in the United States, and the number of cases continues to grow (Christensen et al., 2016). Along with urbanization, road density and number of vehicles will also increase, which may lead to more traffic-related air pollution. These pollutants are detrimental to brain development (Dadvand et al., 2015). However, effective and feasible measures to mitigate autism at the population level are unavailable. Our findings suggest that tree cover in areas of high road density has beneficial effects on childhood autism, and may shed light on identifying feasible measures to reduce autism prevalence. As green space has been shown to have numerous health benefits (Bolund and Hunhammar 1999; Dadvand et al., 2015; Hystad et al., 2014; Lee and Maheswaran 2011; Pugh et al., 2012; van den Berg et al., 2015; Wolch et al., 2014), increasing tree cover might be a practical and beneficial measure to mitigate increasing autism prevalence while also addressing many additional public health issues.

Our study has a few strengths: We used multiple green space metrics, including the percentages of forest and grassland, and percent overall and near-road tree canopy. Rather than exploring only one metric, as in many other studies of eco-health relationships, our approach helps to understand potentially distinct effects caused by different types of green space. This study is also the first to examine the benefit to autism of near-road tree canopy, which may have important implications for autism mitigation. The spatial dependence of the autism data was taken into account in modeling the relationship between autism and green space metrics; this issue is rarely considered in other studies on health effects of green space or environmental risk factors for autism (Dadvand et al., 2015; Volk et al., 2011; Volk et al., 2013). It is commonly understood that the similarity of two objects in space relates in part to their proximity. Therefore, spatial dependence may affect the relationship between a dependent variable and exploratory variables. Our examination of Moran’s I indicated that autism prevalence in these school districts had weak spatial autocorrelation (I= 0.197, $p<0.001$), which explains the similarity of results from the spatial lag and negative binomial regression models.

Our study also has a few limitations. First, small patches of green space such as urban lawns and gardens are omitted from the classified NLCD product. The NLCD cartographic canopy dataset does capture the spectrum of urban tree cover, but no comparable NLCD datasets quantify other green space within urban land uses. Second, our study unit is the elementary school district rather than the individual child. We are unable to verify the residences of these children. Because we cannot rule out the possibility that they moved into their school districts from other places, it is difficult to link the timing of critical exposures to the development of autism. Furthermore, it is difficult to accurately measure exposures to green space due to the lack of daily activity logs. Therefore, the conclusions drawn at the school district level cannot confirm a causal relationship between green space and autism prevalence. It is also a concern that the locations of special autism schools might influence the autism prevalence in these school districts. However, from the map of autism schools (Figure S2), we could not discern a pattern of school districts with higher autism prevalence near special autism schools. In our models, though we considered some confounding factors such as SES and road density, residual confounding effects might still exist and affect the model results. One cause of residual confounding is failure to include additional key factors, such as pesticide use and exposure to heavy metals. Another cause is insufficient control for confounders that were included. For example, we categorized road density into only four categories. Finally, our study design does not resolve the potential mechanism(s) responsible for the inverse association between tree cover and autism prevalence. Buffering traffic-related air pollution might be the main mechanism; however, we did not directly measure traffic-related air pollution or any mitigation of it by green space. Reducing maternal stress by buffering noise or by other mechanisms such as promoting social interaction are also possible mechanisms by which urban tree cover may reduce autism in children. Though this ecological study has many limitations due to the nature of the study design and data availability, this work is the first to examine the relationship between green space and autism and to explore potential health benefits of green space on childhood autism. More investigations with stronger study designs are needed to further explore whether green space is protective for childhood autism, and by which mechanism(s).

Conclusions

We found that several green space metrics, particularly percent forest, average tree canopy and near-road tree canopy, were inversely associated with childhood autism prevalence in California public elementary school districts, after adjusting for demographic and socioeconomic factors. These associations were significant only in school districts with high road density. Urban area and road density were positively associated with autism prevalence in these schoolchildren. Our findings help to formulate a reasonable hypothesis that an increase in near-road tree cover may be an effective mitigation measure for childhood autism in urban areas. Further studies are needed to explore this hypothesis and to investigate the major mechanisms, such as buffering traffic-related air pollution and noise, which could underlie the beneficial associations between green space and the population potentially vulnerable to autism.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References:

American Psychiatric Association, 2013 Diagnostic and statistical manual of mental disorders (DSM-5®), American Psychiatric Pub.

Amoly E; Dadvand P; Forns J; Lopez-Vicente M; Basagana X; Julvez J; Alvarez-Pedrerol M; Nieuwenhuijsen MJ; Sunyer J, 2014 Green and Blue Spaces and Behavioral Development in Barcelona Schoolchildren The BREATHE Project. Environ Health Persp 122, 1351–1358.

Anselin L; Syabri I; Kho Y 2010 GeoDa: an introduction to spatial data analysis. Handbook of applied spatial analysis: Springer.

Autism Society of California, 2012. Autism in California 2012 Survey.

Bailey A; Lecouteur A; Gottesman I; Bolton P; Simonoff E; Yuzda E; Rutter M, 1995 Autism as a Strongly Genetic Disorder - Evidence from a British Twin Study. Psychol Med 25, 63–77. [PubMed: 7792363]

Becerra TA; Wilhelm M; Olsen J; Cockburn M; Ritz B, 2013 Ambient Air Pollution and Autism in Los Angeles County, California. Environ Health Persp 121, 380–386.

Becker KG, 2010 Autism and Urbanization. Am J Public Health 100, 1156–1157. [PubMed: 20466946]

Beyer KMM; Kaltenbach A; Szabo A; Bogar S; Nieto FJ; Malecki KM, 2014 Exposure to Neighborhood Green Space and Mental Health: Evidence from the Survey of the Health of Wisconsin. Int J Env Res Pub He 11, 3453–3472.

Bolund P; Hunhammar S, 1999 Ecosystem services in urban areas. Ecological Economics 29, 293–301.

Brantley HL; Hagler GS; Deshmukh PJ; Baldauf RW, 2014 Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. Sci Total Environ 468, 120–129. [PubMed: 24008075]

Buescher AVS; Cidav Z; Knapp M; Mandell DS, 2014 Costs of Autism Spectrum Disorders in the United Kingdom and the United States. Jama Pediatr 168, 721–728. [PubMed: 24911948]

Chaste P; Leboyer M, 2012 Autism risk factors: genes, environment, and gene-environment interactions. Dialogues Clin Neurosci 14, 281–292. [PubMed: 23226953]

Chen X; Li BL; Allen MF, 2010 Characterizing urbanization, and agricultural and conservation land-use change in Riverside County, California, USA. Annals of the New York Academy of Sciences 1195.

Christensen DL; Baio J; Braun KV; Bilder D; Charles J; Constantino JN; Daniels J; Durkin MS; Fitzgerald RT; Kurzius-Spencer M; Lee LC; Pettygrove S; Robinson C; Schulz E; Wells C; Wingate MS; Zahorodny W; Yeargin-Allsopp M, 2016 Prevalence and Characteristics of Autism Spectrum Disorder Among Children Aged 8 Years - Autism and Developmental Disabilities Monitoring Network, 11 Sites, United States, 2012. Morbidity and Mortality Weekly Report 65, 1–23. [PubMed: 26766396]

Coombes E; Jones AP; Hillsdon M, 2010 The relationship of physical activity and overweight to objectively measured green space accessibility and use. Soc Sci Med 70, 816–822. [PubMed: 20060635]

Croen LA; Grether JK; Hoogstrate J; Selvin S, 2002 The changing prevalence of autism in California. J Autism Dev Disord 32, 207–215. [PubMed: 12108622]

Dadvand P; Nieuwenhuijsen MJ; Esnaola M; Forns J; Basagana X; Alvarez-Pedrerol M; Rivas I; Lopez-Vicente M; Pascual MD; Su J; Jerrett M; Querol X; Sunyer J, 2015 Green spaces and cognitive development in primary schoolchildren. Proc Natl Acad Sci USA 112, 7937–7942. [PubMed: 26080420]

de Keijzer C; Gascon M; Nieuwenhuijsen MJ; Dadvand P, 2016 Long-Term Green Space Exposure and Cognition Across the Life Course: a Systematic Review. Current environmental health reports 3, 468–477. [PubMed: 27730509]

Dietert RR; Dietert JM; Dewitt JC, 2011 Environmental risk factors for autism. Emerg Health Threats J 4, 7111. [PubMed: 24149029]

Fischer L; Ramirez C; Maurizi B; Haunreiter E, 2007 Monitoring land cover changes in California-South Coast Project Area, Cycle II

Flouri E; Midouhas E; Joshi H, 2014 The role of urban neighbourhood green space in children's emotional and behavioural resilience. J Environ Psychol 40, 179–186.

Gascon M; Triguero-Mas M; Martinez D; Dadvand P; Forns J; Plasencia A; Nieuwenhuijsen MJ, 2015 Mental Health Benefits of Long-Term Exposure to Residential Green and Blue Spaces: A Systematic Review. Int J Env Res Pub He 12, 4354–4379.

Geschwind DH, 2009 Advances in autism. Annu Rev Med 60, 367–380. [PubMed: 19630577]

Gidlof-Gunnarsson A; Ohrstrom E, 2007 Noise and well-being in urban residential environments: The potential role of perceived availability to nearby green areas. Landscape Urban Plan 83, 115–126.

Grundstrom M; Pleijel H, 2014 Limited effect of urban tree vegetation on NO2 and O-3 concentrations near a traffic route. Environ Pollut 189, 73–76. [PubMed: 24631975]

Gunier RB; Hertz A; Von Behren J; Reynolds P, 2003 Traffic density in California: Socioeconomic and ethnic differences among potentially exposed children. J Expo Anal Env Epid 13, 240–246.

Hallmayer J; Cleveland S; Torres A; Phillips J; Cohen B; Torigoe T; Miller J; Fedele A; Collins J; Smith K; Lotspeich L; Croen LA; Ozonoff S; Lajonchere C; Grether JK; Risch N, 2011 Genetic Heritability and Shared Environmental Factors Among Twin Pairs With Autism. Arch Gen Psychiat 68, 1095–1102. [PubMed: 21727249]

Hystad P; Davies HW; Frank L; Van Loon J; Gehring U; Tamburic L; Brauer M, 2014 Residential Greenness and Birth Outcomes: Evaluating the Influence of Spatially Correlated Built-Environment Factors. Environ Health Persp 122, 1095–1102.

Kalkbrenner AE; Daniels JL; Chen JC; Poole C; Emch M; Morrissey J, 2010 Perinatal exposure to hazardous air pollutants and autism spectrum disorders at age 8. Epidemiology 21, 631–641. [PubMed: 20562626]

Kalkbrenner AE; Schmidt RJ; Penlesky AC, 2014 Environmental chemical exposures and autism spectrum disorders: a review of the epidemiological evidence. Curr Probl Pediatr Adolesc Health Care 44, 277–318. [PubMed: 25199954]

Kalkbrenner AE; Windham GC; Serre ML; Akita Y; Wang X; Hoffman K; Thayer BP; Daniels JL, 2015 Particulate matter exposure, prenatal and postnatal windows of susceptibility, and autism spectrum disorders. Epidemiology 26, 30–42. [PubMed: 25286049]

Keaton P, 2013 Selected Statistics from the Common Core of Data: School Year 2011–12. First Look. NCES 2013–441 National Center for Education Statistics.

Kuo FE; Taylor AF, 2004 A potential natural treatment for attention-deficit/hyperactivity disorder: Evidence from a national study. Am J Public Health 94, 1580–1586. [PubMed: 15333318]

Lam J; Sutton P; Kalkbrenner A; Windham G; Halladay A; Koustas E; Lawler C; Davidson L; Daniels N; Newschaffer C; Woodruff T, 2016 A Systematic Review and Meta-Analysis of Multiple Airborne Pollutants and Autism Spectrum Disorder. Plos One 11.

Landrigan PJ, 2010 What causes autism? Exploring the environmental contribution. Curr Opin Pediatr 22, 219–225. [PubMed: 20087185]

Lauritsen MB; Astrup A; Pedersen CB; Obel C; Schendel DE; Schieve L; Yeargin-Allsopp M; Parner ET, 2014 Urbanicity and Autism Spectrum Disorders. J Autism Dev Disord 44, 394–404. [PubMed: 23807204]

Lee AC; Maheswaran R, 2011 The health benefits of urban green spaces: a review of the evidence. J Public Health (Oxf) 33, 212–222. [PubMed: 20833671]

Leigh JP; Du J, 2015 Brief Report: Forecasting the Economic Burden of Autism in 2015 and 2025 in the United States. J Autism Dev Disord 45, 4135–4139. [PubMed: 26183723]

Li D; Sullivan WC, 2016 Impact of views to school landscapes on recovery from stress and mental fatigue. Landscape Urban Plan 148, 149–158.

London E, 2000 The environment as an etiologic factor in autism: a new direction for research. Environ Health Persp 108, 401.

Maas J; van Dillen SME; Verheij RA; Groenewegen PP, 2009 Social contacts as a possible mechanism behind the relation between green space and health. Health Place 15, 586–595. [PubMed: 19022699]

Maas J; Verheij RA; Groenewegen PP; De Vries S; Spreeuwenberg P, 2006 Green space, urbanity, and health: how strong is the relation? J Epidemiol Commun H 60, 587–592.

Markevych I; Tiesler CMT; Fuertes E; Romanos M; Dadvand P; Nieuwenhuijsen MJ; Berdel D; Koletzko S; Heinrich J, 2014 Access to urban green spaces and behavioural problems in children: Results from the GINIplus and LISAplus studies. Environ Int 71, 29–35. [PubMed: 24953038]

McDonald ME; Paul JF, 2010 Timing of Increased Autistic Disorder Cumulative Incidence. Environ Sci Technol 44, 2112–2118. [PubMed: 20158232]

McEachan R; Prady S; Smith G; Fairley L; Cabieses B; Gidlow C; Wright J; Dadvand P; Van Gent D; Nieuwenhuijsen M, 2015 The association between green space and depressive symptoms in pregnant women: moderating roles of socioeconomic status and physical activity. J Epidemiol Commun H, jech-2015–205954.

Mitchell R; Popham F, 2008 Effect of exposure to natural environment on health inequalities: an observational population study. Lancet 372, 1655–1660. [PubMed: 18994663]

Nevison CD, 2014 A comparison of temporal trends in United States autism prevalence to trends in suspected environmental factors. Environ Health-Glob 13.

Newschaffer CJ; Croen LA; Daniels J; Giarelli E; Grether JK; Levy SE; Mandell DS; Miller LA; Pinto-Martin J; Reaven J; Reynolds AM; Rice CE; Schendel D; Windham GC, 2007 The epidemiology of autism spectrum disorders. Annu Rev Publ Health 28, 235–258.

Nowak DJ; Crane DE; Stevens JC, 2006 Air pollution removal by urban trees and shrubs in the United States. Urban for Urban Gree 4, 115–123.

Nowak DJ; Hirabayashi S; Bodine A; Greenfield E, 2014 Tree and forest effects on air quality and human health in the United States. Environ Pollut 193, 119–129. [PubMed: 25016465]

Ozand PT; Al-Odaib A; Merza H; Harbi SA, 2003 Autism: a review. Journal of Pediatric Neurology 1, 55–67.

Palmer RF; Blanchard S; Stein Z; Mandell D; Miller C, 2006 Environmental mercury release, special education rates, and autism disorder: an ecological study of Texas. Health Place 12, 203–209. [PubMed: 16338635]

Pugh TAM; MacKenzie AR; Whyatt JD; Hewitt CN, 2012 Effectiveness of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons. Environ Sci Technol 46, 7692–7699. [PubMed: 22663154]

Raz R; Roberts AL; Lyall K; Hart JE; Just AC; Laden F; Weisskopf MG, 2015 Autism Spectrum Disorder and Particulate Matter Air Pollution before, during, and after Pregnancy: A Nested Case-Control Analysis within the Nurses' Health Study II Cohort. Environ Health Persp 123, 264–270.

Roberts EM; English PB; Grether JK; Windharn GC; Somberg L; Wolff C, 2007 Maternal residence near agricultural pesticide applications and autism spectrum disorders among children in the California Central Valley. Environ Health Persp 115, 1482–1489.

Ronald A; Pennell CE; Whitehouse AJ, 2010 Prenatal maternal stress associated with ADHD and autistic traits in early childhood. Frontiers in psychology 1.

Rossignol DA; Frye RE, 2014 Evidence linking oxidative stress, mitochondrial dysfunction, and inflammation in the brain of individuals with autism. Front Physiol 5.

Steffens JT; Wang YJ; Zhang KM, 2012 Exploration of effects of a vegetation barrier on particle size distributions in a near-road environment. Atmos Environ 50, 120–128.

Taylor AF; Kuo FE, 2009 Children With Attention Deficits Concentrate Better After Walk in the Park. J Atten Disord 12, 402–409. [PubMed: 18725656]

van den Berg M; Wendel-Vos W; van Poppel M; Kemper H; van Mechelen W; Maas J, 2015 Health benefits of green spaces in the living environment: A systematic review of epidemiological studies. Urban for Urban Gree 14, 806–816.

Volk HE; Hertz-Picciotto I; Delwiche L; Lurmann F; McConnell R, 2011 Residential Proximity to Freeways and Autism in the CHARGE Study. Environ Health Persp 119, 873–877.

Volk HE; Lurmann F; Penfold B; Hertz-Picciotto I; McConnell R, 2013 Traffic-Related Air Pollution, Particulate Matter, and Autism. Jama Psychiat 70, 71–77.

Windham GC; Zhang LX; Gunier R; Croen LA; Grether JK, 2006 Autism spectrum disorders in relation to distribution of hazardous air pollutants in the San Francisco Bay area. Environ Health Persp 114, 1438–1444.

Wolch JR; Byrne J; Newell JP, 2014 Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. Landscape Urban Plan 125, 234–244.

Wu J; Tschakert P; Klutse E; Ferring D; Ricciardi V; Hausermann H; Oppong J; Smithwick EA, 2015 Buruli Ulcer Disease and Its Association with Land Cover in Southwestern Ghana. PLoS Negl Trop Dis 9, e0003840. [PubMed: 26091265]

Wu JY; Yunus M; Islam MS; Emch M, 2016 Influence of Climate Extremes and Land Use on Fecal Contamination of Shallow Tubewells in Bangladesh. Environ Sci Technol 50, 2669–2676. [PubMed: 26844955]

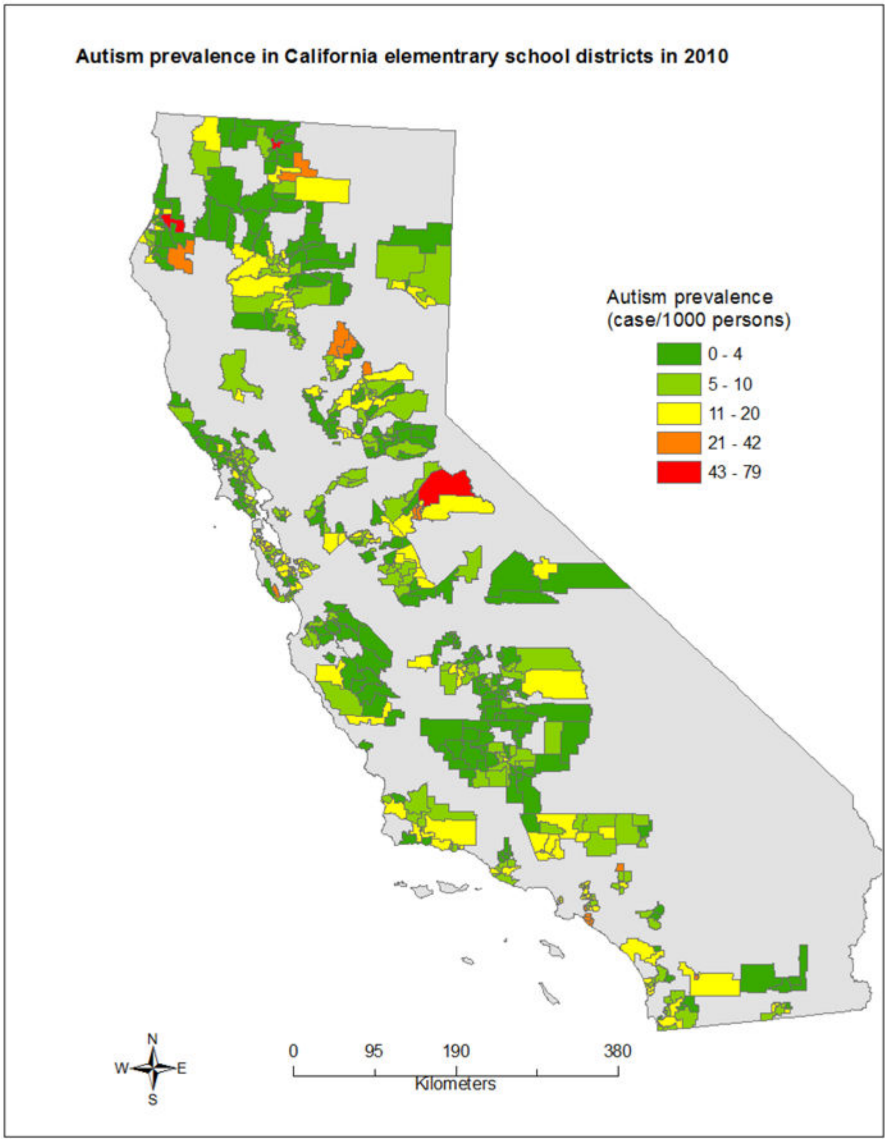

Figure 1.

Autism prevalence in California elementary school districts, 2010

Table 1.

Adjusted associations of childhood autism with green space metrics and road density.

Explanatory variables (unit)	Negative binomial model			Spatial lag model		
	RR[a]	**95% CIs**	**p**	**RR[a]**	**95% CIs**	**p**
Urban land (10%)	**1.08**	**1.06 – 1.10**	**<0.001**	**1.12**	**1.08 – 1.17**	**<0.001**
Forest (10%)	1.01	0.98 – 1.04	0.548	0.99	0.95 – 1.02	0.463
Grassland (10%)	**0.95**	**0.92 – 0.99**	**0.008**	0.96	0.92 – 1.00	0.058
Tree cover canopy (10%)	1.00	0.97 – 1.04	0.864	0.98	0.94 – 1.02	0.428
Near–road tree canopy, 50 m (10%)	1.01	0.96 – 1.07	0.582	0.99	0.94 – 1.05	0.778
Road density (1 km/1 km^2)	**1.19**	**1.12 – 1.27**	**<0.001**	**1.25**	**1.013 – 1.039**	**<0.001**

a: adjusted for economic status (median household income), race (proportion of white population) and gender (proportion of male population).

Table 2.

Associations between childhood autism and green space metrics in elementary school districts stratified by road density examined with negative binomial regression models.

Explanatory variables (unit)	High road density (Q4)			Low road density (Q1)		
	RR[a]	**95% CI**	**p**	**RR**[a]	**95% CI**	**P**
Urban land (10%)	**1.08**	**1.05 – 1.10**	**<0.001**	1.28	0.43 – 3.84	0.657
Forest (10%)	**0.90**	**0.84 – 0.95**	**0.001**	1.06	0.99 – 1.14	0.080
Grassland (10%)	**0.90**	**0.83 – 0.97**	**0.008**	0.95	0.87 – 1.04	0.292
Average tree canopy (10%)	**0.89**	**0.83 – 0.95**	**<0.001**	1.03	0.94 – 1.13	0.480
Near–road tree canopy, 50 m (10%)	**0.81**	**0.73 – 0.91**	**<0.001**	1.06	0.95 – 1.18	0.298

a: adjusted for economic status (median household income), race (proportion of white population) and gender (proportion of male population).

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Table 3.

Associations between childhood autism and green space metrics in elementary school districts stratified by road density examined with spatial regression models.

Explanatory variables (unit)	**High road density (Q4)**			**Low road density (Q1)**		
	RR[a]	**95% CI**	**p**	**RR[a]**	**95% CI**	**p**
Urban land (10%)	**1.10**	**1.06 – 1.15**	**<0.001**	**1.22**[b]	**1.01**[b] **– 1.74**[b]	**0.040**
Forest (10%)	**0.87**	**0.78 – 0.96**	**<0.001**	1.03	0.96 – 1.11	0.421
Grassland (10%)	0.94	0.85 – 1.05	0.259	0.95	0.87– 1.04	0.233
Average tree canopy (10%)	**0.86**	**0.79 – 0.93**	**<0.001**	1.01	0.92 – 1.10	0.843
Near–road tree canopy, 50 m, (10%)	**0.79**	**0.71 – 0.87**	**<0.001**	1.05	0.95 – 1.17	0.307

a: adjusted for economic status (median household income), race (proportion of white population) and gender (proportion of male population).

b: the RR value is corresponding to the 1% change of urban land.