Multiple health benefits of urban tree canopy: The mounting evidence for a green prescription

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ABSTRACT

The purpose of this study was to enhance the understanding of the health-promoting potential of trees in an urbanized region of the United States. This was done using high-resolution LiDAR and imagery data to quantify tree cover within 250 m of the residence of 7910 adult participants in the California Health Interview Survey, then testing for main and mediating associations between tree cover and multiple health measures. The results indicated that more neighborhood tree cover, independent from green space access, was related to better overall health, primarily mediated by lower overweight/obesity and better social cohesion, and to a lesser extent by less type 2 diabetes, high blood pressure, and asthma. These findings suggest an important role for trees and nature in improving holistic population health in urban areas.

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1. Introduction

Rapid global urbanization brings economic, educational, and social opportunities. However, an increasing number of urban dwellers are not within easy access and contact with nature that is fundamental to human health and well-being (Wolf and Robbins, 2015). Investing in green infrastructure and natural environments within urbanized settings is becoming increasingly important. Humans evolved and have lived in mostly natural settings until very recently (Turner et al., 2004). Although many residents in urban areas typically benefit from superior access to health care, education, and other services compared to their rural counterparts, these benefits are offset by the sedentary aspects of modern living and the presence of urban threats to physical and psychological health (Ng and Popkin, 2012; Vlahov and Galea, 2002).

Urbanization is often associated with social stress, physical threats (e.g., crime, traffic safety), and adverse environmental exposures (e.g., noise, air pollution) (Lederbogen et al., 2011; Peen et al., 2010; Vlahov and Galea, 2002). Contemporary lifestyles are generally associated with large reductions in occupational, domestic, and transportation-related physical activity, offset by only a small increase in leisure activity (Brownson et al., 2005; Ng and Popkin, 2012). In combination with changes in dietary intake, these trends have led to the high current rate of obesity and associated health risks, quality of life reduction, and health care cost increases (Jia and Lubetkin, 2005; Li et al., 2005; Ogden et al., 2014; Withrow and Alter, 2011). Urbanization and modernization are trends that will continue; therefore researchers have recommended the cultivation of urban nature to help counteract these health threats (Frumkin, 2001; Largo-Wight, 2011; Hartig et al., 2014).

Decades of research suggest that exposure to nature and green spaces can help to reduce stress, promote restoration, and generally improve mental health (Bowler et al., 2010; Bratman et al.,

2012; Maller et al., 2006). Frederick Law Olmsted, a 19th century landscape architect and designer of major urban parks across the USA, noted that access to green space and sunlight was needed to "re-create" oneself (Olmstead, 2010). Hypothesized explanations of the mental health-promoting influence of natural environments espouse that nature can help to replenish directed attention (Kaplan and Kaplan, 1989; Kaplan, 1995) and reduce stress (Ulrich, 1983, 1979). Others have hypothesized that humans have an innate affiliation and need for connection with the natural world (the biophilia hypothesis), and we have yet to fully adapt to urban environments (Kellert and Wilson, 1993; Wilson, 1984).

This study was an effort to provide evidence to support this theory. In an exploratory study situated in the Sacramento California region, more neighborhood tree cover was found to be significantly associated for adults of age 18–64 with more vigorous physical activity, less obesity, better general health, less asthma, and better social cohesion (Ulmer et al., 2014). The purpose of the analysis reported here was to enhance the understanding of the interrelationships between the health-promoting characteristics of tree cover in an urbanized area. The primary hypothesis was that more neighborhood tree cover was associated with better general health. The secondary hypothesis was that the association between more tree cover and better general health was explained by the cumulative effect of more tree cover on better social cohesion, more physical activity, and less prevalent overweight/obesity, type 2 diabetes, high blood pressure, and psychological distress. This study fills a gap in the existing research by focusing specifically on exposure to tree cover independent from other types of green space or vegetation, and by assessing tree cover associations with a comprehensive range of health measures within a local human population.

2. Literature review

A rapidly expanding scholarly literature indicates there is health promotion and disease prevention potential of nature experiences in cities ranging from site to community scale (Wolf and Robbins, 2015). For instance, one body of literature links nature and green space access or views to improved psychosocial health (Branas et al., 2011; Fan et al., 2011; Hartig et al., 2003; Leather et al., 1998; Nielsen and Hansen, 2007; Ulrich et al., 1991). Of studies focused specifically on trees, one study found an association between more streetscape greenery and better mental health status, better social cohesion, and reduced stress (de Vries et al., 2013). Sugiyama et al. (2008) found an association between higher self-reported neighborhood "greenness" (which included tree cover and other green measures) and better mental and social health in Danish adults. A series of studies of public housing residents in Chicago found that residents with more vegetation outside their windows reported less stress, less mental fatigue, and lower severity of life issues, had more social ties, used common spaces more, and reported lower levels of fear, violence, aggression, and other incivilities (Kuo and Sullivan, 2001a, 2001b, Kuo, 2001; Kuo et al., 1998).

More recently, the nature and well-being research has expanded to consider the impacts on physical health. Several researchers have suggested the potential benefit of green spaces towards reducing obesity and improving health in general (Bedimo-Rung et al., 2005; Feng et al., 2010; Lachowycz and Jones, 2013). Lachowycz and Jones (2013) suggested that both physical usage within and psychosocial benefits derived from green space contribute to improving physical health, but those benefits may be moderated by time availability for using green spaces, transportation accessibility, personal motivations, and neighborhood conditions. Recent reviews and original studies have provided some

evidence in support of the benefits of green space for physical activity and obesity, though the findings are somewhat inconsistent (Lachowycz and Jones, 2011; Lee and Maheswaran, 2011; Villeneuve et al., 2012).

The specific impact of tree cover on physical activity, obesity, and physical health has received far less attention than has green space. van Dillen et al. (2012) found that both the quality and quantity of streetscape greenery were related to better perceived general health and fewer acute health-related complaints. In a follow-up study, de Vries et al. (2013) found that quality but not quantity of streetscape greenery was associated with more physical activity in green spaces, and neither quantity nor quality were associated with overall physical activity. The greenery-health associations were partially mediated by better social cohesion, reduced stress, and increased physical activity in green spaces. In an unrelated natural experiment, Donovan et al. (2013) found that extensive loss of tree canopy due to the emerald ash borer (a beetle that feeds on and ultimately kills ash trees) in northern Midwest U.S. communities was associated with increased mortality related to cardiovascular and lower-respiratory-tract illness. Several additional studies of physical activity and obesity have considered the impact of tree cover as one of many environmental variables considered simultaneously, resulting in a wide range of findings including both significant healthful associations, and null associations (Foltête and Piombini, 2007; Lovasi et al., 2013b; Hoehner et al., 2005; Cain et al., 2014; Pikora et al., 2006; Boarnet et al., 2011; Lee and Moudon, 2006; Giles-Corti and Donovan, 2002a; Lovasi et al., 2012).

The literature on tree relationships with respiratory health is also mixed, as certain tree species have been linked to increased allergen exposure, while other studies have identified trees as a potential means for reducing airborne pollutants, particularly from motor vehicles (Dales et al., 2004; Lovasi et al., 2008; Nowak et al., 2006; Wang and Yousef, 2007). A recent study by Lovasi et al. (2013a) found evidence contradicting their earlier study of street trees, finding that greater tree cover within ¼-mile of the prenatal address was associated with higher likelihood of asthma and allergic sensitization to tree pollen in young children. New research also suggests that street-trees may disrupt wind flow that would otherwise help disperse vehicular pollutants, and may actually trap pollutants below the canopy, thereby increasing pollutant concentrations at street level (Vos et al., 2013; Wania et al., 2012).

3. Methods

This study made use of several pre-existing cross-sectional datasets for the Sacramento, California, region, which were acquired for this study between 2012 and 2013. These datasets, data development methods, and analytical methods are described in further detail below.

3.1. Study area

The Sacramento region has an urban forest which is a dynamic living resource requiring planning and investment to be sustained on an ongoing basis. The biogeographical conditions of the region support tree growth; but urban forestry best practices and stewardship programs are necessary interventions to support this civic investment. Clark and Matheny (1998) outlined three key elements of the sustainable urban forest: resource assessment, resource management, and community engagement. In recognition of environmental and ecosystem services, many communities have established tree canopy goals. The City of Sacramento set a canopy goal of 35% following a NASA thermal flyover assessment in 1998. Necessary routine management practices to sustain the forest

include soils improvements, structural and utility pruning, weed control, and irrigation.

Local governments rarely have adequate resources to address all their local tree needs so the third sustainability element, community engagement, is essential. Fifty-seven percent of responding cities in a national survey maintain formal partnership agreements with volunteer, nonprofit, or community groups (The United States Conference of Mayors, 2008). Civic leadership within the study community is provided by Sacramento Tree Foundation (STF), a non-profit that partners with local and regional government agencies to implement urban forest policy, collaborates with utility service providers on energy-saving tree planting programs, supports civic organizations doing urban forest activities, enlists citizen tree stewards, and conducts special events to maintain community awareness and celebrate the region's urban forest.

3.2. Participant data

Individual-level demographic/socioeconomic descriptors, health outcomes, and residential locations were derived from the California Health Interview Survey (CHIS). The CHIS was administered as a random-dial, biennial, telephone survey from 2001 to 2011 (it is now administered continuously) and is the largest state health survey in the United States, with sample sizes typically around 50,000 households per cycle. Four cycles of CHIS data (2003, 2005, 2007, and 2009) were acquired and pooled into a single analytical sample. CHIS data were self-reported by participants, with survey results further processed and maintained by the University of California-Los Angeles (UCLA) Data Access Center (DAC). DAC staff geocoded residential locations and calculated raked weights (a post-stratification method for developing sample weights to match population control totals) for each participant based on county-level demographic and socioeconomic control totals. The data described below were derived only from the CHIS adult survey, which is a separate instrument from the CHIS adolescent and child surveys.

The outcome of interest for this study was the general health status variable, which was self-reported by participants on a 5-point Likert scale ranging from "excellent" to "Poor". Seven potential mediating variables were also derived from CHIS data. Physical activity (PA) was self-reported as the frequency and duration over the past week of four types of moderate or vigorous physical activity (MVPA): walking for transportation purpose, walking for recreational purposes, moderate recreational PA (other than walking), and vigorous recreational PA. For this research, weekly total PA was converted to metabolic equivalents (METs) by multiplying total walking minutes by 3.5 (in accordance with the Compendium of Physical Activities), total moderate PA by 4.0, and total vigorous PA by 8.0 (in accordance with procedures used for the International Physical Activity Questionnaire) (Ainsworth et al., 2011; Craig et al., 2003). Weekly METs were used to categorize participants as having met physical activity recommendations (METs $> =525$, equivalent to at least 150 min of walking) or not (Haskell et al., 2007).

Height and body weight were self-reported by participants, then used to derive body mass index (BMI). BMI was then used to categorize participants as overweight or obese (BMI $\geq$ 25). Participants reported whether a doctor has told them that they have high blood pressure, type 2 diabetes, or current asthma. Participants were considered as having experienced psychological distress in the past 30 days if their total distress score for six questions (derived from the Kessler K6 scale) was $\geq$ 13 (out of a range of 0–24) (Kessler et al., 2002). The neighborhood social cohesion index was derived from the responses to three questions on neighborhood social conditions, and ranged from 3 (weakest) to 12 (strongest).

Table 1
Unweighted demographic, socioeconomic, neighborhood environment, and tree cover descriptive statistics for 2003–2009 CHIS sample in urbanized Sacramento region. For categorical variables where levels were excluded or combined in the table, footnotes describe all levels that were used in the analytical models.

Predictor variables	Variable type	Sample mean/percent
Female	dichotomous	58%
Age	continuous	46 years
Race/ethnicity: White, non-Hispanic	categorical	69%
Race/ethnicity: Hispanic	categorical	14%
Race/ethnicity: Asian	categorical	8%
Race/ethnicity: Other	categorical	9%
Married	dichotomous	55%
Education: No high school diploma	categorical	6%
Education: High school diploma or associate's degree	categorical	49%
Education: Bachelor's degree or higher	categorical	45%
Currently employed	categorical[a]	71%
Household size	continuous	2.8 people
Household income	continuous	$70,000
Home owned	dichotomous	64%
Below 200% of Federal Poverty Line	categorical[b]	20%
Food insecure	categorical[c]	8%
Without health insurance at any point in past year	categorical[d]	19%
Time living at current address	continuous	101 months
Speaks English well	dichotomous	95%
Current smoker	categorical[e]	14%
Park percentage within 500 m buffer	continuous	6%
Distance to nearest major road	continuous	395 m
Walkability index	continuous	48
Tree cover percentage within 250 m buffer	continuous	23%

[a] currently employed; unemployed & job seeking; unemployed & not job seeking.
[b] household income as % of federal poverty level: 100% or less; 101–200%; 201–300%; 301% or more.
[c] insured now and for past 12 months; insured now but not for all of past 12 months; not insured.
[d] food secure; food insecure without hunger; food insecure with hunger.
[e] current smoker; former smoker; never smoked.

Socio-demographic variables from CHIS data were also used in multivariate models, including gender, age, race/ethnicity, marital status, educational attainment, employment status, English language ability, time living at the current address, smoking status, health insurance status, household size, food security status, household income, home ownership status, poverty status and survey cycle. Because household income, home ownership status, and poverty status were highly correlated, they were further combined into an "economic resources" index. Additional description of covariate types and levels are provided in Table 1.

3.3. Tree canopy cover data

Tree canopy cover was mapped at a resolution of 1 m using high-resolution imagery and LiDAR as the primary data sources. The LiDAR data were acquired in 2008 through the Central Valley Floodplain Evaluation and Delineation Program with an average point spacing of 1.2 points per meter. The imagery was acquired in 2009 through the National Agricultural Imagery Program (NAIP) at a resolution of 1 m. Using techniques documented in MacFaden et al. (2012) and O'Neil-Dunne et al. (2012) tree canopy was automatically extracted from the imagery and LiDAR using an object-based expert systems approach in the eCognition software package. This was followed by a manual correction process in which the tree canopy data were edited at a scale of 1:2000. Accuracy was determined using a stratified sampling approach following Congalton and Green (2009). The user's accuracy (a measure of the error of commission) was determined to be 98% and the

Table 2
Unweighted outcome and mediator descriptive statistics for CHIS sample in urbanized Sacramento region.

Outcome/mediator variables	Variable type	CHIS data availability				Sample size	Sample mean/percent
		03	05	07	09		
General health (1–5, 1=excellent, 5=poor)	Likert	x		x	x	x	4,820	n/a
Overweight or obese (BMI > =25)	dichotomous	x		x	x	x	4,820	59%
High blood pressure	dichotomous	x		x	x	x	4,820	24%
Type 2 diabetes	dichotomous	x		x	x	x	4,820	6%
Current asthma	dichotomous	x		x	x	x	4,820	12%
Physically active (> 525 METs MVPA / wk)	dichotomous			x	x	x	3,854	62%
Psychological distress past 30 days	dichotomous				x	x	2,765	35%
Social cohesion index (3–12, 3=low, 11=high)	count	x				x	1,510	9.4

producer's accuracy (a measure of the error of omission) was determined to be 99%.

3.4. Built environment data

Several Sacramento region built environment data sources were used to assess neighborhood characteristics for each CHIS participant. The Environmental Protection Agency's Smart Location Database (2013) was used to derive a walkability index based on four component variables: housing density, employment density, land use mix, and intersection density. The walkability index was calculated at the US Census block group-level and scaled to range from 0 to 100. Two vector datasets from the Sacramento Area Council of Government's (SACOG) Regional GIS Clearing House were also used: Regional Parks and Open Space (2013) and Arterials and Highways (2013).

3.5. Statistical analysis

The initial sample size for this analysis was 7910 adult CHIS respondents living in urbanized areas of Sacramento, Yolo, Placer, and Solano counties. The adult sample was limited to include only respondents younger than 65, both to reduce the confounding effect of age on tree cover-health outcome associations, and out of recognition of differences in lifestyle between younger and older adults. Participants were excluded from each sample if they had missing outcome or socio-demographic data, if they had been living at their current address for less than a year, or if the DAC classified the accuracy of the geocoded home address as either "low" or "medium" (as opposed to "high"). After applying these exclusion criteria, the remaining sample included 4823 adults pooled across the 2003–2009 CHIS samples.

Tree cover variables were calculated within airline (e.g., as the crow flies) buffers radiating out from the participant's geocoded home address. A wide range of geographical scales have been used in prior research for quantifying residential "greenness" in relation to study participant's physical activity and obesity, ranging from the street immediately outside of the participant's home (Giles-Corti and Donovan, 2002b) to the zip code containing the participant's home (Lovasi et al., 2013a, 2013b). For this analysis, a 250 m airline buffer was chosen with the intent of striking a balance between the potential value of nearby tree cover for respiratory and psychosocial health and of more distant tree cover for encouraging physical activity, and reducing obesity and related chronic diseases. Within each buffer, the percent the area classified as "tree canopy" was calculated. Three participants who lived on the edge of the study area and had over 50% of their buffer outside of the study area were excluded from further analysis, leaving a final analytic sample of 4820 adults. A walkability index score was joined to each participant based on the block group containing the participant's home. The SACOG vector datasets were used to calculate the amount of park area with 500 m of each participant's home and the distance from the home to the nearest major road (arterial or freeway).

The mediation analysis was based on the four steps outlined in Baron and Kenny (1986):

1. Test for an association between the predictor (tree cover) and outcome (general health).
2. Test for an association between the predictor (tree cover) and each potential mediator.
3. Test for an association between each potential mediator and outcome (general health) while controlling for the predictor (tree cover).
4. Calculate the percent of the predictor-outcome association mediated in each case and identify if complete mediation occurred.

Three types of multivariate regression models were fit for the mediation analyses. Ordinal logistic regression was used for Likert outcomes, binary logistic regression was used for dichotomous outcomes, and Poisson regression was used for count outcomes, as indicated in Table 2. Sample sizes for each regression model depended on the availability of outcome variables in each CHIS survey cycle, as indicated in Table 2. All demographic, socio-economic, and built environment variables (listed in Table 1) were included in every model as covariates, and all models included adjustment for the DAC-provided raked sample weights.

Ordinal and binary logistic regression results are reported as odds ratios (OR) and Poisson regression results are reported as incidence rate ratios (IRR). For both ratios, the effect sizes are reported in relation to a 10% increase in tree canopy coverage, which is equal to the sample standard deviation for neighborhood tree cover within a 250 m buffer of home. Associations were classified as statistically significant ($p < 0.05$), marginally significant ($p < 0.1$), weakly significant ($p < 0.2$) or not significant ($p > =0.2$). Mediators that were not significantly associated with tree cover in step two were excluded from further analyses.

Remote sensing feature extraction was carried out using eCognition 8.9 (Trimble Navigation Limited, Westminster, USA). R v2.15.2 (R Foundation for Statistical Computing, Vienna, Austria) was used for all statistical analyses (including the "foreign" and "survey" packages). ArcMap v10.0 (ESRI, Redlands, California) and Geospatial Modeling Environment v0.7.2.1 (Spatial Ecology LLC) were used to conduct geospatial analyses.

4. Results

Unweighted means (for continuous variables) or percentages (for categorical variables) for all covariates and tree cover predictor variables from the pooled 2003–2009 CHIS data sets (n=4820

Table 4
Multivariate regression model results from step 3 of the mediation analysis, along with percent mediation results from step 4.

Mediating variable	Mediator association with general health		Tree cover association with general health		Percent mediated
	IRR	95% confidence interval	IRR	95% confidence interval	
Steps 3 & 4: Association of mediator variables with outcome and test for complete mediation					
Overweight or obese	1.079***	(1.059,1.098)	0.897***	(0.829,0.971)	21%
High blood pressure	1.113***	(1.094,1.132)	0.876***	(0.809,0.949)	5%
Type 2 diabetes	1.212***	(1.174,1.250)	0.877***	(0.809,0.950)	5%
Current asthma	1.088***	(1.066,1.112)	0.877***	(0.807,0.953)	5%
Social cohesion index	0.988***	(0.980,0.997)	0.892***	(0.797,0.999)	11%[a]

*** $p < 0.05$.
[a] Because the social cohesion index was only available for the 2003 and 2009 CHIS samples, percent mediation was calculated by comparing the mediated association between tree cover and general health (IRR=0.892) to the unmediated association using only the sample of CHIS participants reporting social cohesion (IRR=0.879).

participants) are provided in Table 1. As compared to general population characteristics of the Sacramento Metropolitan Statistical Area according to the 2009 American Community Survey 5-year estimates (data not shown), CHIS participants were more likely to be female, older, non-Hispanic, more educated, and wealthier. CHIS-provided sample weights were used to account for these differences in the regression models. In terms of their neighborhood environment, the average CHIS participant had access to nearly 12 acres of park space within 500 airline meters of home (or 6% of the 500 m buffer), had a walkability index of 48 out of 100 (moderately walkable), and lived about 400 airline meters from the nearest arterial road or highway.

Descriptive statistics for the outcome and mediator variables are provided in Table 2. For general health, 23% reported "excellent," 37% "very good," 27% "good," 10% "fair," and 3% "poor." The most commonly-reported health condition was being overweight or obese (59%), while type 2 diabetes was the least common (6%). Sixty-two percent of respondents reported engaging in the equivalent of at least 30 min of walking, five times per week. The mean social cohesion index was 9.4, which corresponded to an average response slightly stronger than "agree" to the two positive social cohesion questions and slightly stronger than "disagree" to the one negative social cohesion question.

The following summarizes the findings from each of the four steps of the mediation analysis:

4.1. Step 1: Association of predictor with outcome variable

After adjusting for demographic, socioeconomic, and built environment covariates, more neighborhood tree cover was significantly associated ($p < 0.01$) with a 13% greater odds of reporting a better general health score. A 10% increase in tree cover was

Table 3
Multivariate regression model results from steps 1 and 2 of the mediation analysis.

Model outcome	Tree coverage association with outcome	
	OR or IRR	95% confidence interval
Step 1: Association of predictor with outcome variable		
Poor general health	0.871***	(0.799,0.949)
Step 2: Association of predictor with mediator variables		
Overweight or obese	0.815***	(0.741,0.896)
High blood pressure	0.926~	(0.828,1.036)
Type 2 diabetes	0.811~~	(0.640,1.027)
Current asthma	0.896~~	(0.789,1.019)
Physically active	1.028	(0.933,1.133)
Psychological distress	1.042	(0.733,1.481)
Social cohesion index	1.014***	(1.004,1.023)

*** $p < 0.05$.
~ $p < 0.2$.
~~ $p < 0.1$.

associated with a 2.9% improvement in reported general health score.

4.2. Step 2: Association of predictor with mediator variables

After adjusting for demographic, socioeconomic, and built environment covariates, more neighborhood tree cover was significantly associated ($p < 0.05$) with less overweight/obesity and higher social cohesion index, as shown in Table 3. More neighborhood tree cover was marginally associated ($p < 0.1$) with less type 2 diabetes and less current asthma and weakly associated ($p < 0.2$) with less high blood pressure. Neighborhood tree cover was not associated with physical activity or psychological distress, so these outcomes were excluded from further mediation analyses.

The largest effect size was found for overweight/obesity and type 2 diabetes, with a 10% increase in tree cover associated with approximately 19% reduction in both outcomes. The same 10% increase in tree cover was associated with a 10.4% reduction in current asthma, a 7.4% reduction in high blood pressure, and a 1.4% increase in the social cohesion index.

4.3. Step 3: Association of mediator variables with outcome

The five remaining mediator variables were added one at a time to the Poisson regression model predicting poor general health, and in every case the mediator was significantly associated ($p < 0.05$) with poor general health, as shown in Table 4. Of the dichotomous mediators, reporting having type 2 diabetes was associated with the highest risk for reporting worse general health, as reporting having type 2 diabetes was associated with a 34% worse general health score. Reporting having high blood pressure, current asthma, or being overweight or obese were associated with 11, 9, and 8% greater odds of reporting a worse general health score, respectively. A one point increase in the social cohesion index was associated with a 1% greater odds of reporting a better general health score.

4.4. Step 4: Test for complete mediation

Using the same models, the neighborhood tree cover association with general health was weaker in every case after adding the mediator variable, as shown in Table 4. , In every case, the mediator-general health association remained statistically significant ($p < 0.05$). In no case was the association weakened sufficiently to be considered complete mediation. Partial mediation of the tree cover-general health association was strongest when adding the overweight/obesity variable, which resulted in 21% mediation. This was followed by social cohesion (11% mediation), while the remainder mediated only 5% each.

For the 2003–2009 sample, the four available mediators (overweight/obesity, high blood pressure, type 2 diabetes, and current asthma) were added simultaneously, resulting in a reduction of the tree cover-general health OR to 0.906, for a cumulative mediation of 28%. For the smaller 2003 and 2009 sample of only participants with children, the same four mediators plus social cohesion were added simultaneously, resulting in a reduction of the tree cover-general health IRR to 0.934, for a cumulative mediation of 37%.

5. Discussion

This study linked high-resolution tree canopy data to a large sample of participants in the California Health Interview Survey (CHIS), consisting of adults living in urbanized areas of the Sacramento region, to explore associations between neighborhood tree cover and health outcomes. The findings indicated that more tree cover within 250 m of home was associated with better self-reported general health, and that the association was partially mediated by lower prevalence of overweight/obesity and better neighborhood social cohesion. Although they did not reach statistical significance in step 2 of the mediation tests, the tree cover-general health association was also partially and weakly mediated by lower prevalence of high blood pressure, type 2 diabetes, and current asthma. Counter to expectations based on prior research, no association was found between tree cover and physical activity or psychological distress.

The use of high-resolution (1-meter) land cover data derived from a combination of LiDAR and aerial imagery was a key innovation of this research. While some researchers have derived tree cover data from local censuses (Lovasi et al., 2013b), field audits (Pikora et al., 2006) or by digitizing tree locations from aerial imagery (Boarnet et al., 2011), most studies of "greenness" associations with health have relied on pre-existing 30-meter or lower resolution land cover data based on imagery alone (Almanza et al., 2012; Fan et al., 2011; Laurent et al., 2013; Villeneuve et al., 2012). Such datasets are less accurate, with tree canopy often mislabeled as other types of vegetation, thus limiting the precision of imagery-based measures to general classifications of "greenness." The use of LiDAR data in this study allowed for the identification of object height, which was critical for accurately isolating trees from shrubs, grass, and other green surfaces (MacFaden et al., 2012). The high resolution of the data allowed for more precise and disaggregate identification of tree cover, which was especially important given the high diversity and variation of land cover inherent in an urbanized study area. Adjusting for neighborhood access to parks and open space helped to further ensure that the associations were due to the presence of tree cover, independent from the effect of parks or other accessible natural spaces.

While most results were in the hypothesized direction and of reasonable strength, two exceptions were physical activity and psychological distress. Neighborhood tree cover was associated with greater likelihood of meeting physical activity recommendations, but the relationship was non-significant (p=0.58). This non-significant association was inconsistent with the model results for the three outcomes related to physical activity, as more tree cover was significantly associated with less overweight/obesity, marginally associated with less type 2 diabetes, and weakly associated with less high blood pressure. It is possible that biased self-reporting of physical activity contributed to the lack of association between tree cover and physical activity, as physical activity recall questionnaires tend to have poor validity compared to accelerometers or other objective physical activity measures (van Poppel et al., 2010). In contrast, while BMI calculated from self-reported height and weight is often underestimated, the accuracy of self-reported BMI is typically much better than for recalled physical activity (Gorber et al., 2007). Alternatively, the association between tree cover and the three physical activity-related outcomes could be explained by unadjusted confounding (e.g., participants living in neighborhoods with greater tree cover may be more educated and have greater socioeconomic resources, allowing for a better diet, thus confounding the tree cover-overweight/chronic disease association by dietary factors). Another possibility is that neighborhood tree cover is associated with only certain types of especially health-promoting physical activity but not with overall physical activity. As the exploratory study indicated, more tree cover was associated with more vigorous physical activity but not with other types of physical activity (Ulmer et al., 2014).

Exploratory analyses were conducted to attempt to explain the unexpected lack of association between tree cover and adult psychological distress. Stratified models (data not shown) indicated that more tree cover was significantly associated with lower psychological distress (p=0.015) for those adults unemployed and not job seeking (which could include those retired, independently wealthy, in a household where other adults were providing the income, or unable to work), while no association was found for those currently employed or unemployed and job seeking. One possible explanation is that the unemployed spend more time in their residential environment, and that those not job seeking have more opportunity for leisure enjoyment. CHIS data did not allow for testing this hypothesis, but the impact of temporal exposure to tree cover and spatial context should be considered in future studies. For those spending significant amounts of daylight time away from the residential neighborhood, the presence of tree cover and nature in non-residential contexts (e.g., work, commuting route) may prove to be more relevant for psychological health, suggesting the need for increasing tree canopy near workplaces, commercial centers, and other heavily-used non-residential areas. No other significant associations between tree canopy and distress were found by socioeconomic status or other strata. Another possible explanation for the inconsistency in the current finding may simply be due to differences in tree cover and outcome variable measurements (which vary widely across studies).

Results related to asthma should be interpreted with caution, as the relationship between trees and asthma is particularly complex, as explained in the introduction/literature review. Although we were able to simply adjust for vehicular pollution exposure by controlling for the proximity of the participant's home to the nearest major road, a better understanding of the impact of trees on respiratory conditions will require more detailed data on specific tree species and size, streetscape characteristics, and a more comprehensive understanding of CHIS participants' exposures to indoor and outdoor airborne pollutants. The effective health-promoting distance of tree cover to the home is also a necessary consideration. The lack of significant association found in this analysis may have been affected by using too large of a buffer area (250 m) for measuring tree cover. In an initial exploratory analysis, more tree cover within a 100 m buffer was found to be significantly associated with less asthma.

5.1. Limitations

One limitation of this study was the cross-sectional nature of the data, which precluded the ability to draw causal conclusions about the influence of tree cover on health. Excluding CHIS participants living at their current address for less than one year eliminated participants least likely to have been effected by tree canopy at their current address. There were no data available from CHIS to adjust for residential self-selection or participants' daily

temporal exposure to their residential environments.

Another limitation related to the CHIS data was that all data were self-reported and subject to several types of bias common in survey measurement. This can be particularly problematic with outcomes like physical activity and psychological health (Löwe et al., 2004; van Poppel et al., 2010) where variations are considerable and comparative data show substantial deviations between reported and objectively measured data. Similarly, properly controlling for socioeconomic status is a known challenge, particularly given the limited scope of socioeconomic questions on most surveys (Braveman et al., 2005). It is possible that part of the explained variation in some key outcomes is the result of uncontrolled confounding factors, where living in a neighborhood with more tree cover and having better health were linked by a third common factor that was not fully adjusted for in the regression models, such as socioeconomic status. To address this concern to the degree possible with the available data, a comprehensive selection of socioeconomic variables were controlled for in all models, including race/ethnicity, English language ability, educational attainment, income, poverty status, home ownership, food security, and health insurance status.

Uncontrolled confounding may also bias the association between the mediators and the general health outcome, as an assumption inherent to the regression methods used in this paper is that the explanatory variables are uncorrelated with the model error (exogenous). All available confounders of the association between the mediators and general health were included in the models, though many other potential co-determinants (e.g., diet) were unmeasured in some or all years of CHIS data. Endogeneity bias could potentially be reduced through the use of instrumental variables, if CHIS variables could be identified for each mediator that were correlated with the mediator but not the error term. Path analysis could also more explicitly model the causal linkages between mediators and outcomes, though uncontrolled confounding may remain a problem given limitations in CHIS data. Ultimately, bias (and the determination of causality) in the mediation analysis would best be resolved by using data collected as part of an experiment or other longitudinal design.

5.2. Urban forestry implications

Considering both rapidly increasing costs and diminished quality of life associated with illness, there is an expanding interest in innovative disease prevention and health promotion practices (Fielding and Kumanyika, 2013; McGinnis et al., 2002). Community health strategies are becoming more common, in addition to individual health care, to construct settings that can improve the health of a population across a geographic area, such as a neighborhood or county (Sallis et al., 2006; Whitelaw et al., 2001). Built or 'grey' infrastructure may be upgraded to promote better community health, such as sidewalk installation for walkability or complete streets to support active transit. 'Green' infrastructure systems can also support community health (Tzoulas et al., 2007).

The City of Sacramento has initiated tree planting programs based on multiple benefits assessments. Most of these have focused on environmental services such as energy savings, and improved air and water quality (Nowak et al., 2013). Based on this study's results the urban forest may be a health intervention that offers additional co-benefits, with economic implications (Wolf and Robbins, 2015). Of particular interest in recent literature is the equitable distribution of natural amenities across a city (Wolch et al., 2014). Another policy consideration for the City of Sacramento would be to evaluate and assure that residents of all socioeconomic and cultural situations have adequate access to urban nature, including parks, gardens, and forest.

6. Conclusions

The results of this study suggest that more neighborhood tree cover in urbanized areas, independent from green space access, is related to better overall health, primarily through lower overweight/obesity and better social cohesion, and to a lesser extent through less type 2 diabetes, high blood pressure, and asthma. The key contribution of this research is a specific focus on tree cover as differentiated from other types of "greenness" by using a highly accurate measure of neighborhood tree cover derived from a high-resolution combination of LiDAR and imagery data and by adjusting for neighborhood access to parks and open spaces. These findings add to the existing evidence base, suggesting an important role for trees and nature in improving human health at the community scale in urban areas.

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