Journal of Environmental Management 285 (2021) 112207

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Are street tree inequalities growing or diminishing over time? The inequity remediation potential of the MillionTreesNYC initiative

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ARTICLE INFO

Keywords:
Urban forestry
Environmental inequality
Disaggregated analysis
Street tree census
Tree planting

ABSTRACT

Most street tree inequality studies focus on examining tree abundance at single time point, while overlooking inequality dynamics measured based on a complete set of tree measures. Whether the severities of street tree inequalities vary with different tree structure measures, whether street tree inequalities are diminishing or growing over time, and how the inequality dynamics are affected by tree-planting programs remain largely unexplored. To fill these gaps, this study applied binned regression and cluster analyses to street tree census data of 1995–2015 in New York City. We investigated different structural measures of street tree inequalities pertaining to various aggregations of people, compared street tree inequalities over time, and revealed the inequity remediation role of the MillionTreesNYC initiative. We found that the underprivileged populations, characterized by higher percentages of the poor, racial minorities, young people, and less-educated people, are more likely to have lower tree abundance, less desired tree structure, poorer tree health condition, and more sidewalk damages. When disaggregating inequalities across various aggregations of people, income-based and education-based inequalities were the most severe, but the inequalities diminished over time. The race-based and age-based inequalities show mixed results that disfavor Hispanics, Blacks, and young people. The equity outcome of the MillionTreesNYC initiative is not ideal as the inequalities decrease when measured using tree count and species diversity, whereas they increase when measured using tree health and average diameter at breast height. The findings have important implications for more effective decision-making to balance resources between planting trees and protecting existing trees, and between increasing tree abundance and improving tree structure.

1. Introduction

1.1. Street tree inequality studies

As an important component of green infrastructure, street trees provide numerous ecosystem services and benefits to help build a sustainable city and a healthy community (Mullaney et al., 2015). Although street trees contribute significantly to ecological sustainability and human well-being, their role in environmental justice is uncertain, depending on the associations between multiple aspects of street tree assemblages and the residents' characteristics. The location, distribution, structural measures, and local site conditions of street trees interact with socioeconomic and demographic dimensions of populations, and can lead to various degrees of street tree inequalities (Lin et al., 2021). Some studies have suggested that inequalities are more prevalent in streetscapes than in private landscapes (Kendal et al., 2012; Pham et al., 2012). Landry and Chakraborty (2009) report that African Americans, low-income residents, and renters are associated with lower street tree canopy cover in Tampa, Florida. Different aspects of street tree inequalities have also been identified in New York City (NYC), NY in two separate studies. Neckerman et al. (2009) found that poor communities have significantly fewer street trees, whereas Lin et al. (2021) reported that severe race- and education-based street tree inequalities exist. One study in Montreal, Canada also reported that there exists income-based inequality as street tree cover is higher in affluent neighborhoods than in low-income neighborhoods (Pham et al., 2017). Based on case studies in

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https://doi.org/10.1016/j.jenvman.2021.112207
Received 10 July 2020; Received in revised form 8 February 2021; Accepted 14 February 2021
Available online 23 February 2021
0301-4797/

six Australian cities, Kirkpatrick et al. (2011) found that local areas that have higher percentages of high income and education levels are likely to have more street trees. Most studies employ tree canopy cover to measure street tree inequalities (Lin et al., 2021). When measured using other aspects of street trees, only a few studies are identified, and the patterns of inequality seem to be different from the studies using tree canopy cover. For example, no evidence of severe street tree inequalities is reported when measured based on basal area in Cincinnati, Ohio and based on street tree benefits in Barcelona, Spain (Baró et al., 2019; Berland and Hopton, 2014).

Despite growing recognition of environmental inequality in streetscapes, studies on street tree inequalities remain limited, particularly compared with the inequality studies in private landscapes. Previous studies have typically focused on examining inequalities either in residential areas or at the entire city level (Conway et al., 2013; Grove et al., 2014). Street tree inequality studies should receive a higher level of scrutiny as street trees are publicly owned and maintained, and substantial public resources are devoted to growing and caring for street trees (Ferguson et al., 2018). This study focused exclusively on street tree inequality and contributes to the existing literature in several ways. First, most street tree studies focus on specific socioeconomic and demographic aspects of inequalities, with income-based inequality being the most examined (Kirkpatrick et al., 2011; Neckerman et al., 2009). This study examined 11 variables that cover diverse aspects of residents' characteristics, including income, race, education, age, and lifestyle. These aspects were examined both individually and collectively to reveal the relative severity in different dimensions of inequalities. Second, tree canopy cover has been widely used to measure street tree inequalities, and inequalities in terms of other tree attributes have been rarely investigated (Lin et al., 2021). In addition to tree abundance, whether disadvantaged subpopulations are more likely to experience less desirable tree structure, lower species diversity, poor tree health condition, and more tree-related sidewalk damages warrants greater attention. Third, previous inequality studies are typically based on a single point in time, and whether street tree inequalities are diminishing or growing over time remains largely unexplored. By filling the above-mentioned gaps, this study has important implications for decision-makers in effectively allocating public resources between increasing tree abundance and protecting existing trees, and in tackling the dual tasks of improving environmental quality and addressing environmental inequity concerns.

1.2. Tree planting programs

Cities worldwide have launched tree planting and conservation projects to increase tree canopy coverage and maximize the benefits of trees (Ali et al., 2019; Danford et al., 2014; Lin et al., 2019). Large-scale tree-planting programs significantly increase urban forest abundance, raise awareness and appreciation of local communities towards trees, build strong connections between people and trees, and shape people's stewardship behaviors (Moskell et al., 2010; Rae et al., 2010). Notable examples of tree-planting programs are summarized in Table 1, and one such program is the MillionTreesNYC (https://www.milliontreesnyc.org/). MillionTreesNYC is an ambitious and massive campaign that commits to planting and caring for a million new trees across all available public and private land in NYC (Campbell et al., 2014). The program was launched in October 2007 with the goal of being completed by 2017. Due to good budget support, collaboration, partnerships, and participation, the goal was achieved in 2015 (NYC Parks, 2020). Under the MillionTreesNYC initiative, the specific goal for street trees was to plant all the empty street tree sites with approximately 220,000 additional trees to increase stocking levels from 73% to full coverage (Rae et al., 2010). To achieve this goal, the planting policy of street trees shifted from 'Request Planting' (calls to 311 Customer Service Center) to the combination of 'Request Planting' and 'Block Planting'. The 'Block Planting' policy targets blocks with the greatest need of street trees (e.g., low street tree stocking level and high population density blocks). Additionally, building owners could not deny a suitable tree planting in the public right-of-way (Rae et al., 2010).

Table 1
Examples of massive tree planting programs.

Tree planting program	Location	Target	Reference
Million Tree Initiative	New York City, Los Angeles, and Denver in US; Shanghai, China; Pune, India; London Ontario, Canada	Plant and care for one million new trees	a
One Million-Mu Plain Afforestation Project	Beijing, China	Plant 50 million trees and increase forest cover by 10%	Yao et al. (2019)
Greenest City 2020 Action Plan	Vancouver, Canada	Plant 150,000 new trees, of which 54,000 on private land	b
Manchester's City of Trees project	Manchester, UK	Plant 3 million trees, one for every person across Greater Manchester	c
Trees Atlanta	Atlanta, US	Plant more than 133,000 trees throughout the metro area	d
Nature in Cities under the Greening Australia	Multiple cities in Australia	Establish 25 million plants, restore 15,000 ha of habitat, and sequester 50,000 tonnes of carbon	e

[a] https://en.wikipedia.org/wiki/Million_Tree_Initiative.
[b] https://vancouver.ca/green-vancouver/greenest-city-action-plan.aspx.
[c] https://www.cityoftrees.org.uk/about-city-trees.
[d] https://www.treesatlanta.org/programs/treeplanting/.
[e] https://www.greeningaustralia.org.au/programs/nature-in-cities/.

Although these programs typically increase tree abundance, their effects on inequities are seldom measured and are unclear. Many tree-planting programs have explicit tree canopy goals while less attention is given on addressing social inequities (Danford et al., 2014; Flocks et al., 2011). Consequently, some studies show that tree-planting programs might even exacerbate inequity by planting more trees in wealthy neighborhoods (Watkins et al., 2017). This phenomenon has been referred to as 'procedural inequity', which corresponds to the decisions and processes that lead to uneven distribution of tree resources and therefore aggregate the inequity (Nesbitt et al., 2018; Pham et al., 2012). In addition to 'procedural inequity', 'compensatory inequity' is also proposed to emphasize the greater needs of public greening resources for disadvantaged subpopulations and vulnerable groups who typically cannot afford private trees (Pham et al., 2012). Although outcome inequity has been extensively studied, procedural and compensatory inequities remain largely unexplored due to the recent establishment of tree-planting programs and the lack of before-after time series data.

We argue that the procedural and compensatory inequities of urban forest programs merit investigation as the public, governments, and non-profit organizations have invested tremendous efforts and resources to urban forest programs. Their interventions and goals (procedural inequity) should be better measured and scrutinized to justify that these public expenditures are essential. Current aggregating or averaging expressions of urban forest measures at the city level typically hide geographic variations and disparities of tree distribution and cause local patterns or anomalies to disappear. Disaggregated analyses of urban forest programs, with explicit recognition of differentiated investment of public resources across geographical areas and among social groups, have important policy implications. The public and decision-makers are concerned not only with the average impact but also the consequences of tree-planting programs for specific subpopulations such as minorities, low-income groups, the elderly, and young children (compensatory inequity). The people at the bottom of the socioeconomic spectrum are typically insufficiently protected from environmental exposures, most vulnerable to natural hazards, and most in need of urban forest resources. To take tree-planting initiatives as an opportunity to reduce social inequity and gain support for future tree-planting activities across all population groups, it is important to explicitly incorporate the inequity framework into tree-planting goals.

2. Objectives

By applying quantile regression and cluster analysis to street tree census over the past two decades (1995–2015) in NYC, this study investigated multiple aspects of street tree assemblages among different socioeconomic and demographic groups, compared street tree inequalities over time, and examined the potential effects of the MillionTreesNYC initiative to remedy street tree inequities. The impact of the MillionTreesNYC initiative (2007–2015) was examined by comparing street tree inequalities in 2005 and 2015, and referencing the changes in inequalities during the second decade (2005–2015) to that during the first decade (1995–2005). This study addressed three questions. First, how have street tree inequalities changed over the past two decades? Second, which socioeconomic groups experience the most severe inequalities, and how do the inequalities change based on different street tree measures (e.g., tree abundance, tree structure, species richness, and tree health)? Third, does the MillionTreesNYC initiative help remedy the inequity?

3. Study area

NYC is one of the most populous cities in the United States (US), with an estimated population of 8,560,072 in 2015, according to the US Census (U.S. Census Bureau, 2017). The city consists of five boroughs: Brooklyn, Queens, Manhattan, The Bronx, and Staten Island. Based on street tree census data, there were 666,134 street trees in NYC in 2015, 592,130 in 2005, and 498,470 in 1995, with a 12.5% increase from 2005 to 2015 and an 18.8% increase from 1995 to 2005 (Street Tree Census Report, 2016). We conducted statistical analyses at the census tract (CT) level, which has been frequently employed as an analysis unit in previous urban forest studies (Nesbitt et al., 2019; Tooke et al., 2010). We aggregated and summarized street tree structure and socioeconomic variables at the CT level. Although the physical environment in a CT may be heterogeneous, residents within a CT typically have relatively homogenous socioeconomic characteristics (Pham et al., 2012).

4. Methods

4.1. Dataset description and processing

A flowchart of the research methodology is presented in Fig. 1. First, we identified street tree locations, and extracted and summarized street tree attributes at the CT level. Second, we extracted socioeconomic and demographic variables from the American Community Survey (ACS). Finally, we combined street tree attributes and socioeconomic-demographic variables to examine the dynamics of street tree inequalities.

4.1.1. Street tree locations

The street tree census datasets of 1995, 2005, and 2015 were downloaded from the NYC Open Data (https://opendata.cityofnewyork.us/). Due to the use of the TreeKIT mapping method and the accompanying mobile app (Silva et al., 2013), the street tree census in 2015 was able to place trees precisely where they were located along the curb and generated an accurate tree map. However, in the 2005 census, 23,993 trees out of the 592,372 were not located accurately. The 15,153 trees with valid latitude and longitude coordinates were mapped using ArcGIS 10.5. The 5808 trees with detailed street addresses were mapped using the Google Maps API. The remaining 3032 trees could not be located and mapped, and therefore were ignored in this study. The 1995 street tree census is only available in a tabular format. Out of a total of 516,989 records in the 1995 census, 484,602 were mapped using

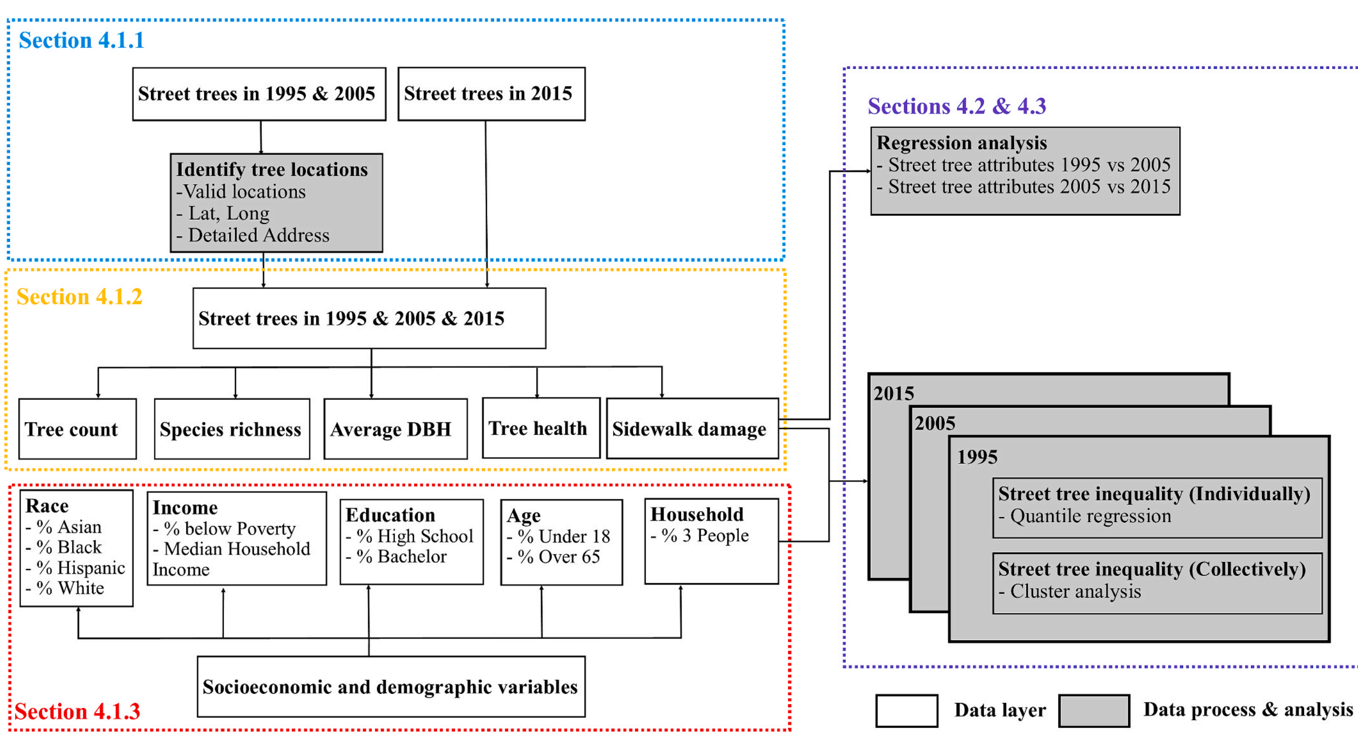

Fig. 1. Flowchart of the data layers and the analysis methods.

geo-coordinates, 30,490 were mapped using detailed street addresses, and the remaining 1797 trees were ignored. The effect of removing 3032 (0.51%) trees from the 2005 census and 1797 (0.35%) trees from the 1995 census was considered negligible. We also deleted invalid records, such as the records having a diameter at breast height (DBH) equal to 0 and tree conditions of 'Stump' and/or 'Shaft'.

4.1.2. Street tree attributes

Five tree attributes (e.g., tree number, species, DBH, health, and sidewalk) were selected and analyzed in this study as they are available for all three censuses, and represent different dimensions of tree structure and site conditions (Table 2). Tree abundance was represented as a tree count aggregated at the CT level. For DBH, the average DBHs for CTs were calculated to represent the overall tree size. For species diversity, species richness, defined as the number of tree species per CT, was calculated. For tree health and sidewalk conditions, the number of trees with poor conditions (e.g., dead and poor), and the number of damaged sidewalks (e.g., damaged, raised, and cracked) were summed for each CT, and the percentages of sites with poor conditions and damaged sidewalks were calculated.

4.1.3. Socioeconomic and demographic variables

By examining previous environmental injustice studies, variables pertaining to income, race, education, age, and housing characteristics were employed in this study (Table 2) (Conway and Bourne, 2013; Landry and Chakraborty, 2009; Schwarz et al., 2015). We chose variables that focus on marginalized groups who are disadvantaged in one or several aspects of socioeconomic and demographic conditions. For income, we used median household income and percentage of households below poverty line. For race/ethnicity, we focused on the percentage of Blacks, Hispanics, and Asians as they comprise the three largest minority groups in NYC. We also included percent non-Hispanic Whites for comparison. For education attainment, we used percent population with no high school diploma, and percent population with a bachelor's degree or higher was also included for comparison. For age, we used the proportion of people under 18 and the proportion of people over 65. For housing characteristics, we used the percentage of households with three or more people. All variables were extracted from the ACS at the CT level. Given the rolling nature of the ACS 5-year data (Locke et al., 2016), the 2005–2009 ACS and the 2013–2017 ACS were appropriate for the second and third street tree censuses, respectively. For the first street tree census, the corresponding variables were extracted from the 2000 Decennial Census.

4.2. Statistical analysis

Bivariate and multivariate regressions are frequently employed in urban forestry inequality studies (Landry and Chakraborty, 2009; Nesbitt et al., 2019; Schwarz et al., 2015). Bivariate regressions can easily identify the associations between socioeconomic-tree variable pairs, but the identified associations may vary with the addition of confounding variables. Therefore, bivariate analyses may provide only a partial view of the relationships. In contrast, multivariate analyses generally have greater explanatory power and are able to capture a more complete picture of the associations. However, they have two drawbacks: (1) they typically suffer from multicollinearity, which leads to unreliable coefficient estimates and high standard errors (Graham, 2003); and (2) there is evidence that income- and race-based variables may have strong effects, which may hide inequality identifications in other socioeconomic-demographic dimensions that show subtler impacts (Pham et al., 2012).

To fully capture the complicated relationships between socioeconomic-demographic variables and tree structure, and disaggregate the inequalities across various aggregations of people, we implemented a binning bivariate regression. Following the approach of Li et al. (2017), we divided the entire range of a targeted socioeconomic-demographic variable into bins, calculated the mean of tree structure within each bin, and employed the mean values in the bivariate analyses. The mean within each bin is more representative and appropriate for further analysis. In the inequality studies, socioeconomic variables such as income are commonly divided into seven groups: extremely poor (10% of the entire household number), poor (10%), lower middle (20%), middle (20%), middle high (20%), rich (10%), and

Table 2
Description, mean, and standard deviation for street tree measures and socioeconomic-demographic variables.

Variable Set	Variable	Description	Mean and standard deviation		
			1995	2005	2015
Street tree measures	Tree count	The tree count in CT	241 ± 265	275 ± 315	316 ± 305
	Species richness	The species count in CT	15.8 ± 6.3	28.5 ± 15.9	33.4 ± 13.2
	Average DBH	Average DBH of all trees in CT (cm)	11.8 ± 3.8	12.7 ± 3.6	11.5 ± 3.4
	Tree health	Percent of the dead and poor trees in CT	0.11 ± 0.07	0.11 ± 0.07	0.06 ± 0.04
	Sidewalk damage	Percent of damaged sidewalks in CT	0.10 ± 0.13	0.35 ± 0.19	0.31 ± 0.13
Socioeconomic and demographic variables	Percent below Poverty	Percent of households which have an income below the poverty line	20.1 ± 13.2	14.8 ± 12.7	18.3 ± 12.0
	Median Household Income	Median household income in the past 12 months (thousand dollar)	41.1 ± 18.8	54.5 ± 26.0	64.6 ± 31.6
	Percent Hispanic	Percent of population that is Hispanic-American	24.4 ± 22.2	25.0 ± 22.6	26.3 ± 22.2
	Percent Black	Percent of population that is Black-American	25.7 ± 31.5	25.0 ± 31.2	23.4 ± 29.2
	Percent Asian	Percent of population that is Asian-American	9.8 ± 12.4	11.9 ± 15.2	14.5 ± 17.0
	Percent White	Percent of population that is Non-Hispanic White-American	36.0 ± 32.3	35.7 ± 32.2	32.7 ± 29.6
	Percent Under 18	Proportion of people under 18 years of age	27.0 ± 8.6	22.8 ± 8.2	20.9 ± 7.1
	Percent Over 65	Proportion of people older than 65 years of age	11.9 ± 5.9	12.2 ± 6.4	13.7 ± 6.3
	Percent High School	Proportion of people without high school degree	28.6 ± 14.5	20.9 ± 12.3	18.8 ± 11.6
	Percent Bachelor	Proportion of people with bachelor or higher degrees	24.6 ± 18.6	28.6 ± 19.2	34.7 ± 20.8
	Percent 3 People	Percent of households with three or more people	45.9 ± 14.8	43.7 ± 15.8	44.1 ± 15.5

extremely rich (10%) (Zhao et al., 2019). We adopted this scheme to divide all socioeconomic-demographic variables into seven bins. An example of the binned regression for the tree count as a function of percent below poverty in 1996 is shown in Fig. 2. We employed the slope values from the binned regression to indicate the inequalities of different tree measures across various aggregations of people.

In addition to using the mean values, we examined tree measures at different quantile levels (e.g., 25th, 50th, and 75th) to assess the uncertainty of the identified associations. Quantile regression estimates multiple rates of slopes on the conditional median and other quantiles of the response variable, and therefore can capture the differences due to the complexity of interactions between the explanatory variables (Li et al., 2017). Under quantile regression, the response of the dependent variable cannot change by less than the lower limit set by the explanatory variable, but may change by more when there are other limiting factors (Cade and Noon, 2003). For example, education-based inequality may be best revealed at upper quantiles if less-educated people have lower income, whereas it may be observed at lower quantiles if they happen to be rich. To facilitate comparisons of inequalities among different socioeconomic groups, regression models were built by standardizing the response and explanatory variables by subtracting the mean from each value and dividing by the standard deviation.

4.3. Cluster analysis

In addition to examining inequalities across various population groups separately and individually, we employed cluster analysis to identify groups of CTs with similar characteristics of socioeconomic variables and tree measures. Based on different similarity measures (e.g., correlation coefficient, and distance measures) and algorithms (e.g., connectivity-based, centroid-based, and density-based clustering), clusters were formed by grouping a set of objects (e.g., CTs) based on the criteria of maximizing intra-cluster similarity and inter-cluster dissimilarity (Maechler et al., 2012). In this study, clusters were analyzed and identified using the k-means cluster analysis in the R version 4.0.2, and scree plots were employed to determine a suitable number of clusters. The clustering results were visualized and mapped using ArcGIS 10.5.

5. Results

5.1. The changes of street tree structure over geographic areas during the past two-decades

The variations in five street tree attributes over space showed a distinct difference over the past two decades (Fig. 3). The scatters represent the changes in specific tree attributes at CTs between 1995 and 2005 (Fig. 3, lower panel), and between 2005 and 2015 (Fig. 3, upper panel). The slopes are expressed as the mean for a 95% confidence range, and indicate the spatial patterns (e.g., clustering and spreading) in variations of selected tree attributes. Higher slope values indicate that more CTs experienced an increase in selected tree attributes as compared to the previous time period.

The changes in tree count over the past two decades appeared to be highly correlated, with scatters centered around the 1:1 line with R-squared values greater than 0.8 (Fig. 3a and b). More than half of the CTs experienced an increase in tree number during 1995–2005 (suggested by a slope of >1 for the regression line), whereas the opposite was observed during 2005–2015 with a slope of <1. This indicated that tree-planting activities were more likely to concentrate on certain geographical areas in the second decade than in the first decade. The same was true for species richness, with slope values of 1.51 for 1995–2005 and 0.62 for 2005–2015 (Fig. 3c and d, respectively). This indicated that more than half of the CTs witnessed a gain in species richness during 1995–2005, and more than half of the CTs experienced a loss in species richness during 2005–2015. For average DBH, the slope values changed from 0.49 (during 1995–2005) to 0.52 (during 2005–2015), and in both time periods more geographic areas witnessed a decrease in average DBH (Fig. 3e and f, respectively). This may be due to tree planting efforts, which lead to an expansion in the small-sized tree population. For the tree health and sidewalk conditions (Fig. 3g, h, 3i, and 3j), the slopes did not accurately capture their temporal changes, as indicated by the low R-squared values. We instead calculated the proportion of CTs with reference to the 1:1 line. For tree health, the proportion of CTs falling above the 1:1 line decreased from 50.8% (1995 vs. 2005) to 21.8% (2005 vs. 2015), indicating that the overall health of trees improved over time, and more than half CTs had better tree health in 2015 than in 2005. A similar pattern was also observed for sidewalk damage, and the proportion of CTs falling above the 1:1 line decreased from 86.8% (1995 vs. 2005) to 45.9% (2005 vs. 2015).

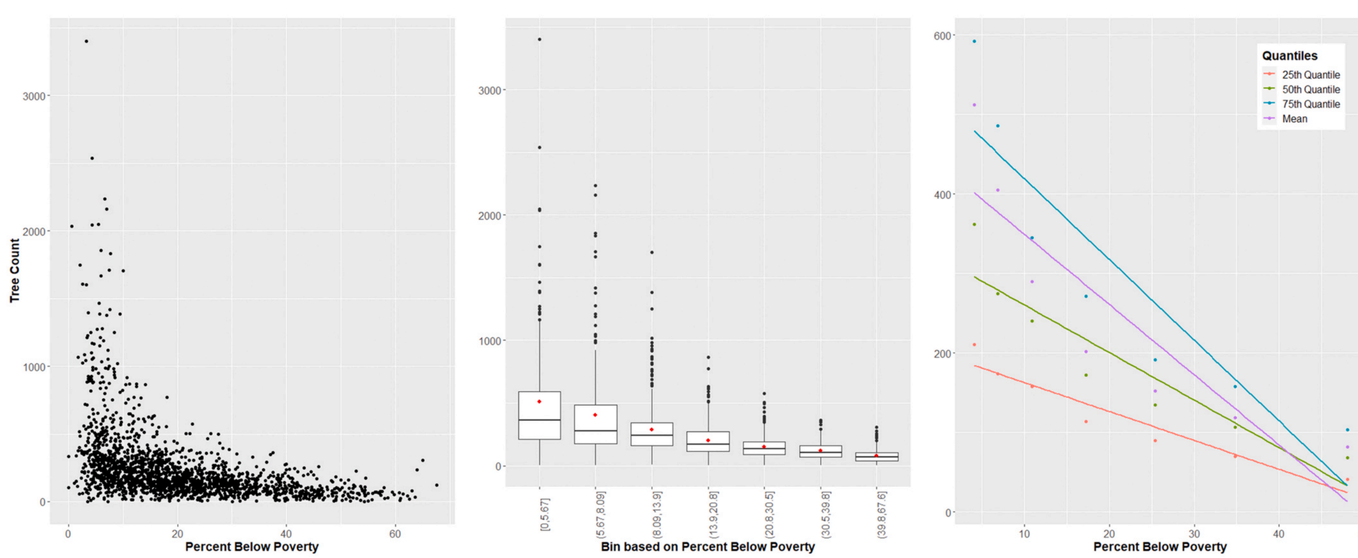

Fig. 2. Bin and quantile regression process: (Left) scatterplot of tree count vs percent below poverty; (Middle) scatterplot divided into 7 bins, and each bin represented as a boxplot with mean values shown as red dots; and (Right) quantile analysis to capture the explanatory-response relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

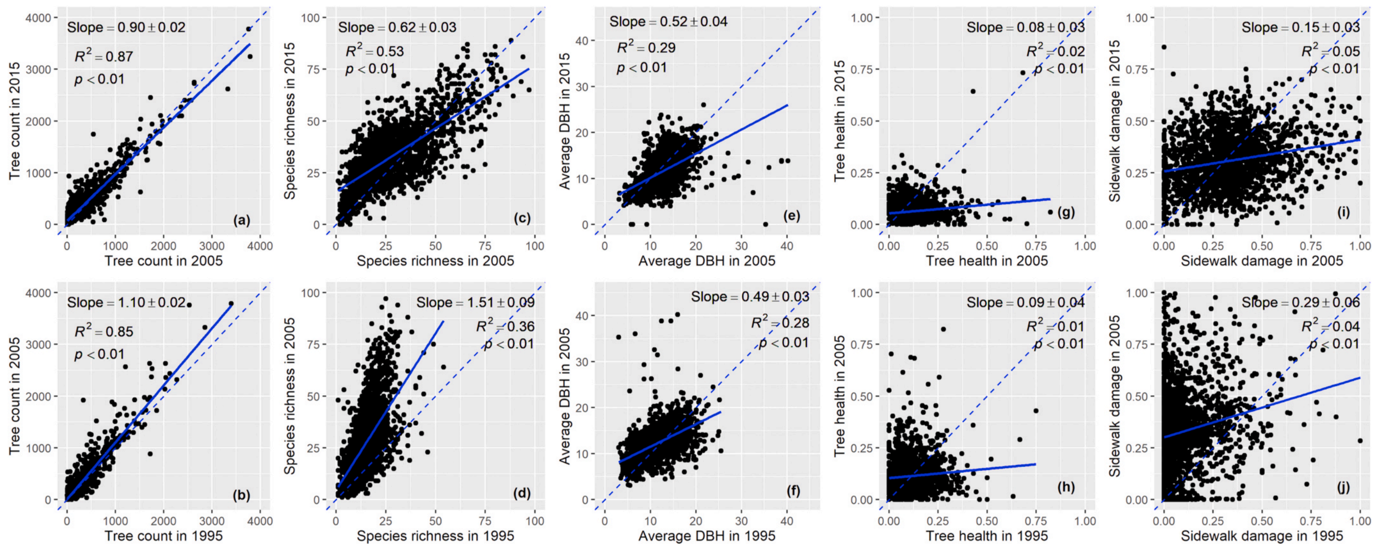

Fig. 3. The variations in five street tree attributes across geographic areas between 1995 and 2005 (lower panel), and between 2005 and 2015 (upper panel). The solid lines represent the regression lines of street tree attributes between different time periods, and the dotted lines are the 1:1 lines.

5.2. *Street tree inequalities across various aggregations of people over the past two-decades*

5.2.1. *Tree abundance*

Tree count-based inequalities were identified along all four socio-economic dimensions, except for household characteristics (Fig. 4). For income, tree count was negatively associated with Percent Below Poverty and positively related to Median Household Income. This indicated that low-income people were more likely to have less tree abundance, whereas rich people tend to live in areas with higher tree abundance. Although income-based inequalities were detected in all three street tree censuses, the severity of the inequalities diminished over time, as indicated by the decreasing slope values. For race, the slope values were negative for Percent Hispanic and Percent Black. This

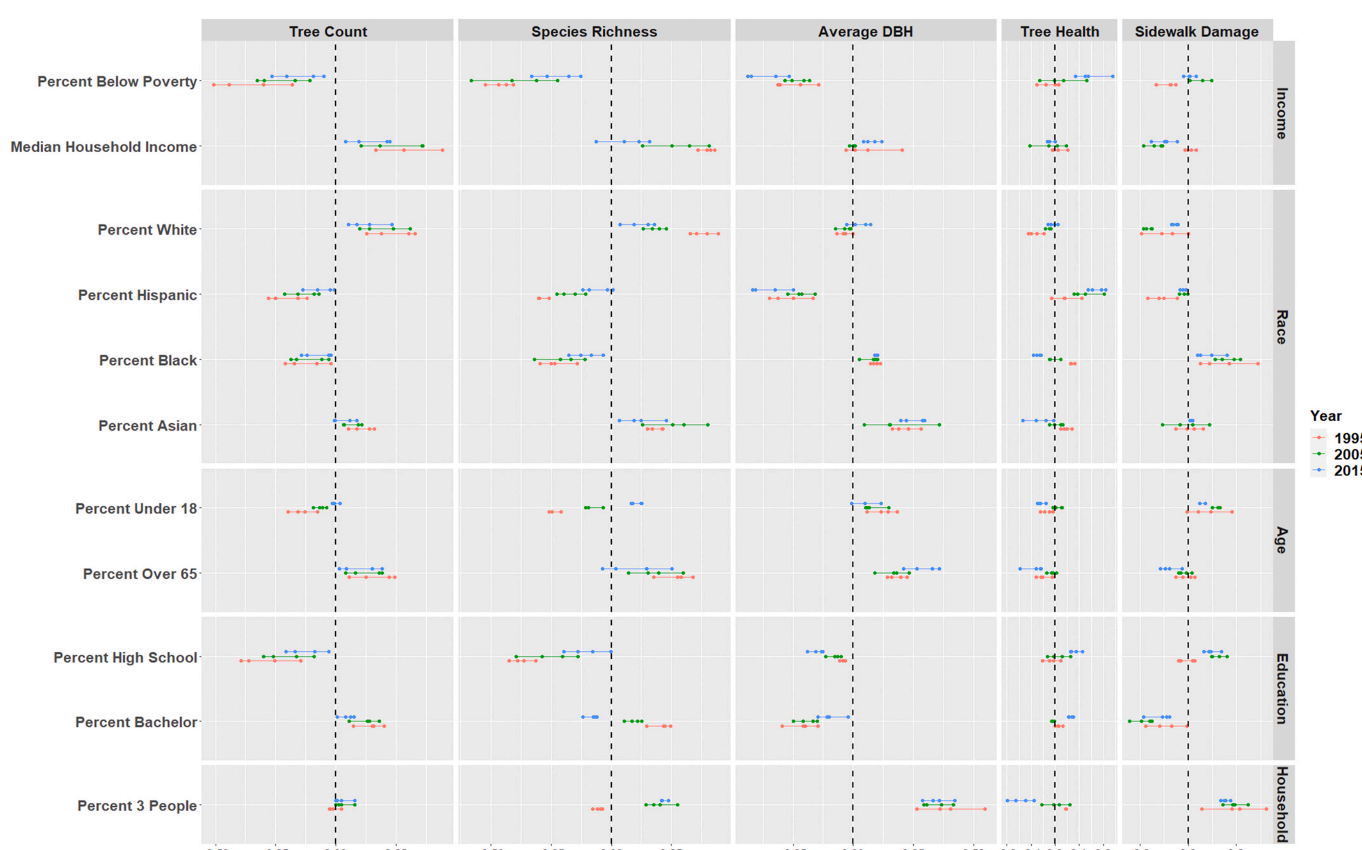

Fig. 4. The binned regression analysis results. The points represent the slope values for the mean, the 25th quantile, the 50th quantile, and the 75th quantile, respectively. The vertical dashed line is the no-effect reference line: the left side (negative values) indicates inequality and the right side (positive values) indicates absence of inequality. The only exceptions are median household income, tree health, and sidewalk damage, as positive values indicate inequality.

indicated that race-based inequalities existed for Hispanic and Black residents. Although the slope values were positive for both Percent Asian and Percent White, Percent White had higher slope values than Percent Asian. This indicated that although Asian residents were associated with higher tree abundance than Hispanic and Black residents, race-based inequalities still existed for Asian residents by reference to non-Hispanic whites. Regarding temporal trends, the decreasing trends for race-based inequalities over the past two decades were not as large as income-based inequalities. For age, inequalities were observed for young people (indicated by negative slopes for Percent Under 18) but not for the elderly (indicated by positive slopes for Percent Over 65). The severity of inequalities for young people decreased over time, and the inequalities became non-significant in 2015 as the slope values crossed the non-effect line. In contrast, the slopes for the elderly over the past two decades significantly overlapped with each other, indicating that there was no temporal trend. For educational attainment, the inequalities were observed for both Percent High School and Percent Bachelor, and they displayed similar temporal patterns of decreasing magnitudes from 1995 to 2015. For household characteristics, the inequalities in terms of Percent 3 People did not exist for any of the time periods.

5.2.2. Species richness

Overall, species richness-based inequalities among different socioeconomic subgroups showed similar patterns and temporal trends with tree-count based inequalities, that is, the inequalities were observed regarding Percent Below Poverty, Median Household Income, Percent Hispanic, Percent Black, and Percent High School, and their inequality severities diminished from 1995 to 2015 (Fig. 4). Despite the similarities, there were notable differences as well. For example, the slopes decreased from 1995 to 2015 for Percent White while increasing for Percent Hispanic, indicating that the corresponding inequalities were diminished. Though Percent White had a higher slope value than Percent Asian in 1995, the slope values in 2005 and in 2015 were similar, indicating that Asian residents were associated with a similar level of species richness as the White residents. Although there were severe inequalities for less-affluent people and visible minorities, the inequalities in the age, educational attainment, and household characteristic groups were either diminishing over time or even favorable towards underprivileged groups. For example, the slope values for Percent Under 18 and Percent 3 People turned from negative to positive from 1995 to 2015, indicating that these groups had access to higher species diversity. In contrast, an opposite trend was observed for the Percent Bachelor, indicating that species diversity may slightly disfavor well-educated people.

5.2.3. Average DBH

When measured based on average DBH, the inequalities displayed three distinct patterns among different socioeconomic groups (Fig. 4). Severe inequalities were observed for income, especially for Percent Below Poverty, and the inequalities enhanced over time. For race and educational attainment, pattern of inequality was mixed. The slope values were positive for Percent Asian and Percent Black, crossed the zero-line for Percent White, and were negative for Percent Hispanic. This indicated that in terms of average DBH, the inequality favored Asian and Black residents while disfavoring Hispanic residents. Regarding educational attainment, the pattern of inequality was unclear as both less and well-educated people were negatively associated with average DBH. For age and household characteristics, the slope values were positive for all three groups, indicating that young people, the elderly, and households with three or more people were more likely to benefit from the higher levels of ecosystem services provided by larger trees.

5.2.4. Tree health

Tree health was measured by the proportion of dead and poor condition trees, which indicated that the positive and negative slope values had opposite interpretations for the above-mentioned tree attributes. In terms of tree health, the most notable inequalities were observed for the poor and Hispanic residents, and a clear temporal trend of growing inequality was also identified for the poor (Fig. 4). In contrast, the inequalities for Blacks, Asians, and households with three or more people diminished from 1995 to 2015. For other population groups, the inequalities were not severe. The slope values had smaller magnitudes compared with other tree measures, and there were more slopes across the vertical zero-line.

5.2.5. Sidewalk damage

Sidewalk damage was indicated by the proportion of damaged sidewalks (e.g., damaged, raised, and cracked), and therefore the slopes were interpreted in the same way as tree health. The inequalities were not severe as the magnitudes of slopes were relatively small, and the slopes of several population groups crossed or were near the vertical zero-line. In addition, the temporal trends were unclear as the slopes across different time periods tended to overlay each other.

5.3. Cluster analysis

When aggregating all socioeconomic variables and tree measures together, two clusters were identified for all three time periods. We interpreted them as privileged/underprivileged clusters, based on the values of the cluster centers for all variables (Table 3). The results for 1995 and 2005 were similar to those for 2015, and therefore are not displayed here. The privileged cluster, characterized by higher percentages of Whites, the elderly, the rich, and well-educated people, was associated with larger values of tree count, higher species richness, larger average DBH, better tree health condition, and less sidewalk damages. In contrast, the underprivileged cluster had higher percentage of racial minorities, the poor, young people, less-educated people, and households with three or more people. This cluster was likely to have a lower tree abundance and less desired tree structure. For all three time periods, the privileged cluster was mainly located in Manhattan, Staten

Table 3
The identification of privileged and underprivileged clusters in 2015 based on the cluster centers.

Variable Set	Variable	Cluster center for each variable	
		Underprivileged cluster	Privileged cluster
Street tree measures	Tree count	−0.26	0.32
	Species richness	−0.22	0.28
	Average DBH	−0.1	0.12
	Tree health	0.04	−0.05
	Sidewalk damage	0.15	−0.18
Socioeconomic and demographic variables	Percent below Poverty	0.54	−0.67
	Median Household Income	−0.56	0.7
	Percent Hispanic	0.43	−0.53
	Percent Black	0.32	−0.39
	Percent Asian	−0.07	0.08
	Percent White	−0.6	0.75
	Percent Under 18	0.43	−0.53
	Percent Over 65	−0.34	0.43
	Percent High School	0.59	−0.74
	Percent Bachelor	−0.61	0.76
	Percent 3 People	0.4	−0.49

Island, southern Brooklyn, and northern Queens, whereas the underprivileged cluster was primarily in Bronx and Brooklyn (Fig. 5).

6. Discussion

6.1. Street tree inequalities over various aggregations of people

Rather than focusing on a single tree measure, this study compared and summarized street tree inequalities based on four street structure and one side condition. Street tree benefits and inequalities are not only determined by tree structure, but also by social-demographic constituents of the exposed population (Lin, 2020). We further disaggregated different aspects of tree structure inequalities across different socioeconomic and demographic groups. We found that inequalities existed in all structural measures of street trees and displayed distinct patterns among different socioeconomic groups. Overall, income-based inequalities were most severe as both metrics in the income group showed that poor people were associated with fewer tree counts, lower species richness, smaller average DBH, and poor tree health. Previous studies have also observed severe income-based inequalities when measured using metrics related to tree abundance. For example, Li et al. (2015) reported a positive association between per capita income and green view index in Hartford, Connecticut, and Landry and Chakraborty (2009) found a positive association between low-income residents and lower street tree canopy cover in Tampa, Florida. This phenomenon is well-explained by social stratification, which states that affluent people with more disposable income are more willing and likely to invest in green amenities, have greater mobility to move to desired locations (e.g., greener areas), and have greater power and resources to influence public investment (Grove et al., 2014; Locke et al., 2016). In addition, income-based inequalities may also depend on the wealth of households and local housing market and policy, which may limit residential choices for low-income residents (Lin et al., 2021).

Race-based inequalities were also severe, but evidence with respect to racial minorities was mixed. In general, Hispanic and Black residents experienced more severe inequalities than Asian residents, and inequalities measured by tree count and species richness were more severe than those measured by average DBH, tree health, and sidewalk damage. These disparities among minority residents were also identified in previous studies (Watkins et al., 2017). Based on a meta-analysis of 40 studies, Watkins and Gerrish (2018) showed that evidence regarding race-based inequalities is mixed, with both severe and no inequalities being reported. The mixed evidence and conflicting results indicate that it is important to examine each racial and ethnic minority individually, and to differentiate the effects of various tree structure. The mechanisms for disparities among racial minorities are complex, and the disparities may be due to the poverty of these communities, various preferences among these communities, and social dynamics such as language barriers and the lack of political mobilization (Pham et al., 2012, 2017). In addition, historical segregation and ethnic stratification among blacks/whites and non-black minorities/whites may also contribute to the disparities. For example, Yang et al. (2017) reported that unlike black residents who are historically forced to live in racially segregated communities, Asian residents tend to be self-segregated to take advantage of ethnically bound communities. The aggregated analysis conducted by combining all minority groups together is unlikely to reveal the underlying mechanisms, and unlike to help design effective intervention policies.

Age-based inequalities were less severe than income- and race-based inequalities. Among the various age groups, young people faced more severe inequality than the elderly, and all the tree structure measures favored the elderly. In the demographic group of household characteristics, the percentage of households with three or more people was examined. Larger family sizes are typically due to families with children or those living with the elderly. Except for the inequalities measured by sidewalk damage, there was little evidence of inequalities in this demographic group. Previous studies have explained the inequalities related to household size using the ecology of prestige theory, which states that location choices and public expenditure and investment vary depending on families in different lifestyles and life-stages (Grove et al., 2014). Both age groups and the household characteristic group have a higher proportion of vulnerable populations and a greater need for urban forests. The elderly tend to be less mobile, live alone, have limited social contact, and have pre-existing illnesses and health conditions (Rosenthal et al., 2014). By close contact and exposure to urban forests, young people can benefit more than adults (e.g., improved cognitive and attention functioning, and improved school performances) (Tzoulas et al., 2007).

Regarding the education-based inequalities, all measures of tree structure favored well-educated people while disfavoring less-educated people, except for the average DBH. Both well-educated and less-educated people were associated with a smaller average DBH. This is probably attributed to high rates of tree planting in NYC, which results in an increase in small-sized trees. Although education-based inequality has also been identified in previous studies (Nesbitt et al., 2019), it has received less attention than income- and race-based inequalities. Typically, education-based inequalities are not explicitly considered or examined indirectly, and educational attainment is treated as one reason to explain the unequal tree distributions for the poor and racial minorities (Pham et al., 2012). Besides explicitly allocating more tree resources in less-educated communities, increasing residents' educational levels is also beneficial in reducing inequalities. There is evidence that people with higher education typically have more knowledge of tree benefits, greatly appreciate and value trees, and tend to undertake stewardship activities (e.g., planting and caring for trees) to increase tree population and health (Kendal et al., 2012).

It is important to disaggregate the effects of different tree structure measures on various aggregations of people in order to reveal the

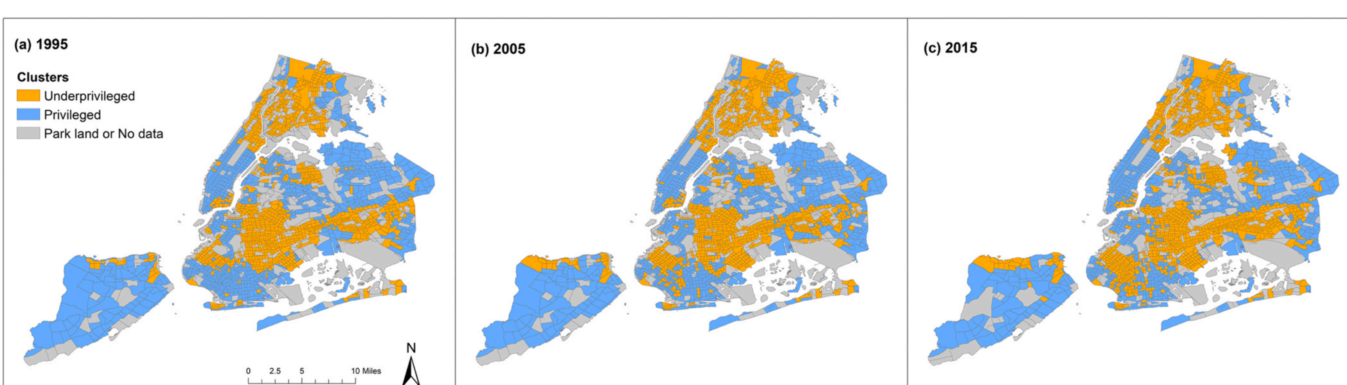

Fig. 5. Spatial patterns of privileged and underprivileged clusters in 1995, 2005, and 2015.

underlying mechanisms of disparities, and design more effective interventions and tree policies. Ferguson et al. (2018) suggested that public expenditures (e.g., street tree planting) should be allocated more to the underprivileged groups that typically have fewer private greenspaces and to remedy compensatory inequity for vulnerable groups (Pham et al., 2012).

6.2. Temporal changes of street tree inequalities and the effects of MillionTreesNYC

In addition to differentiating street tree inequalities among various aggregations of people and capture how the inequalities vary by different tree structure measures, we employed street tree census data to investigate temporal changes in street tree inequalities, and examined the potential impacts of the MillionTreesNYC initiative to remedy street tree inequity. The temporal trends of inequalities were identified over multiple dimensions. When measured based on tree count, inequalities in income and education, as well as for young people and Hispanic residents, have decreased over the past two decades. Similar patterns were also observed for species richness, and the temporal diminishing trends of inequalities were notable for the income (Median Household Income) and age (Percent Under 18) groups. For tree health, the inequalities were enhanced over time for the poor and Hispanic residents, while they were diminished for Black and Asian residents, and the households with three or more people. The temporal patterns of inequalities for sidewalk damages were not clear. Although MillionTreesNYC is aware of equity problems and introduces the block planting approach that takes care of neighborhoods with fewer street trees (Rae et al., 2010), the equity outcome is not ideal as the diminished inequalities are only observed for specific tree measures, and the inequalities for specific subpopulations are even growing. This is probably because MillionTreesNYC has other primary goals (e.g., increasing overall canopy cover, maximizing ecosystem services, mitigating climate change, and trees for public health) and operates within a set of constraints (e.g., limited budgets and shortage of staff) (Campbell et al., 2014). In this situation, although equity is often a desired outcome, it is rarely prioritized over other sustainability goals, particularly when there are tradeoffs and conflicts between goals. Similar outcomes have also been identified in other tree-planting programs. Based on studies in four US cities, Watkins et al. (2017) reported that tree planting may reduce existing income-based inequity while aggregating race-based inequity. It is challenging to achieve the equitable distribution of new tree-plantings and take current tree-planting programs as a chance to reduce the existing inequity due to the difficulties from policy and funding aspects, as well as from physical aspects (e.g., site availability and suitability) (Danford et al., 2014). One potential solution to overcome this challenge is to emphasize on ‘procedural inequity’. Tree-planting processes should be restructured and reframed to be more representative (i.e., including various social groups) to increase the level of public participation (Aryal et al., 2019; Nesbitt et al., 2018). Avenues should be created for the public to participate in tree planting and stewardship activities, and involve them in all or most parts of tree-planting programs, including setting objectives and allocating resources (Vogt and Fischer, 2014).

In terms of average DBH, temporal trends were identified for Percent Below Poverty and Percent High School. Both showed that the existing inequalities were aggravated over time as these two subpopulations were associated with more small-sized trees. Unlike other tree structure measures that can be interpreted directly, the interpretation of average DBH needs to take into account different time frames as trees take years to grow, and there are time lags between current tree planting activities and future tree benefits. This indicates that not enough time has passed to allow a valid examination of the equity outcome of the MillionTreesNYC initiative. In the long-term, the current inequalities measured by average DBH may become more beneficial if small-sized trees can successfully mature.

7. Conclusions and future studies

By employing street tree census data for 1995–2015, we investigated temporal changes in street tree inequalities pertaining to various aggregations of people, and examined the potential effects of the MillionTreesNYC initiative to remedy street tree inequalities. Overall, the underprivileged populations, characterized by higher percentages of the poor, racial minorities, young people, less-educated people, and households with three or more people are more likely to be associated with lower tree abundance, less desired tree structure, poor tree health condition, and more sidewalk damage. The degree of inequality varies with different street tree measures, and inequalities are prevalent when measured using tree count and species richness, followed by averaged DBH, and become less severe when measured using tree health and sidewalk damage. When disaggregating inequalities across various aggregations of people, the following patterns were identified: (1) income-based and education-based inequalities are notable, but the inequalities diminish over time when measured using tree count and species richness; and (2) the results for race-based and age-based inequalities were mixed. Overall, Hispanic and Black residents, and young people experience more severe inequality issues, whereas Asian residents and the elderly are associated with more tree populations and more desirable species diversity. As for the MillionTreesNYC initiative, its role in mitigating street tree inequity is not ideal as the inequalities are decreasing when measured using tree count and species diversity, while they are increasing when measured using tree health and average DBH. A similar pattern was found across various aggregations of people, with both diminished and increased inequalities identified for specific subpopulations.

Unlike previous studies that typically examine the inequality of street tree abundance at a single point in time, this study examined the dynamics of street tree inequalities using a complete set of tree measures. In addition to tree abundance, other tree-related measures (e.g., species diversity, tree structure, tree health, and site condition) have important implications for tree benefits and management costs. This information can inform more effective allocation of public resources when planting new trees, increasing the health status of existing trees, improving size structure, increasing species diversity, and maintaining side conditions. Rather than being driven by the goal of increasing tree population, tree-planting programs should balance different aspects of tree attributes and allocate resources between existing and planting new trees. In addition, our study reveals the importance of considering outcome and procedural inequities in tree-planting programs to alleviate urban tree inequity.

Nevertheless, it is worth noting several limitations of our study. First, the inequity remediation role of the MillionTreesNYC initiative is constrained to street trees, and not enough time has passed to allow a thorough evaluation of the equity outcome of the initiative. The MillionTreesNYC initiative is known to be a massive tree-planting campaign, and it is uncertain whether the initiative can serve as a replicable model for future tree-planting and care programs to reduce urban tree inequity. In other words, the unprecedented scale of the MillionTreesNYC initiative may limit its generalizability to small- and medium-sized tree-planting programs. Second, this study is based on urban areas in the US, and the applicability of findings to other locales and cities merits further investigation. The inequity issues, unless explicitly incorporated and addressed, will substantially diminish the benefits of current and future tree planting programs. To take current and future tree-planting programs as opportunities to reduce inequity, tree-planting programs should be framed in the context of both expanding tree canopy cover and promoting equity, and emphasize on increasing the participation scales and levels of the public. In addition, a systematic investigation and comparison of tree-planting programs of various sizes should be conducted, and a complete long-term tree inventory data across diverse land uses should be collected to facilitate temporal analyses and examine the impacts of tree-planting programs on both public and private lands. To support the applicability of knowledge in urban forest practices, a comparative study should be conducted to assess commonalities and disparities of findings across a network of cities in diverse social, ecological, and climatic contexts.

CRediT author statement

Jian Lin: Conceptualization, Methodology, Software, Data curation, Writing – original draft. Qiang Wang: Data curation, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Jian Lin would like to thank the USDA Forest Service's Urban and Community Forestry Challenge Cost Share Grant Program as recommended by the National Urban and Community Forest Advisory Council, and the SUNY ESF Department of Environmental Resources Engineering for supporting his graduate studies.

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