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The equity of urban forest ecosystem services and benefits in the Bronx, NY

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ABSTRACT

Trees provide important ecosystem services and benefits, with some, such as air pollutant and heat reductions, being linked to improved human health and well-being. The uneven distribution of tree cover in urban areas and subsequently the ecosystem services and benefits it provides has potential implications related to environmental justice, especially if disadvantaged socio-demographic or socio-economic and marginalized communities lack these services and benefits. This study explores the distribution of ecosystem services and benefits provided by tree cover in the Bronx, NY. Utilizing census block group specific spatial datasets, we employ a Mann-Kendall trend test and the Sen slope estimator to describe the relationship between median income, per capita income, percent minorities, population density, poverty percent and total educational attainment, and carbon storage and sequestration, stormwater runoff reduction, air pollutant removal and heat index reduction ecosystem services and benefits for 2010 tree cover conditions. We explore the equality in ecosystem service and benefit distributions across socio-demographic and socio-economic subgroups using the Atkinson inequality and Theil entropy indices decomposed into within and between subgroup inequalities for each ecosystem service and benefit. These inequality indices allow us to better assess current inequalities and work to achieve greater equity in the distribution of ecosystem services. Using population and ecosystem service data, all ecosystem services and benefits appear to be unequally and inequitably distributed in the Bronx, with disadvantaged socio-demographic and socio-economic block groups receiving disproportionately lower ecosystem services from urban trees. The vast majority of the inequality is explained by variations within each socio-demographic and socio-economic subgroup rather than variations between subgroups. To reduce this inequity, efforts should be made to strategically increase services and benefits by initially targeting disadvantaged block groups with extremely low tree cover.

1. Introduction

Empirical studies have documented the direct and indirect environmental, social, and economic benefits of urban trees including temperature reduction (Livesley et al., 2016; Salmond et al., 2016), air pollutant removal (Nowak, 2002; Nowak et al., 2014), carbon sequestration (Nowak and Crane, 2002; Nowak et al., 2013), climate regulation (Salmond et al., 2016; Nowak and Crane, 2002), stormwater runoff and nutrient pollution reduction (Bolund and Hunhammar, 1999; Livesley et al., 2016); energy savings (Akbari et al., 2001; McPherson and Simpson, 2003); improved human health (physical, mental and social well-being) (Donovan et al., 2013; Jiang et al., 2016; Tzoulas et al., 2007) and increases in residential property values (Anderson and Cordell, 1988; Tyrväinen and Miettinen, 2000). However, the distribution of urban trees is typically not uniform across cities (Flocks et al., 2011), which can lead to potential environmental injustice issues if the health, well-being, and other documented social benefits of urban forests are inequitably distributed.

Environmental justice refers to both procedural fairness and distributive equity and is concerned with equal rights, equalizing

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opportunity and benefiting the least advantaged (Pellow, 2000; Schlosberg, 2003; Friedman et al., 2018). Equity, a term used synonymously with fairness or justice, refers to the fair distribution of resources, especially the absence of systematic disparities between more and less advantaged social groups (Reidpath and Allotey, 2007). McDermott et al. (2013) and Friedman et al. (2018) highlight that equity is a multi-dimensional concept of ethical concerns and social justice with distributive, procedural and contextual dimensions. Distributive equity, which this study is centered on, addresses the distribution of benefits and costs while procedural equity alludes to fairness in the political processes that allocate resources. Contextual equity is focused on understanding the pre-existing conditions that limit or facilitate access to decision making procedures, resources and benefits. Inequity is often used to define inequalities (uneven distribution of resources in the population) that are avoidable, unjust or unfair (Asada, 2005; Dahlgren and Whitehead, 1991; Hamann et al., 2018). Measures of inequality, such as the Gini coefficient, generalized entropy measures and Atkinson's class of inequality measures, allow us to better assess current inequalities and work to achieve greater equity in the distribution of ecosystem services (Braveman and Gruskin, 2003; Reidpath and Allotey, 2007).

Traditional environmental justice studies seek to determine if socially disadvantaged demographic and socio-economic groups are disproportionately impacted by environmental burdens such as pollution. However, recent studies have emerged, incorporating environmental justice in the distribution of environmental goods or amenities (such as parks and trees) that have a bearing on both environmental quality and human health (Benra and Nahuelhual, 2019; de la Barrera et al., 2019; Fleischer et al., 2018; Jennings et al., 2012; Keeler et al., 2019; Laterra et al., 2019; Mullin et al., 2018; Szaboova et al., 2019; Wang and Lan, 2019; Watkins et al., 2017). These studies reveal inequitable distributions of environmental amenities along socio-demographic and socio-economic parameters including wealth, class and race. Racial and ethnic minorities and low-income neighborhoods tend to have lower vegetation cover and associated ecosystem services relative to more affluent areas, yet these areas tend to be the underprivileged and the most vulnerable areas that rely more heavily upon these ecosystem services (Flocks et al., 2011; Escobedo et al., 2015; Jenerette et al., 2011; Soto et al., 2016). Low-income and often minority communities tend to be located within lower quality natural environments, are disproportionately exposed to environmental burdens that threaten their health, and access fewer environmental amenities. In addition, these communities often have inadequate access to health care and are thus more dependent on biodiversity for a wide range of natural resources and ecosystem services essential for their well-being (Billé et al., 2012; Massey, 2004; Millennium Ecosystem Assessment, 2005). Various factors have been used to explain these observed trends in the distribution of tree cover and services including the availability of planting space and funding for maintenance, perceptions and preferences, historical processes such as social stratification, climate and landscape heterogeneity, housing tenure and population density (Wolch et al., 2014; Danford et al., 2014; Landry and Chakraborty, 2009; Mincey et al., 2013; Wei et al., 2017).

Given the links between tree cover benefits and health, some citywide tree planting initiatives, including the million tree planting initiatives in Los Angeles (CA) and New York City (NY), are addressing environmental inequity in their attempts to increase tree cover and associated benefits. In NYC, the MillionTreesNYC initiative launched in 2007 to plant and care for one million new trees throughout the city by 2017 (MillionTrees NYC, 2018), took an explicit environmental justice approach to address the uneven distribution of urban forests (Campbell et al., 2014). Due to a high correlation between poverty, lack of services, low air quality, and incidences of childhood diseases such as asthma, the initiative prioritized six Trees for Public Health neighborhoods: Morrissania and Hunts Point in the Bronx, East Harlem in Manhattan, Far Rockaway in Queens, East New York in Brooklyn, and Stapleton in Staten Island (Campbell et al., 2014; Locke et al., 2010).

In designing solutions that identify locations to not only increase tree cover but make its distribution more just, some cities (e.g., Portland (OR), Chicago (IL) and Columbia (MO)) have prioritized tree planting based on diverse ecological, social and economic goals and preferences with a special focus on equity (Portland Parks and Recreation, 2018; Chicago Region Trees Initiative, 2019; City of Columbia, 2018). For example, Austin (TX) considers public health and safety, air quality, environmental justice, water quality, forest replenishment, preservation and development, and urban heat island in their urban forest planning and management (Halter, 2015). Arizona's Shade Tree Planting Prioritization identifies underserved cities and communities and considers population density, lack of canopy cover, low-income, traffic proximity, sustainability, air quality, and urban heat effect (Grunberg et al., 2017). This commitment to more equitably distributed environmental services is a key component of urban planning and management. However, it remains to be seen whether these programs have been successful and whether disadvantaged stakeholders have improved access to the important ecosystem services and benefits of tree cover.

Despite the growing relevance of ecosystem services and benefits and the important links to human health and well-being, literature examining the distributional equity of ecosystem services and benefits provided by urban trees is limited (Mullin et al., 2018; Landry and Chakraborty, 2009; Wolch et al., 2014; Escobedo et al., 2015; Flocks et al., 2011; Nesbitt et al., 2019; Geneletti et al., 2020; Garrison, 2018, 2019; Nesbitt et al., 2018; Koo et al., 2019), especially in large cities such as NYC that are undertaking large-scale tree plantings and urban greening initiatives. More research is needed to evaluate the long-term outcomes of different planting strategies to ensure that the environmental benefits of the urban forest are shared more widely and equitably (Garrison, 2019). There is need for more equity assessments that consider: (a) the existing distribution of urban trees, (b) the spatial distribution of ecosystem service and benefit supply and demand, and (c) whether the supply and demand are equitably distributed across urban areas, especially with respect to groups who have been traditionally disadvantaged, marginalized or lack the resources or capacity to overcome a scarcity of environmental benefits. Studies that examine equity issues beyond total inequality and attempt to identify the sources of inequality (within-group and between-group) are necessary to inform urban forestry management and create actionable policy recommendations that prioritize approaches that lead to a fairer and more equitable society.

To address literature gaps regarding the distributional equity of ecosystem services and benefits provided by urban trees, this paper presents an analysis of the relationships between urban forest ecosystem services and socio-demographic and socio-economic variables in the Bronx, NY. The study extends previous research in the field by contributing to ecosystem service and benefit assessment methodology by examining total inequality as well as identifying the sources of that inequality (within-group and between-group) for different ecosystem services and benefits. We seek to establish whether there is an equitable distribution of ecosystem services derived from trees among various socio-demographic and socio-economic variables at the census block group level in the Bronx, NY. Specifically, this paper addresses whether the ecosystem services and the monetary benefits of tree carbon storage and sequestration, reductions in particulate matter less than 2.5 microns ($PM_{2.5}$), heat index reduction, and stormwater runoff are disproportionately distributed based on per capita and median income, percent minorities, population density, percent poverty and total educational attainment characteristics. The Bronx was chosen as the study location because of: (a) air quality, stormwater and urban heat island issues in this borough, (b) its diverse demographics, and (c) the lack of ecosystem services and benefits to some communities (Nyelele et al., 2019).

2. Research methodology

The Mann-Kendall trend test and the Sen slope estimator (Mann, 1945; Kendall, 1975; Sen, 1968; Helsel and Hirsch, 2002) were used to describe the relationship between socio-demographic and socio-economic data (per capita income, median income, population density, total educational attainment (sum of the population with at least a high school education), poverty percent (percent of the population below the poverty line) and percent minorities) at the census block group level (a total of 1132 block groups) and different ecosystem services and benefits derived from trees in the Bronx. Socio-demographic and socio-economic variables were selected from previous studies examining the equity of green spaces, ecosystem services or benefits (Landry and Chakraborty, 2009; Geneletti et al., 2020; Fleischer et al., 2018; de la Barrera et al., 2019; Danford et al., 2014; Schwarz et al., 2015; Ferguson et al., 2018; Nesbitt and Meitner, 2016; Grove et al., 2014). Ecosystem services refer to the conditions and processes through which natural ecosystems sustain and fulfill human life whilst benefits illustrate the final outputs from ecosystems that directly affect human well-being (Nyelele et al., 2019; Daily, 1997; Haines-Young and Potschin, 2012). In this study, ecosystem services include carbon storage (kgs) and sequestration (kgs/yr), stormwater runoff reduction (m^3/yr), $PM_{2.5}$ air pollutant removal (kgs/yr) and heat index reductions (in degrees Kelvin) for 2010 tree cover conditions. Ecosystem benefits refer to the monetary benefits associated with these services, including the monetary benefit ($/yr) of $PM_{2.5}$ air pollutant removal, monetary benefits of carbon storage ($) and sequestration ($/yr) and the avoided stormwater runoff monetary benefits ($/yr) based on stormwater treatment and management costs and fees. Next, we present Lorenz curves, a common visual aide to observe inequality that was first employed to examine income disparity (Lorenz, 1905). Here the Lorenz curves show the cumulative proportion of ecosystem services against the cumulative proportion of the socio-demographic or socio-economic variables; the Gini coefficient (Gini, 1997), is calculated using areas under the Lorenz curve. The Gini coefficient, though, is not decomposable and thus limits our ability to explore sources of inequality and inequity. We then explore potential environmental inequality in ecosystem services using two common measures of inequality, the Atkinson inequality index (Atkinson, 1970) and the Theil entropy index (Theil, 1972). Both of these indices are decomposable, allowing us to examine inequity both within and between socio-demographic and socio-economic subgroups for each ecosystem service following methods by Lorenzo and Liberati (2006a) and Lasso de la Vega and Urrutia (2003).

2.1. Ecosystem service and benefit estimates

Ecosystem services and benefits for 2010 tree cover conditions used in this study were estimated using spatially distributed versions of i-Tree models implemented by Nyelele et al. (2019) at the census block group level in the Bronx. i-Tree is a freely available suite of tools developed by the United States (U.S.) Forest Service designed to assess forest structure, ecosystem services and benefits. The model integrates field data from complete inventories of trees or randomly located plots, U.S. Census data, and readily available databases of environmental (e.g., meteorology and air quality) and land cover variables to develop estimates of forest structure, environmental effects and the value of a given urban forest service (Hirabayashi et al., 2012; Nowak et al., 2013; Nowak, 2018). Specifically, $PM_{2.5}$ air pollutant reductions and the monetary benefits of those reductions (based on estimates of incidences of adverse health effects and associated monetary values resulting from changes in pollutant concentrations) were modeled using i-Tree Eco (Nowak et al., 2008). Stormwater runoff reductions were modeled using i-Tree Hydro (Wang et al., 2008) and the monetary benefits of the runoff reductions were calculated at the national average of $2.36/$m^3$ based on the USFS' Community Tree Guide series (Hirabayashi, 2013). Carbon storage and sequestration were calculated using the latest per area of tree canopy cover carbon removal rates for NYC (Nowak et al., 2018) while the monetary benefits of carbon storage ($) and sequestration ($/yr) were estimated from the social costs of carbon (Nowak and Greenfield, 2018). One improvement over Nyelele et al.'s methodology was in the estimation of the heat related benefits of trees. In this study we adopt methods detailed in Bodnaruk et al. (2017) and consider the reduction in heat index (in degrees Kelvin) as an ecosystem service. This was obtained by subtracting the average block group heat index values for 2010 tree cover conditions described in Nyelele et al. (2019) from the 2010 heat index of the block group without any tree cover. In the scenario without tree cover all tree cover is removed and replaced with impervious surface. This approach is similar to how i-Tree Hydro estimates avoided stormwater runoff. The heat index values for the scenario without tree cover were calculated following the same methodology detailed in Nyelele et al. (2019) using i-Tree Cool derived air temperature and humidity output for the month of July 2010. i-Tree Cool is based on the Physically based Analytical Spatial Air Temperature and Humidity model (Yang et al., 2013) and generates spatially distributed urban microclimate conditions including air temperature and humidity. This heat index is chosen because it is a human-perceived equivalent temperature, it is a measure of how hot it feels when relative humidity is factored in with air temperature, and it is widely used in environmental health research, including studies of air pollution exposure, outdoor temperature exposure, and the development of heat warning systems (Anderson et al., 2013; Rothfusz, 1990).

2.1.1. Trend estimation

The Moran's Index (I) statistic (Moran, 1950), a common measure of spatial autocorrelation (feature similarity), was used to determine the magnitude of the spatial relationship between ecosystem service values, socio-demographic as well as socio-economic variables. The spatial autocorrelation tool in Geographic Information System (GIS) software ArcMap® (version 10.3) was used to calculate Moran's I statistic for each ecosystem service, socio-demographic and socio-economic variable. Given a set of features and an associated attribute (e.g ecosystem service), the tool evaluates whether the pattern expressed is clustered, dispersed, or random (Leong and Sung, 2015). To identify the trends and relationships between total block group ecosystem services and block group socio-demographic or socio-economic data from the 2010 census, the non-parametric Mann-Kendall test was used (Pohlert, 2018; Helsel and Hirsch, 2002; Meals et al., 2011). The Mann Kendall was selected based on several factors. The test is a non-parametric test that does not require the data to be normally distributed and is thus applicable even for data with outliers. In addition, the test is applicable in the detection of linear or nonlinear monotonic trends in data (Adarsh and Janga Reddy, 2015; Drápela and Drápelová, 2011). This test was used to evaluate whether ecosystem services increase or decrease with different socio-demographic or socio-economic variables, and whether the observed trend was significantly different than zero using a type I error of $\alpha = 0.05$. The Sen slope estimator was used to capture the magnitude of the trend. The Sen slope estimator was selected because it is an unbiased estimator of the true slope in simple linear regression and is a distribution free method (Sen, 1968). Another advantage of this estimator is that it limits the effect of outliers on the slope and is robust and free from restrictive statistical constraints (Kocsis et al., 2017). Combining the Mann–Kendall and the Sen slope estimator in trend analysis has the advantage of showing not only the relationship but proffers a way of visualizing the trend and response of one variable due to changes in the other.

2.1.2. Assessing environmental inequality

Several inequality metrics have been used to develop a more nuanced understanding of the distribution of environmental variables, including carbon emissions, resource use and industrial air toxics exposure (Boyce et al., 2014). These metrics include the Gini coefficient, generalized entropy measures such as the Theil entropy index, analysis of variance and the Atkinson index (Cowell, 2011; Bourguignon, 1979; Foster and Shneyerov, 1999; Boyce, et al., 2014; Lopes et al., 2015; De Maio, 2007; Lynch et al., 1998; Fields, 1979). These indices are commonly used to assess inequality in income and were applied to assess the inequality of ecosystem benefits delivered by urban trees. Kawachi and Kennedy (1997) compared six different measures of inequality: the Gini coefficient, the decile ratio, the proportion of income earned by the poorest 50%, 60% and 70% of households, the Robin Hood index, the Atkinson index and the Theil entropy measure and concluded that all measures behaved similarly and were highly correlated. The Theil entropy index and Atkinson index allow for distinguishing the effects of inequalities in different areas of the distribution spectrum, providing more meaningful quantitative assessments of inequalities (De Maio, 2007).

Cowell (2011) and the World Bank Institute (2005) discuss the criteria (population independence, symmetry, scale independence, Pigou–Dalton Transfer sensitivity and decomposability) that make a good measure of inequality. Several measures, including the generalized entropy class of measures of the Theil entropy index and the Atkinson index, satisfy all five criteria (Bourguignon, 1979; Foster and Shneyerov, 1999). The Gini coefficient, despite being a popular measure of inequality, only satisfies the first four criteria and is not easily decomposable or additive across groups. Decomposability means that inequality may be broken down by population groups or other dimensions. For a decomposable index, the total inequality of a population is equal to the sum of the inequality existing within subgroups of the population and the inequality existing between subgroups (Bourguignon, 1979).

In this analysis, the Atkinson inequality index and Theil entropy index were decomposed into within and between socio-demographic or socio-economic subgroup inequality in the distribution of ecosystem services from trees in the Bronx. The within group inequality element captures the inequality due to the variability of ecosystem services within each subgroup, while the between group inequality captures the inequality due to the average variability of ecosystem services across different subgroups. Decomposition helps identify the contribution of each socio-demographic or socio-economic subgroup (classified in this study from per capita income, median income, percent minorities, population density, poverty percent and total educational attainment data) to the total inequality of ecosystem services, considering that inequality may stem from different groups of the population with different intensities (Lorenzo and Liberati, 2006a). Although not decomposable, the Gini coefficient was used to measure the degree of inequality in socio-economic and socio-demographic subgroup ecosystem services and benefits. The Gini coefficient is usually defined based on the Lorenz curve, which shows the cumulative proportion of resources against the cumulative proportion of the population (Lorenzo and Liberati, 2005). On the Lorenz curve, a 45° line represents perfect equality of resources and the Gini coefficient is the ratio of the area between the line of perfect equality and the observed Lorenz curve to the total area under the line of equality. The extent to which the Lorenz curve sags below the line of equality indicates the degree of inequality in the distribution of resources. The Gini coefficient ranges from 0 to 1; the higher the Gini coefficient, the more unequal the distribution (Lorenzo and Liberati, 2006b).

Each socio-demographic and socio-economic variable was sorted from highest to lowest and divided into five equal subgroups created from the 1132 block groups. The five socio-demographic and socio-economic subgroups were then used to decompose the Theil and Atkinson's indices. According to the World Bank Institute (2005), the simplest way to measure inequality is by dividing the population into five groups, for example from smallest to largest income, and reporting the levels or proportions of income (or expenditure) that accrue within each level. Several studies have decomposed inequality using five subgroups in their analysis (e.g., Yiengprugsawan et al., 2009; Hosseinpoor et al., 2006; Gradín, 2018; Dubois and Muller, 2017; Rahman and Huda, 1992).

2.1.2.1. Atkinson inequality index. The Atkinson inequality index ranges from 0 to 1, where a value of 1 indicates maximum inequality and 0 indicates minimum inequality (De Maio, 2007). Traditionally the Atkinson index has been used to illustrate the percentage of total income that a given society would have to forego to have more equal shares of income between its citizens (United Nations, 2015). The Atkinson index depends on a weighting parameter, epsilon (ε), which is subjectively determined by the researcher. ε measures the aversion to inequality (De Maio, 2007; Haughton and Khandker, 2009); by varying ε, which can range from 0 (representing indifference about the nature of the ecosystem service distribution) to infinity (showing concern only with the ecosystem service of the very lowest socio-economic or socio-demographic group), the Atkinson index allows for varying the sensitivity to inequalities in different parts of the ecosystem service distribution. Typically, ε values used in the literature are 0.5, 1, 1.5 or 2 (De Maio, 2007; Jenkins, 1999; Mendoza, 2017); the higher the value, the more sensitive the Atkinson index becomes to inequalities at the bottom of the distribution (De Maio, 2007). Higher ε entails greater social utility or willingness by individuals to accept smaller ecosystem services and benefits in exchange for a more equal distribution (United Nations, 2015).

An important feature of the Atkinson index is that it satisfies the elementary factorial decomposability property, making it is possible to decompose the measure into within and between group inequality (Lasso de la Vega and Urrutia; 2003). Moreover, unlike other indices, it can provide welfare implications of alternative policies and allows the researcher to include some normative content to the analysis. De Maio (2007) highlights that Atkinson values can be used to calculate the proportion of total resources that would be required to achieve an equal level of social welfare if these services were perfectly distributed. The Atkinson index was calculated as:

$$\mathrm{AI} = 1 - \left[\frac{1}{n} \sum_{i=1}^{n} \left[\frac{x_i}{\bar{x}} \right]^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} \tag{1}$$

where AI is the Atkinson index, n is the total population size (in this case total number of block groups in the Bronx), $\bar{x}$ is the population's average value of ecosystem service, x_i is each census block group's value of ecosystem service, and ε represents the degree of concern over inequality (Lasso de la Vega and Urrutia, 2003). For this analysis three ε values (0.5 for a small inequality aversion, 1 for a medium inequality aversion, and 2 for large inequality aversion) were used to assess the impact of ε.

To decompose the Atkinson index into within and between socio-demographic or socio-economic indices for each ecosystem service, a factorial decomposition (Lasso de la Vega and Urrutia, 2003), was conducted using the five subgroups calculated from the values of the socio-demographic or socio-economic variable. The between subgroup inequality ($\mathrm{AI_B}$) was defined by:

$$\mathrm{AI_B} = 1 - \frac{\left(\sum \frac{n_1}{n}(\bar{x}_1)^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} + \left(\sum \frac{n_2}{n}(\bar{x}_2)^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} + \left(\sum \frac{n_3}{n}(\bar{x}_3)^{1\varepsilon}\right)^{\frac{1}{1-\varepsilon}} + \left(\sum \frac{n_4}{n}(\bar{x}_4)^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} + \left(\sum \frac{n_5}{n}(\bar{x}_5)^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}}{\bar{x}} \tag{2}$$

This index represents the case in which every census block group in the first socio-demographic or socio-economic group has the group 1 mean ecosystem service value ($\bar{x}_1$), every census block group in the second socio-demographic or socio-economic group has the group 2 mean ecosystem service value ($\bar{x}_2$), and so forth. n_i/n represents the population share of each socio-demographic or socio-economic group. The within group inequality ($\mathrm{AI_w}$) was calculated from the overall Atkinson inequality index and between group Atkinson inequality index

Table 1
Mann–Kendall relationships between socio-demographic variables and ecosystem services.

Socio-demographic or socio-economic variable	Carbon services		Avoided runoff		$PM_{2.5}$ removal (kgs/yr)		$PM_{2.5}$ removal ($/yr)		Heat Index Reduction (K)	
	τ	*p val*	τ	*p val*	τ	*p val*	τ	*p val*	τ	*p val*
Minority percent	**−0.12**	**0.00**	−0.02	0.30	**−0.12**	**0.00**	**−0.06**	**0.00**	**−0.07**	**0.00**
Median income	**0.24**	**0.00**	**0.05**	**0.01**	**0.25**	**0.00**	**0.18**	**0.00**	**0.24**	**0.00**
Per capita income	**0.28**	**0.00**	**0.04**	**0.04**	**0.29**	**0.00**	**0.22**	**0.00**	**0.26**	**0.00**
Poverty percent	**−0.33**	**0.00**	**−0.04**	**0.05**	**−0.34**	**0.00**	**−0.21**	**0.00**	**−0.33**	**0.00**
Total educational attainment	**0.19**	**0.00**	0.03	0.10	**0.19**	**0.00**	**0.33**	**0.00**	**0.10**	**0.00**
Population density	**−0.54**	**0.00**	−0.03	0.15	**−0.53**	**0.00**	**−0.05**	**0.01**	**−0.36**	**0.00**

τ = Kendall's τ.
p val = *p*-value. *p* val < 0.05 are in bold.

as:

$$\mathrm{AI_w} = 1 - \left(\frac{1-\mathrm{AI}}{1-\mathrm{AI_B}}\right) \quad (3)$$

2.1.2.2. Theil entropy index. The Theil entropy index is derived from information theory and likens the dispersion of shares across the population to the concept of entropy, a measure of randomness in a given set of information (Lynch et al., 1998). The Theil index measures an entropic distance the population is away from the ideal egalitarian state of everyone having the same income (United States Census Bureau, 2018a). As a member of the generalized entropy class of inequality indices, the Theil index is perfectly decomposable into within and between elements (Lorenzo and Liberati, 2006a), enabling analysis of between and within area effects. Unlike the Atkinson index that ranges between 0 and 1, the values of the Theil index vary between 0 and infinity (or one, if normalized), with zero representing an equal distribution and higher values representing a higher level of inequality (Litchfield, 1999; United Nations, 2015). The Theil index is most sensitive to the middle range of the distribution (Boyce et al., 2016) and was calculated as:

$$T = \frac{1}{n}\sum_i \left(\frac{x_i}{\bar{x}}\right)\ln\left(\frac{x_i}{\bar{x}}\right) \quad (4)$$

where T is the Theil index, n is the total population size, x_i is the ecosystem service value of each census block group and $\bar{x}$ is the mean ecosystem service value from the entire population. Using the five subgroups for each socio-demographic and socio-economic variable, the within subgroup inequality was calculated as follows:

$$\mathrm{T_W} = \left(\frac{n_1}{n}\frac{\bar{x}_1}{\bar{x}}\right)\mathrm{T1} + \left(\frac{n_2}{n}\frac{\bar{x}_2}{\bar{x}}\right)\mathrm{T2} + \left(\frac{n_3}{n}\frac{\bar{x}_3}{\bar{x}}\right)\mathrm{T3} + \left(\frac{n_4}{n}\frac{\bar{x}_4}{\bar{x}}\right)\mathrm{T4} + \left(\frac{n_5}{n}\frac{\bar{x}_5}{\bar{x}}\right)\mathrm{T5} \quad (5)$$

$\mathrm{T_W}$ is the within subgroup Theil index; T1, T2, T3, T4 and T5 are the Theil indices for each of the five subgroups of the socio-demographic or socio-economic variable in question, respectively; in the brackets are the weights for each group, which include the population share of each socio-demographic or socio-economic subgroup (n_i/n), the relative mean ecosystem service of each socio-demographic or socio-economic subgroup ($\bar{x}_i$) and the average ecosystem service of the population ($\bar{x}$).

The between subgroup Theil inequality was calculated using subgroup means instead of actual ecosytem services as follows :

$$\mathrm{T_B} = [\frac{n_1}{n}(\frac{\bar{x}_1}{\bar{x}})\ln(\frac{\bar{x}_1}{\bar{x}})] + [\frac{n_2}{n}(\frac{\bar{x}_2}{\bar{x}})\ln(\frac{\bar{x}_2}{\bar{x}})] + [\frac{n_3}{n}(\frac{\bar{x}_3}{\bar{x}})\ln(\frac{\bar{x}_3}{\bar{x}})] + [\frac{n_4}{n}(\frac{\bar{x}_4}{\bar{x}})\ln(\frac{\bar{x}_4}{\bar{x}})] + [\frac{n_5}{n}(\frac{\bar{x}_5}{\bar{x}})\ln(\frac{\bar{x}_5}{\bar{x}})] \quad (6)$$

where $\mathrm{T_B}$ is the between subgroup Theil index; n_i/n represents the population shares of each socio-demographic or socio-economic group and $\bar{x}_i/\ \bar{x}$ is the relative mean ecosystem service of each socio-demographic or socio-economic group.

3. Results

3.1. Relating socio-demographic and socio-economic data to ecosystem services

3.1.1. Moran's I test

Based on statistically significant *p*-values and positive *z*-scores, results of the Moran's *I* test indicate that the spatial distribution for all ecosystem services and benefits (with the exception of avoided runoff which is completely random with $I = -0.003$) as well as socio-demographic and socio-economic variables is more spatially clustered than would be expected if the underlying spatial processes were random. However, on the basis of the Moran's *I* values which are particularly low (ranging between 0.006 and 0.3 across all ecosystem services and benefits and between 0.045 and 0.3 for socio-demographic and socio economic variables), there appears to be limited spatial clustering of the variables associated with the geographic features in the study area indicating some general randomness in the majority of the features. Poverty percentage has a relatively higher Moran's *I* value of 0.5 as evidenced by the presence of high poverty clusters in the southwest parts of the borough as well as some low poverty clusters predominantly in the northern and eastern parts of the Bronx.

3.1.2. Mann−Kendall trend test

Population density, poverty percentage and minority percentages exhibit significant negative relationships with carbon storage and sequestration, $PM_{2.5}$ pollutant removal and heat index reductions (Table 1). Significant negative relationships are also observed for poverty percentage and avoided runoff services and monetary benefits. The carbon storage and sequestration services as well as monetary benefits have the same τ and p-values since carbon-related ecosystem services were estimated using per area of tree canopy cover removal and monetary rates. Similarly, avoided runoff services and benefits have the same τ and p-values based on the $2.36/m^3 used to estimate the monetary value of the estimated avoided runoff (see Nyelele et al., 2019 for estimation of ecosystem services and benefits). No significant trends were observed for the avoided runoff services and benefits and minority percent, educational attainment and population density. Significant positive relationships are observed for median and per capita income for carbon storage and sequestration, avoided runoff, heat index reductions and $PM_{2.5}$ pollutant removal ecosystem services as well as for educational attainment with carbon storage and sequestration, $PM_{2.5}$ pollutant removal and heat index reductions.

3.1.3. Sen's estimator of slope

Sen's estimator of slope was used to capture the magnitude of the trend or relationship between ecosystem services and socio-demographic or socio-economic variables. The slope enables a better understanding of how ecosystem services respond to changes in socio-

Table 2
Sen's slope values for each socio-demographic or socio-economic variable and ecosystem service.

		Carbon storage		Carbon Sequestration		Avoided runoff		$PM_{2.5}$ removal		Heat index reduction
		kg	$	kg/yr	$/yr	m^3/yr	$/yr	kgs/yr	$/yr	(K)
Minority percent	$\hat{b}_1$	-6×10^2	-90	-30	-5.0	-1.2	-3.0	-1.5×10^{-2}	-20	-6×10^{-4}
Median income	$\hat{b}_1$	1	1.4×10^{-1}	5×10^{-2}	7×10^{-3}	3×10^{-3}	6×10^{-3}	3×10^{-5}	4×10^{-2}	1.8×10^{-6}
Per capita income	$\hat{b}_1$	2	3.8×10^{-1}	0.1	2×10^{-2}	5×10^{-3}	1×10^{-2}	7×10^{-5}	1.3×10^{-1}	4.7×10^{-6}
Poverty percent	$\hat{b}_1$	-1.5×10^3	-2.4×10^2	80	-13	-3.0	-7.0	-4×10^{-2}	-70	-3×10^{-3}
Total educational attainment	$\hat{b}_1$	40	6.7	1.4	0.4	0.1	0.3	1×10^{-3}	5.8	5.1×10^{-5}
Population density	$\hat{b}_1$	-1.7×10^6	-2.7×10^5	-9×10^4	-1.4×10^4	-1.5×10^3	-3.6×10^3	-50	-1.4×10^4	-2.7

demographic and socio-economic variables. For example, for every $1000 increase in median income in the Bronx, there is an increase in the monetary benefit of $140 for carbon storage, $7 for carbon sequestration, $6 for avoided runoff and $40 for $PM_{2.5}$ pollutant removal services. For every 10% increase in the poverty percent in the Bronx, there is a decrease in the monetary benefit of $2400 in carbon storage, $130 in carbon sequestration, $70 in avoided runoff and $700 in $PM_{2.5}$ pollutant removal services (Table 2). For those relationships that are significant based on the Mann – Kendall test, when the slope values are normalized and rescaled between 0 and 1 to enable comparison of the data, results indicate that total educational attainment is an important variable for explaining carbon storage and sequestration, $PM_{2.5}$ pollutant removal services and monetary benefits as well as heat index reductions in the Bronx as it has the greatest slope value. Per capita income is important for explaining avoided runoff services and benefits.

3.1.4. Inequality metrics

To better observe inequity in the ecosystem services provided by urban trees in the Bronx, the 1132 census blocks were divided into 100 subgroups based on the percentage of poverty (group 1 being the group with the highest level of poverty and group 100 having the lowest level of poverty). Fig. 1a shows a scatter plot of the median $PM_{2.5}$ air pollutant removal services for each subgroup, and Fig. 1b shows the Lorenz curves developed from these subgroup medians. There is a clear trend in the scatterplot, where the subgroups with the lowest level of poverty have an observable increase in $PM_{2.5}$ air pollutant removal services. The Gini coefficient from the Lorenz curve was 0.41, indicating some inequality in the distribution of $PM_{2.5}$ air pollutant removal services. Figs. 1c and 1d are scatterplots of median $PM_{2.5}$ air pollutant removal services and the Lorenz curve as a function of educational attainment. Again, there appear to be inequality in the delivery of these ecosystem services, though slightly less pronounced than when we examined these services versus poverty percentage. On Fig. 1c, an unusually high median is observed for one subgroup with low total educational attainment. A closer examination of this subgroup indicated that this subgroup contains census block groups with parks that include Van Cortlandt and Pelham Bay (the two largest parks in the Bronx) as well as Soundview and Ferry Point. Parks are generally associated with more tree cover and leaf area resulting in high air pollutant removal rates.

Fig. 2 contains the within subgroup (black) and between subgroup (blue) Theil and Atkinson indices for each ecosystem service and benefit examined. Overall, the Theil and Atkinson indices depict inequality in the distribution of ecosystem services in the Bronx. Compared to other services, the level of inequality for heat index reduction benefits and $PM_{2.5}$ monetary benefit distributions are relatively low for the Theil index and the Atkinson index when $\varepsilon = 0.5$. This is because there is little variability in the spatial distribution of these services, as shown in the box plot in Fig. 2 for heat index reduction benefits across the census block groups. This result may be due to limitations in the model employed to estimate heat reduction services and the lack of data to describe the spatial distribution of air quality. Avoided runoff services and monetary benefit also exhibit low Atkinson's index values for $\varepsilon = 0.5$. In addition, most of the inequality in the distribution of ecosystem services across socio-demographic and socio-economic subgroups for all Theil and Atkinson's indices appears to be due to the within group inequality as compared to the between group inequality. Exceptions are observed between population density and carbon related ecosystem services and benefits using Atkinson Index with $\varepsilon = 1$ or 2. These metrics provide us with an understanding of what variables are most important in driving inequality in the distribution of ecosystem services in the Bronx.

Looking at the between subgroup inequalities, both metrics highlight that population density drives inequality in carbon storage and sequestration services, heat index reductions as well as $PM_{2.5}$ pollutant removal services, while median income drives inequality related to avoided runoff reduction services. In the Bronx, total educational attainment explains inequalities associated with $PM_{2.5}$ pollutant removal monetary values. As expected, varying ε (0.5, 1 and 2) shows that increasing the value of ε will result in increases in the Atkinson index value for all the ecosystem services across all the socio-demographic and socio-economic variables, indicating less equality between groups.

Note that when the number of subgroups is increased from five (which is standard in the literature) to one hundred (which the Lorenz curves and Gini index presented in Fig. 1 were based on), results (not presented here) showed that between group variations in the Atkinson and Theil indices were higher than within group variations. As expected, by partitioning the services into more subgroups, the variability in ecosystem services within subgroups decreased. These results showed the drivers of inequality were the same as those shown in Fig. 2.

4. Discussion

This study was framed by environmental justice, focusing on the socio-economic and socio-demographic characteristics of census block groups. The environmental justice hypothesis posits that environmental amenities are inequitably low in disadvantaged socio-economic or socio-demographic communities and predicts these communities experience fewer urban environmental benefits (Watkins and Gerrish, 2018). Low Moran's *I* values obtained from this analysis imply that although there is some spatial clustering of the ecosystem services and benefits as well as socio demographic and socio economic variables associated with the geographic features in the study area, in general these variables are randomly distributed in the majority of the census block groups and the results of the study are not driven by spatial associations between the block groups. The findings in this study show that ecosystem services in the Bronx are related to socio-demographic and socio-economic characteristics of the census block groups. Specifically, the ecosystem services from trees are disproportionately distributed with respect to per capita and median income, poverty percent, population density, minority percent and total educational attainment, with disadvantaged socio-demographic and socio-economic neighborhoods being associated with disproportionately low levels of these

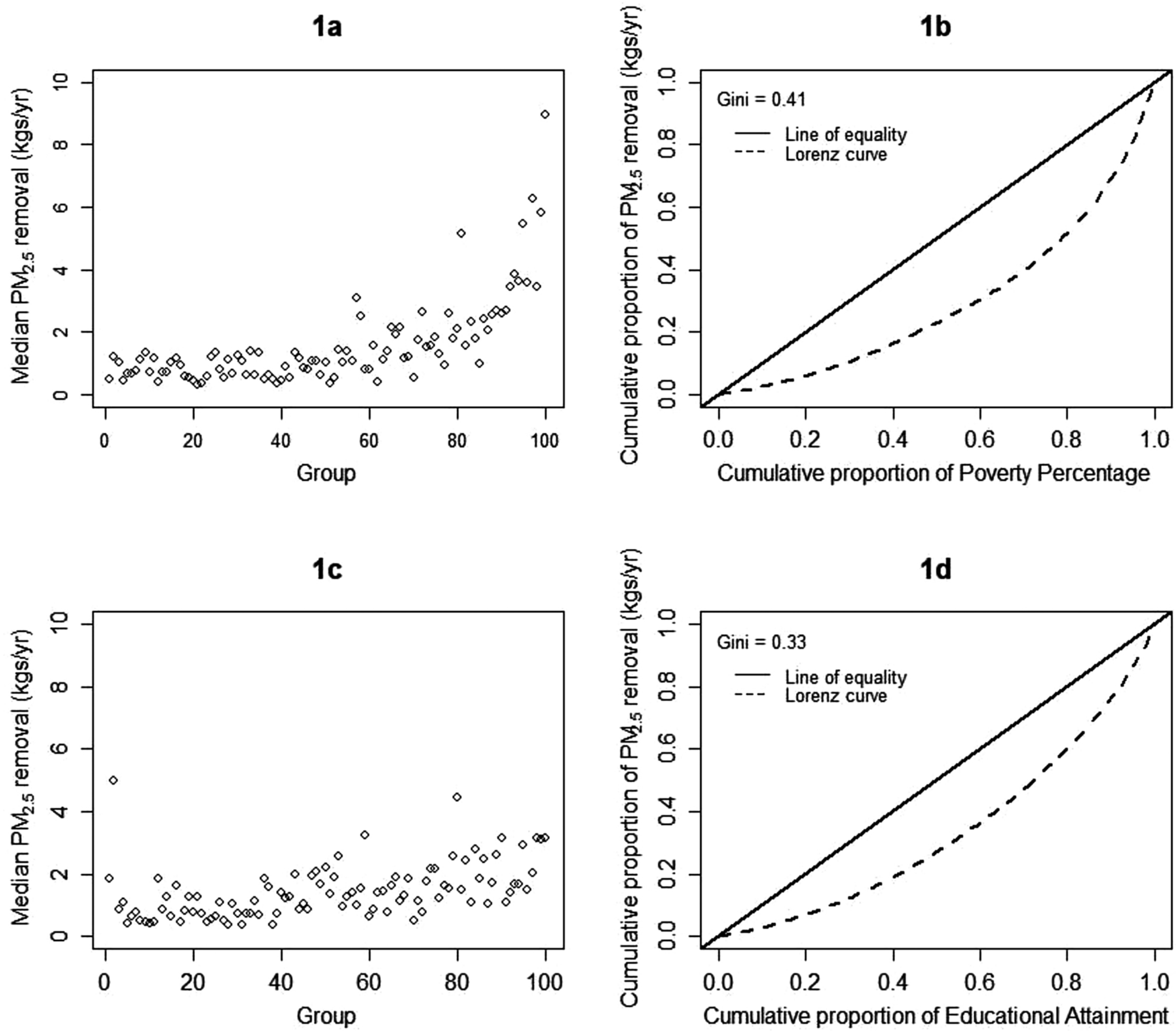

Fig. 1. Scatter plots and Lorenz curves illustrating the distribution of $PM_{2.5}$ air pollutant removal services for the hundred poverty percent (a and b) and educational attainment (c and d) subgroups.

services. The Theil and Atkinson's inequality indices also highlight overall inequality in the distribution of carbon storage and sequestration, avoided runoff and $PM_{2.5}$ reduction services across the census block groups of the Bronx. Similar findings of inequity and inequality in the distribution of tree cover and related ecosystem services and benefits have been reported in the literature (Danford et al., 2014; Landry and Chakraborty, 2009; Jenerette et al., 2011; Schwarz et al., 2015; Heynen and Lindsey, 2003; Kendal et al., 2012; Flocks et al., 2011; Wolch et al., 2014; Pham et al., 2012; McPhearson et al., 2013) where more advantaged socio-demographic or socio-economic neighborhoods will have larger amounts of tree cover and services while disadvantaged socio-demographic and socio-economic neighborhoods have minimal coverage.

The observed trends between ecosystem services and the socio-demographic or socio-economic variables can be explained within the context of tree cover distribution. As the amount, type, condition, and distribution of urban forests varies across an urban landscape, so will ecological function and the subsequent provision of ecosystem services by urban trees (Flocks et al., 2011). Thus, many of the ecosystem services from trees, for example air pollutant removal and related health benefits of improved air quality, tend to accrue primarily to those living in the immediate vicinity of trees (Schwarz et al., 2015). McPherson and Rowntree (1989) also highlight that many of the ecosystem benefits provided by trees are proportional to leaf surface area and that tree canopy cover is a measure related to leaf surface area. For example, among other local conditions (e.g., pollutant concentration, length of growing season, percent evergreen leaf area, meteorological conditions), leaf area will be highly related to the pollutant removal gradients since filtering capacity increases with more leaf area (Givoni, 1991; Nowak et al., 2014; Hirabayashi and Nowak, 2016). The monetary benefit of this service is obtained by modeled air quality changes, population demographics and baseline incidence rates (U.S. Environmental Protection Agency, 2017).

Several possible reasons have been brought forward to explain why trees and their ecosystem services are disproportionally distributed, with disadvantaged socio-economic or socio-demographic neighborhoods benefiting less. Firstly, high income earners have been shown to afford and be willing to pay more for properties in neighborhoods with attractive amenities that include greener areas with trees (Heynen and Lindsey, 2003; Hamann et al., 2018; Landry and Chakraborty, 2009). Zhu and Zhang (2008) highlight that urban forests are economic goods and when income increases, the demand will also rise. For every one percent rise in income in U.S. cities with populations greater than 100,000, demand for tree canopy cover increased by 1.76%; for every

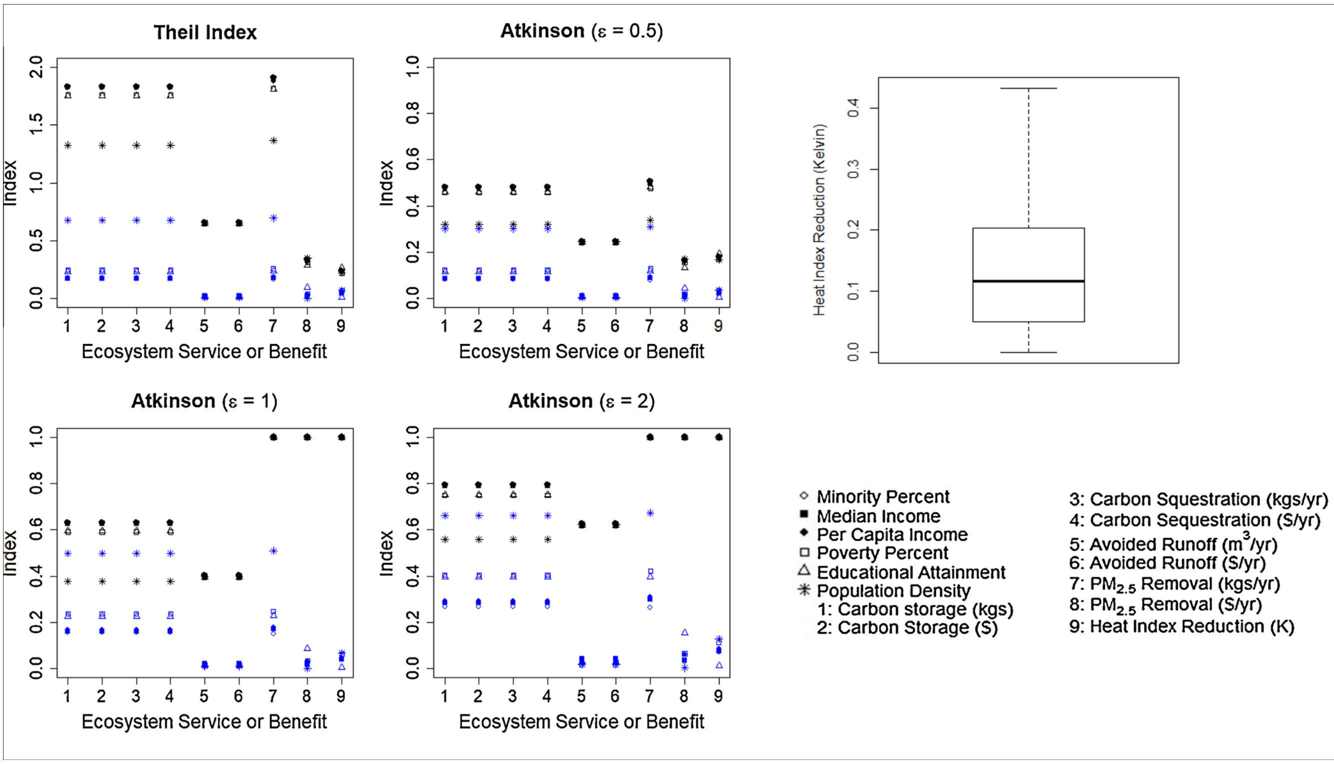

Fig. 2. Within subgroup (black) and between subgroup (blue) Theil and Atkinson indices for each ecosystem service and benefit.The distribution of the heat index reductions is shown in the box plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

one percent drop in income, the demand decreased by 1.26% (Zhu and Zhang, 2008). Wealthier households spend more money on environmentally relevant expenditures such as landscaping as a way of investing in the appeal of their own property or neighborhood (Grove et al., 2006; Landry and Chakraborty, 2009). Investing in tree maintenance not only promotes tree health and structural integrity but will result in increased services and benefits from trees.

Grove et al. (2006) further highlight that power and income differences among neighborhoods influence the levels of public investment in green infrastructure; in this regard members of some higher socio-economic groups are better able to attract public investment in local greening initiatives that include tree planting as compared to those in lower socio-economic groups. This is evident in the Bronx, where parks and green spaces in low-income neighborhoods often lack trees and landscaping whilst those in high-income neighborhoods thrive and are often supported by conservancies that raise private money (Kusisto, 2014). The Bronx has the lowest per capita ($18,896) and median ($35,302) income of all NYC boroughs, as well as the highest unemployment rate in NYC (12% in 2016), while 30.7% of the population lives below the poverty line (U.S. Census Bureau, 2018b, 2018d). It is evident that tree planting and landscaping cannot be afforded by some people in the Bronx. Thus, it is commendable that of the half-dozen low-income neighborhoods with particularly poor tree canopy cover that were singled out for plantings under MillionTreesNYC, two are in the Bronx (Morrisania and Hunts Point) (Campbell et al., 2014; MillionTreesNYC, 2018). However, future tree plantings could target more of these low-income neighborhoods, such as those in New York's 15th congressional district, including most of the southern and western neighborhoods of the Bronx, the poorest congressional district in the country (Food Research and Action Center, 2018).

Participation in tree planting in Portland, OR was much lower in neighborhoods with lower high school graduation rates (Donovan and Mills, 2014). A possible explanation could be that trees, especially when young, require more attention (e.g., watering, fertilization), which requires an investment of time and money. Neighborhoods with lower educational attainment tend to have a higher proportion of minority residents and lower median income residents who might not be able to afford this investment. Of the nearly 800,000 people in the Bronx who were at least 25 years old, 71.2% had graduated from high school and 19.1% held a bachelor's or higher college degree (U.S. Census Bureau, 2018d). Census block groups with less educational attainment are sometimes associated with higher rates of crime, and increasing tree cover is sometimes seen as an opportunity for increased crime (Donovan and Mills, 2014). Whereas houses nearer to parks in high-income neighborhoods attract higher sale prices, in low-income neighborhoods they have lower prices (Donovan and Mills, 2014; Troy and Grove, 2008; Troy et al., 2012). Block groups with lower educational attainment levels and lower incomes have also been correlated with more renters (Perkins et al., 2004). Given that trees are a long-term investment, renters may not participate in tree planting initiatives because they are unlikely to reap the rewards of increased property values, or they may simply want to avoid gentrification and its outcomes, such as rising rents (Schwarz et al., 2015; Vogt et al., 2015). Studies have also shown that when green infrastructure is incorporated into the design of underserved areas, vulnerable populations may be displaced, an unintended result. For example, Garrison (2018) highlights that large-scale parks may catalyze gentrification; as green infrastructure appears in neighborhoods, neighborhoods become more desirable, rents and housing values rise, and many residents are displaced and priced out of their newly improved neighborhoods. The Bronx has the lowest owner-occupied housing units (19.1%) between 2012 and 2016 in NYC (U.S. Census Bureau, 2018c).

Studies have shown that where minority residents are concentrated, the environment tends to be more degraded and they are more likely to be exposed to the negative impacts of urban environmental hazards such as air pollution and heat stress (Heynen and Lindsey, 2003; Landry and Chakraborty, 2009; Flocks et al., 2011; Wolch et al., 2014). Despite this pattern, racial and ethnic minorities have relatively lower access to parks and green spaces that provide important ecosystem services. Garrison (2018) notes that the history of disinvestment in greenspace in low-income communities of color has always been engrained in New York's landscape; parks are distributed unequally, with areas with more non-white residents generally having less park space. Despite this, parks were the location of 83% of MillionTreesNYC new trees, creating a significant obstacle to environmental justice. In the Bronx, there is an overrepresentation of racial minorities in low-income communities; for example, African Americans and Hispanics account for 40% and 57% of the South Bronx population, respectively (Statistical Atlas, 2018). Although trees provide many ecosystem services, it is important to also consider that trees can also create disamenities such as increased water demand, maintenance costs, allergies, and perceived safety concerns (Schwarz et al., 2015). What is perceived as an ecosystem service in one location may be seen as a disservice in another, and a lack of inclusive decision-making can produce green spaces that are ill-suited for communities. As such tree planting and other greening activities might be met with resistance from residents who simply do not want trees in front of their houses or in their neighborhoods. Lohr et al. (2004) highlight that in some African-American neighborhoods, residents prefer few trees in public areas because of concerns about safety and crime. Thus, while keeping equity in mind in designing solutions and siting future green spaces that ensure the provision of ecosystem services for everyone, it is imperative for planners to meet the needs and match the values of different locations for ecosystem services while finding ways to deal with people's perceptions and fears.

Our results indicating that ecosystem services from trees decrease as population density increases are consistent with Fei et al. (2016), Meacham et al. (2016) and Eigenbrod et al. (2011). Fei et al. (2016) state that as population density increases, the environment becomes degraded due to the industrial and human activities that result in vegetation fragmentation and land deterioration. The effects of these activities on ecosystems in areas with lower population density are less than those in areas with higher population density, while the different types of ecosystem services decrease as population density increases. While other studies (Schwarz et al., 2015) included population density as a proxy for building density, Grove et al. (2014) highlight that population density has been previously proposed by ecologists to explain variations in the distribution of tree canopy cover (and subsequently the services and benefits it provides). Geneletti (2020) also notes that the distribution of vulnerable individuals is typically proportional to the distribution of population density, i.e. the area with the highest population density are also typically the area with highest number of vulnerable individuals.

Achieving equitable access is difficult because urban forests take space to produce the structure and processes necessary to generate ecosystem services. Population density is presumed to drive vegetation change (and ecosystem service provisioning) through development and the subsequent loss of space for existing trees and growth of new trees (Locke and Grove, 2016). This could be the case in the Bronx where historically the burden of NYC's environmental hazards has been disproportionately imposed on Bronx communities (Pasquel, 2015). For example, street standards and historical development patterns shape the proportion of space that is public versus private property, affecting the availability of tree planting sites (Debats, 2014). Densely populated neighborhoods primarily in the western and southern sections of the borough are characterized by several major highways, nine waste transfer stations (almost one-third of the total number in NYC), and other industrial and polluting land uses, such as Hunts Point Cooperative Market wholesale food distribution center (the largest in the world), power plants, and extremely heavy industrial truck traffic (Spira-Cohen et al., 2011). Debats (2014) notes that in such densely populated and industrial areas it is difficult to plant trees because they have more overhead wires, more driveways, narrower sidewalks, and more hollow sidewalks, all of which consume space that might otherwise have been planted.

While the Mann–Kendall and Sen slope estimator results show lower ecosystem service and benefit provisions in disadvantaged socio-demographic and socio-economic block groups, the Theil and Atkinson inequality indices show that inequality and subsequently inequity are more related to variations within individual subgroups than between the subgroups. Haughton and Khandker (2009) also document similar trends in income inequality studies, where typically over three quarters of inequality is due to within group inequality, and the remainder due to between group differences. This result implies that while some block groups have more ecosystem services, other block groups in the same subgroup and with similar socio-demographic or socio-economic characteristics do not have similar ecosystem services. The data in each subgroup point to demographically and economically mixed block groups, possibly explaining the within subgroup variations. The Bronx is an ethnically diverse borough, with a mixed workforce (blue and white collar) and thus contains both high- and low-income residents (NeighborhoodScout, 2019; DiNapoli and Bleiwas, 2013). Another potential explanation could be the unit of analysis used in the study. Maantay (2002) highlights that many contradictions and discrepancies in environmental justice studies can be traced to the geographic unit of analysis used, and altering the geographic boundaries of the study area can have dramatic implications for the results of the analysis. However, the availability of data is often what dictates the level of aggregation, and in this study the analysis was carried out at the census block level, where demographic data is readily available from the U.S. Census. The trends could also be attributed to the data used in the analysis and how the subgroups were characterized. While the census data came directly from the U.S. Census Bureau, Maantay (2007) notes that the main limitation of census data is the possible undercounting in low-income and immigrant communities. Future studies could supplement census data using data collected by local agencies and community databases were available. Incorporating local knowledge to augment and verify the accuracy of publicly available data sources also allows for direct involvement of the affected people and the incorporation of intimate knowledge of their surroundings. This allows for the development of more detailed, complete, and positionally accurate characterizations of the population subgroups. Although resolving the challenge of inequity will require an in-depth understanding of the local issues that shape it, results of the study show that for increased equality and equity to be achieved, it is important to target new tree plantings in areas with low ecosystem services, particularly within generally disadvantaged socio-demographic and socio-economic groups.

Our Mann-Kendall results do not reveal any significant trends between the avoided runoff services in the Bronx and minority percent, educational attainment and population density These results imply that these services are independent of these socio-demographic and socio-economic variables, and there is a relatively equitable distribution of these services. This result is not surprising since some ecosystem services, for example reductions in storm water runoff, have been shown to benefit a whole city or region. Irrespective of tree planting locations or presence of tree cover, these benefits are experienced by residents in other neighborhoods (Donovan and Mills, 2014). In addition, results of the Theil index and Atkinson index for $\varepsilon = 0.5$ depict low levels of inequality in the distribution of the heat index reduction benefits. While this result could be an artifact of the heat index reduction model and data used in the analysis, this result is not surprising considering both the range and variability of the heat index reduction across the census block groups as depicted by the box plot in Fig. 2. Results of the analysis show minimal variations in the heat index reductions for the majority of the census block groups in the Bronx. There is a need for more studies to assess the impact of local factors in these areas on ecosystem services as well as studies that seek to improve on the methodology of determining heat index reductions and other tree effects on temperature.

While our results show that ecosystem services in the Bronx are related to the socio-demographic and socio-economic characteristics of the census block groups, they are not particularly strong in some cases as depicted by the Mann–Kendall trend test. For example, minority percent exhibits a weak negative relationship with carbon and air pollutant removal services; median and per capita income have a weak positive relationship with avoided runoff services. The small and significant *p*-values are mostly likely a result of the large sample size ($n = 1132$ block groups). *p*-values are influenced by sample size in statistical tests (Sullivan and Feinn, 2012), in this case resulting in significant but weak relationships because the sample size is large enough to make a small effect significant. More research is needed to identify the underserved communities and better understand local factors that are likely to affect tree cover distribution and participation in tree-planting programs.

Results have highlighted that ecosystem service inequity should be improved in the Bronx to foster the development of healthier and more resilient urban communities. The methodology used in this study can help identify trends and estimate the rate of change in ecosystem services and benefits across the various socio-demographic and socio-economic variables, but it does not provide insight in attributing a specific trend to a particular cause. Interpreting the cause of a trend and resolving the challenge of urban green inequity will require an in-depth understanding of the local issues since the distribution of urban vegetation is influenced by local environments, development histories, and local governance (Gobster and Westphal, 2004). A limitation of the Atkinson index is that it depends on the degree of society's aversion to inequality (a theoretical parameter, ε, decided by the researcher). To overcome uncertainties associated with the Atkinson index, we varied ε between 0.5, 1 and 2 and compared Atkinson index values between different ε scenarios before drawing conclusions. Our results were consistent with the literature (Lorenzo and Liberati, 2006a; Creedy, 2016) which shows that lower values of ε indicate a more equal distribution than higher values.

Future work will extend this analysis to other cities with different demographics, scales and environmental conditions to explore if similar trends are observed. We will also seek to improve on the socio-demographic and socio-economic data and seek to better understand local factors that are likely to affect tree cover and ecosystem service and benefit distributions.

5. Conclusions

This study provides novel insights into the relationships between socio-demographic and socio-economic variables, ecosystem service and benefit distributions and the concepts of equity, equality and environmental justice in urban systems. Results reveal that ecosystem services in the Bronx are related to a variety of socio-demographic and socio-economic characteristics of the census block groups and therefore support the conclusion that ecosystem services from urban trees are inequitably distributed in the Bronx, and that this inequity is associated with traditional socio-economic and socio-demographic divisions. Results from the decomposition of the inequality measures to identify the sources of the inequality go against the more traditional expectation of between sub-group inequality and show that inequality in the Bronx is mainly due to within sub-group variations likely due to the heterogenous nature of the census block groups in the Bronx and the wide variations in tree cover across census block groups with similar demographics. With numerous tree planting initiatives being undertaken in different cities, environmental inequity studies such as ours illuminate potential environmental justice issues that can be encountered and have the potential to guide more local and fine scale decision making regarding where to increase tree cover and reduce environmental inequities in the distribution of tree cover and related ecosystem services. Although the study is based on a U.S. city and with a particular focus on the Bronx, the methodological and conceptual approaches of this analysis can be used to advance the study of environmental equity of ecosystem services provided by trees as well as for the planning and evaluation of priority tree planting strategies to improve urban green space and ecosystem services provision in cities around the world. The ecosystem service framework adopted in this study links humans and their environment and has implications for urban forest conservation, planning and policy, leading to more equitable and sustainable land-use decisions in different parts of the world. Overall, the study has shown that decision making and management plans should incorporate environmental justice in their programming activities and ensure that tree-planting is a participatory, collective, and local stakeholder-engaged process to achieve more beneficial outcomes from trees, especially for disadvantaged socio-economic and socio-demographic groups and marginalized communities that lack these services and benefits. Addressing this environmental injustice issue could be part of future tree planting initiatives that seek to create cities that are more resilient, sustainable, livable, and just for all people.

Author statement

Charity Nyelele and Charles N. Kroll contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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