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Present and future ecosystem services of trees in the Bronx, NY

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ABSTRACT

Trees provide ecosystem services such as air pollutant removal, carbon storage and sequestration, urban heat island reduction, stormwater runoff reduction as well as other socio-economic benefits. Large-scale tree plantings are occurring in many cities to increase tree canopy coverage as well as the health, economic and environmental benefits that come with trees. Thus, there is a need to assess the extent to which trees provide these ecosystem services, where services are realized, and most importantly to improve methods of determining future planting locations. Using a new spatially distributed implementation of the i-Tree suite of ecosystem service models and mapping tools, we estimate the current and future ecosystem services and benefits of a recent tree planting initiative within each census block group of the Bronx, NY for 2010 and for three 2030 tree cover scenarios (assuming no tree mortality, 4% and 8% annual mortality). Land cover and tree canopy estimates for 2010 are derived from a high-resolution land cover dataset. A grow-out scenario based on urban tree database information and allometric equations is used to predict future canopy cover. Change analysis is carried out at the census block group level to determine the magnitude and direction of change for each service and benefit over time. The monetary value of trees in the Bronx in 2010 is estimated to be \$37.6 million, and this value is estimated to range from \$40.7 million to \$43.9 million in 2030 if the current canopy is maintained and newly planted trees grow to maturity.

1. Introduction

Urbanization has adverse environmental impacts such as elevated temperatures, increases in air pollution and stormwater quantity, and decreases in stormwater quality, which pose major environmental and public health problems in cities (Seto and Shepherd, 2009). Studies show that increasing tree cover has the potential to provide multiple ecosystem services and benefits 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., 2013a), climate regulation (Salmond et al., 2016; Nowak and Crane, 2002) and stormwater improvements (Bolund and Hunhammar, 1999; Livesley et al., 2016). Ecosystem services refer to the conditions and processes through which natural ecosystems sustain and fulfill human life (Daily, 1997), whilst benefits illustrate the final outputs from ecosystems that directly affect human well-being (Haines-Young and Potschin, 2012). Ecosystem services, as the key functions that underpin the potential for well-being, are integral to sustainable development (Wood et al., 2018) and need to be sustained in terms of both quality and quantity for future generations to meet their needs. The relative importance that people assign to benefits provided by ecosystem services is typically represented in monetary units, ratings or ranking schemes (Schmidt et al., 2016).

Many forest management strategies to improve services as well as the health, economic and environmental benefits from trees are being undertaken in different cities. Increasing the number of healthy trees through tree planting is one such strategy, as evidenced by large tree planting initiatives undertaken in New York City (NY), Chicago (IL) and Los Angeles (CA) (MillionTrees NYC, 2017; Chicago Region Trees Initiative, 2018; City Plants, 2018). However, there is uncertainty over the future ecosystem services and benefits of these plantings. Studies that assess the extent to which these tree plantings provide various ecosystem services and also determine where these services are realized, have the potential to inform policy and decision making regarding urban forest management, particularly areas to target for future tree plantings to ensure environmental equity associated with both tree

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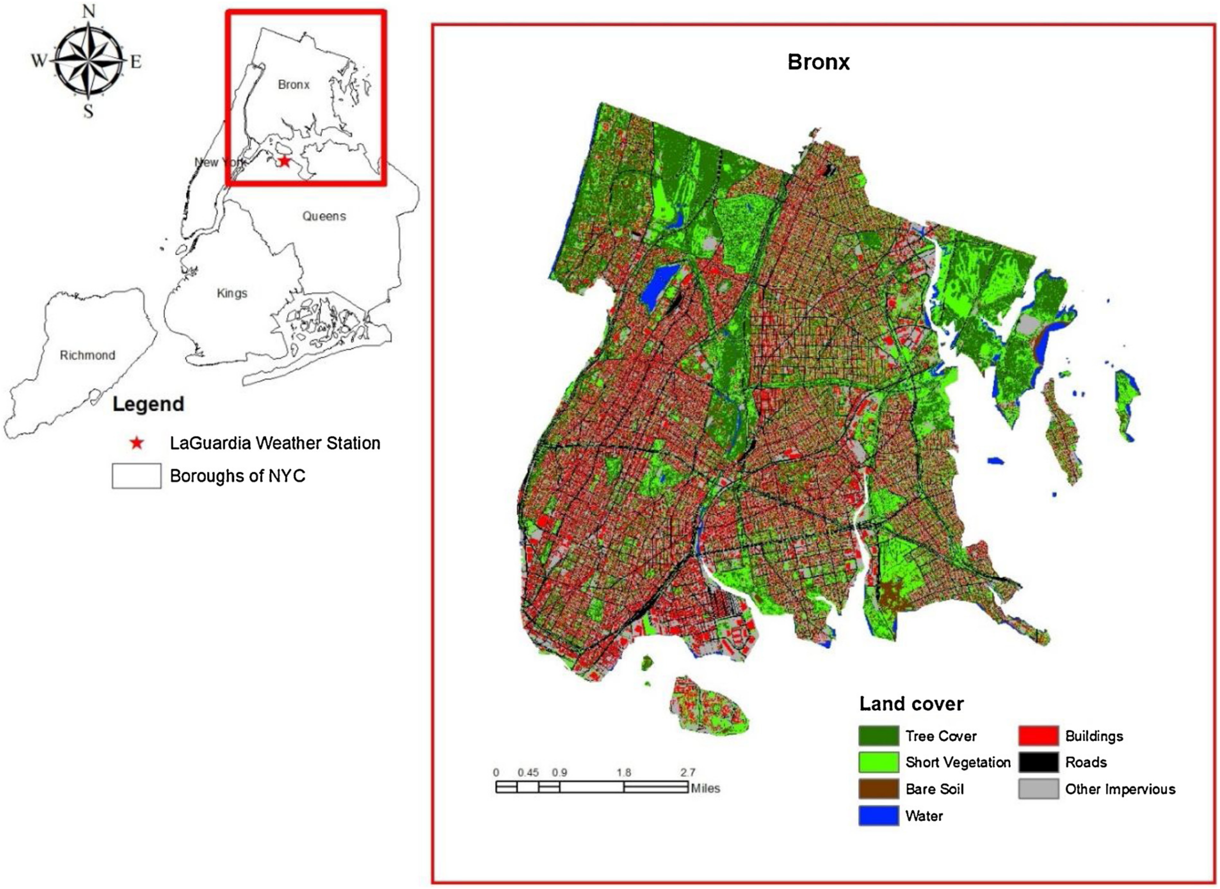

Fig. 1. Land cover of Bronx, New York from 2010 UTC.

cover and resultant ecosystem services and benefits.

In New York City (NYC), MillionTreesNYC (MTNYC) was launched in 2007 to plant and care for one million new trees throughout the city by 2017 (MillionTrees NYC, 2017). The goal of MTNYC is to increase tree canopy cover to 30% by 2030, based upon Luley and Bond's (2002) analysis and recommendation that increasing urban tree canopy (UTC) in NYC by 10% was a realistic and achievable canopy cover increase that would also improve ozone related air quality impacts by 3–4%. The NYC metropolitan area has been designated by the United States Environmental Protection Agency (US EPA) as being a non-attainment area for particulate matter less than 2.5 µm ($PM_{2.5}$) and ozone air quality standards (US EPA, 2017a). Both pollutants can be reduced by forests (Nowak et al., 2013b, 2014).

To better understand the spatial and temporal variations in ecosystem services provided by urban forests, we explore a new spatially distributed implementation of the i-Tree (www.itreetools.org) suite of models and mapping tools to estimate the current and potential future ecosystem services and benefits of urban tree cover. Initially focusing on NYC's recent planting initiative at the census block group level in the Bronx, NY, this spatially distributed implementation of i-Tree Tools will in the future be replicated within other cities with different climates, demographic and environmental variables to understand the role of urban forests across diverse urban ecosystems. This work lays the framework to develop a multi-objective decision support tool that guides urban forest decision making by optimizing ecosystem service provision and equity in evaluating urban tree planting locations. Previous studies and assessments that estimate the ecosystem services and benefits of trees in different cities have utilized the publicly available lumped versions of these i-Tree Tools. Lumped models conceptualize and simulate a spatially heterogeneous region as a single unit (e.g., using a mean value from a sample of the trees in a region) to estimate the tree effects on carbon sequestration, energy use, pest infestations, air pollution, stormwater volumes, and water quality (Wang et al., 2005). While this lumped approach provides city-scale information for urban planning, it makes assumptions that simplify the relationships between the structure and function of urban forests and the representation of urban landscapes. In addition, the lumped models do not estimate services and benefits at the fine scales that link tree effects to specific local conditions and residential populations, a scale at which local urban forest planning occurs. Here we make the assumption that the relationship between ecosystem services and tree cover is not simply linear, and using spatially distributed inputs and models produces a more accurate estimation of ecosystem services and guides towards better urban forest management.

While the focus of the study is on trees recently planted under MTNYC, the contribution of the entire urban forest to ecosystem services and benefits is also explored. The Bronx was chosen as the initial study site based on: a) the availability of tree planting data (City of New York, 2017a; NYC Parks and Recreation, 2017a, b), b) the air quality, stormwater and urban heat island issues in this borough (Kheirbek et al., 2013; Maantay, 2007; City of New York, 2017b; Rosenzweig et al., 2009; Zahmatkesh et al., 2015), c) the diverse demographics across the borough, and d) the lack of ecosystem services and benefits to some communities in the Bronx (Kremer et al., 2016; Maciejczyk et al., 2004). Two of six Trees for Public Health neighborhoods (Hunts Points and Morrisania), which received special attention during the MTNYC plantings because of their limited tree canopy and relatively high asthma rates, are in the Bronx (MillionTrees NYC, 2017). Of the various air pollutants, this study focuses on $PM_{2.5}$ which poses a high risk to health, since smaller particles can travel more deeply into the lungs, penetrate the lung barrier and enter the blood system causing more harmful effects including cardiovascular and respiratory illnesses

(US EPA, 2016).

In this analysis, a spatially distributed implementation of i-Tree Tools is used to characterize and estimate the services and benefits provided by current and future tree cover in the Bronx. These services and benefits include carbon storage and sequestration and reductions in $PM_{2.5}$ modeled using i-Tree Eco (Nowak et al., 2008), air temperature reductions modeled using i-Tree Cool (Yang et al., 2013) and stormwater runoff reduction modeled using i-Tree Hydro (Wang et al., 2008). These ecosystem services are modeled at the census block level, where demographic data is readily available to estimate ecosystem benefits. In addition to the spatially distributed implementation of i-Tree Tools, another distinguishing feature of this analysis is the use of a grow-out scenario and different management options to explore the potential range of ecosystem services and benefits in the future (2030). Specifically, the study grows out the newly planted trees in the Bronx under varying tree mortality scenarios to simulate future canopy conditions.

2. Methodology

A high resolution (3.2 ft) UTC Assessment (2010) of the Bronx (Fig. 1) processed by MacFaden et al. (2012) was utilized for this analysis to determine the baseline tree cover distribution. A tree growth model utilizing equations for calculating tree structure (diameter at breast height (DBH), tree height, crown width and crown height) from the i-Tree Forecast model described in Nowak et al. (2013c) is developed and used to simulate the growth of new tree plantings for estimation of canopy conditions in 2030 (the MTNYC target year). To assess the impacts of tree plantings, tree cover from the existing urban forest was assumed to remain stable (i.e., cover losses equaled gains from tree growth and natural regeneration). This assumption appears reasonable since tree cover in NYC remained relatively constant at 20.9% (standard error = 2%) from 1997 to 2010 (NYC Parks and Recreation, 2012; MacFaden et al., 2012). For modeling the growth of planted trees, high, average and low mortality rates are simulated. Estimates of the current (2010) and future (2030) ecosystem services and benefits were made at the census block group level.

2.1. Study area

The Bronx (Fig. 1), one of the five NYC boroughs, is divided into 1132 census block groups (US Census Bureau, 2010). The elevation of the borough ranges from 0 to 320 ft above mean sea level and the area receives mean annual precipitation of 40–52 inches with a frost-free period of 216–234 days. The native soils of the Bronx are predominately sandy loam while the parent material is asphalt over human-transported material (US Department of Agriculture Natural Resources Conservation Service, 2017). Based on a 2010 UTC Assessment, the Bronx had 22.7% tree cover, 16.3% short vegetation, 1.1% bare soil, 1.9% water, and 58% impervious surfaces. Most of the tree cover in the Bronx is found in large groups of trees, primarily urban parks and natural areas owned and managed by the Department of Parks and Recreation. Of the million MTNYC trees, 280,000 were planted in the Bronx, the second highest number after Queens (285,000) (MillionTrees NYC, 2017). The Bronx is known to have air pollution concerns with high levels of carbon monoxide, nitrous oxide, volatile organic compounds, ozone, and fine ($PM_{2.5}$) and coarse particulate emissions (Kheirbek et al., 2013; Maciejczyk et al., 2004). In addition, some communities in the Bronx have been prone to periodic flooding due to high impervious cover which accelerates stormwater runoff (NYC Parks and Recreation, 2017c). Furthermore, South Bronx neighborhoods have among the highest rates of heat illness and death in NYC. In 2010, ten of the twelve community districts in the Bronx had moderate to high Heat Vulnerability Indices (City of New York, 2017b).

2.2. Current and future land cover

Block group land cover estimates for the Bronx are derived from the 2010 land cover dataset (MacFaden et al., 2012). Assuming the Bronx maintains its baseline 2010 tree cover (22.7%), 2030 block group tree cover was estimated by growing out the planted trees' canopies annually from 2010 to 2030. We employed three datasets to determine the new tree plantings in the Bronx. The first was a dataset showing where plantings were made between 2010 and 2017 in restoration areas, including landscaped parks and other natural areas in the Bronx (NYC Parks and Recreation, 2017a). The second was a 2015–2016 Small Parks and Playgrounds (SPaP) inventory of all trees in parks and playgrounds under 6 acres (NYC Parks and Recreation, 2017b). The third was information from the 2015–2016 Street Tree Census (City of New York, 2017a). We assumed all street, park and playground trees with a DBH less than 5 in. were planted after 2010, which is a conservative estimate considering trees are planted at 2.5–3 in. caliper (Stephens, 2010) and generally have an average 0.33 in. annual diameter growth (Nowak et al., 2008).

While the street trees and SPaP data had geographic location, DBH and other tree parameters for each individual tree, the restoration data only had the container size and number of tree seedlings planted in a park or playground. Following a similar methodology to Morani et al. (2011), these seedlings were assumed to take 5 years to reach the minimum i-Tree Eco model diameter of 1 inch and that 20% of the seedlings would die by year 5. As such, these seedlings were added into the growth model 5 years from when they were initially planted. Table 1 contains a summary of new trees planted in the Bronx since 2010, including the top five (5) species planted in each location. Singling out specific species or ranking them based on how well they provide certain ecosystem services and benefits is not the focus of the study; we instead look generally at the impact of changes in tree canopy cover.

Annual per-tree growth of the new tree plantings was simulated to 2030 using species specific equations and parameters from the i-Tree Forecast model. i-Tree Forecast is a separate component of i-Tree Eco that uses structural estimates (e.g., number of trees, species composition), environmental and location variables, and species characteristics along with anticipated growth and mortality rates to simulate future forest structure (e.g., number of trees and sizes) and various ecosystem services based on annual projections of the current forest structure data (Nowak et al., 2013b). Annual tree diameter growth was estimated based on an average DBH growth rate of 0.33 in. per year adjusted for each species to account for variability in competition levels across different urban land types, growing season lengths, tree conditions and current tree height relative to the maximum tree height. Tree height, crown width, crown height, and leaf area were then estimated based on tree diameter each year using species, genus, order, and family specific

Table 1
Summary of trees planted in the Bronx since 2010.

Location	Number of Trees	Source	Top five species
Small Parks and Playgrounds	300	NYC Parks and Recreation (2017b)	*Prunus, Acer rubrum, Crataegus crus-galli, Quercus palustris, Tilia cordata*
Restoration areas	154,000	NYC Parks and Recreation (2017a)	*Quercus palustris, Quercus rubra, Liriodendron tulipifera, Quercus alba, Liquidambar styraciflua*
Streets	23,000	City of New York (2017a)	*Prunus, Gleditsia triacanthos, Zelkova serrata, Quercus palustris, Tilia cordata*
Total	**177,300**		

equations that were derived from measurements from urban tree data (Nowak et al., 2008, 2013b). If no equation exists at the species level, the average over the genus, family, or order level were used as necessary. Different urban tree mortality rates have been documented. Nowak and Aevermann (2019) highlight that the typical residential average mortality rate is 4% although mortality rates will vary among land use classes due to differences in development, management and competition. Lu et al. (2010) estimated young street tree mortality in NYC to be 8.7–26.2% depending on years since planting, figures that translate to an annual mortality rate of 4.4% based on an average annual mortality rate formula from Nowak et al. (2004). Studies in other cities including Syracuse and Baltimore (Nowak, 1986; Nowak et al., 2004) have also documented average mortality rates of 4%. For the new tree plantings, we simulate a low (0%), average (4%) and high (8%) annual mortality rate to provide a best, average and reasonable worst-case scenario in terms of tree loss.

2.3. Ecosystem services and benefits

For the various simulations used to estimate block group ecosystem services and benefits of the entire tree population in 2010 and 2030, we assume that the 2030 environmental and climatic conditions and demographics are the same as those in 2010, so that all changes in ecosystem services and benefits are due to the tree plantings of MTNYC. As tree canopy increases from 2010 to 2030, there is an increase in tree cover. This increase in tree cover is overset by a decrease in bare soil; when bare soil is no longer present, this decrease occurs in short vegetation. Impervious surface in 2030 is assumed to be the same as in 2010.

2.3.1. $PM_{2.5}$ reduction

A spatially distributed implementation of the i-Tree Eco air pollutant dry deposition model (Hirabayashi et al., 2011) was used to calculate net hourly dry deposition of $PM_{2.5}$ to trees at the block group level for the Bronx. This distributed model applies the lumped i-Tree Eco model to each block group using local estimates of land cover, tree parameters, and environmental variables. i-Tree Eco calculates pollutant flux as the product of deposition velocity (based on Leaf Area Index (LAI), wind speed, and resuspension rate) and pollutant concentration (Nowak et al., 2013b). Hourly meteorological data was obtained from the National Climatic Data Center (https://www.ncdc.noaa.gov/) for 2010 from the LaGuardia Airport weather station located in Queens, NY (for location see Fig. 1), while $PM_{2.5}$ pollutant concentrations for 2010 were block group specific, obtained from the EPA Fused Air Quality Surfaces Using Downscaling project (US EPA, 2017b). Leaf on and off dates and percent evergreen are also inputs to the model which account for differing seasonal dry deposition rates for deciduous versus evergreen trees. Leaf on and off dates for 2010 were obtained from local frost-free dates from the LaGuardia Airport weather station (https://www.ncdc.noaa.gov). National Land Cover Database (NLCD) 2011 percent evergreen (Homer et al., 2015) proportions at the block group level were used for 2010 and 2030. LAI at the block group was calculated from the crown height, tree height, and crown width estimates of the MTNYC tree data (NYC Parks and Recreation, 2017a, 2017b; City of New York, 2017a) based on i-Tree methods (Nowak, 1996; Nowak et al., 2008). LAI was calculated for all planted trees in the block group, and an average value estimated for each block group was used in i-Tree Eco. i-Tree Eco was run with estimated 2010 and predicted 2030 land cover to estimate pollutant removal (tons/yr) and yearly monetary benefit ($USD) of pollutant removal for each block group area. Monetary valuation for $PM_{2.5}$ removal in i-Tree Eco is calculated using US EPA's BenMAP model, which estimates the incidence of adverse health effects and associated monetary values resulting from changes in pollutant concentrations for the conterminous US (Hirabayashi, 2014; Nowak et al., 2013b; US EPA, 2017c).

2.3.2. Carbon storage and sequestration

Carbon storage and sequestration were calculated using the latest per area of tree canopy cover removal rates for NYC. Carbon sequestration was estimated at 1.7 tons of carbon per acre of tree cover per year while carbon storage is 32.03 tons of carbon per acre of tree cover (Nowak et al., 2018). To estimate the monetary value of carbon storage and sequestration, tree carbon values were multiplied by $129.8 per ton of carbon based on the estimated social costs of carbon for 2015 (Nowak and Greenfield, 2018). These removal rates and monetary values were multiplied by local canopy cover (m^2) to estimate carbon-related ecosystem services and benefits.

2.3.3. Stormwater runoff reduction

i-Tree Hydro was used to estimate stormwater runoff reductions by tree cover in 2010 and 2030. The model was first calibrated by minimizing the weekly real-space Nash-Sutcliffe Efficiency using the undiverted 38.4 mi^2 of the Bronx River as the contributing area to the US Geological Survey (USGS) gauging station 01302020 at the NY Botanical Garden in the Bronx for the 2010–2012 calendar years. The upper portion of this watershed is diverted for drinking water (NYC Parks and Recreation, 2017c). As the Bronx River watershed stretches beyond the extent of the UTC data, tree cover in adjacent Westchester County, NY was derived from 2011 one-meter digital orthoimages (US Department of Agriculture Farm Service Agency, 2011). The image data were classified into trees, short vegetation, bare soil, water and impervious cover using 250 training polygons randomly distributed across these images within the non-classified area of the watershed. A confusion matrix (Jensen, 2005; Stehman, 1997) using 250 independent assessment polygons (50 per land cover class) randomly selected from the digital orthoimages, was used to evaluate image classification errors and yielded overall classification accuracy of 94%. The overall accuracy represents the proportion of the assessment polygons that were classified correctly during the image classification process.

i-Tree Hydro's calibrated parameters for the Bronx River were applied to model runs for each of the 1132 block groups in the Bronx for 2010 and 2030. Hourly weather data for 2010 was obtained from LaGuardia Airport weather station while LAI, leaf on and leaf off dates and evergreen percent were derived similar to that described for $PM_{2.5}$ reduction. The amount of impervious area directly connected to the stream was calculated from the Sutherland Effective Imperious Area Equations (Sutherland, 2000). Block group land cover data discussed in Section 2.2 were used in the model. A 2015 USGS 1 arc-second resolution National Elevation Dataset (NED) (https://viewer.nationalmap.gov) was clipped to each block group boundary to determine local elevation data. This elevation dataset (with an approximate horizontal distribution of 30 m) was selected based on recommendations for i-Tree Hydro which suggest elevation data should have a horizontal resolution of 10–30 m as finer resolution data are more likely to cause complications in modeling in urban areas with bridges and elevated roadways (i-Tree Hydro, 2018). To estimate avoided runoff, an alternative 2010 scenario was created where all tree cover is removed and replaced with either herbaceous cover (for tree canopy over pervious area) or impervious surface (for tree cover over impervious area). i-Tree Hydro was then run for this alternative scenario, as well as the actual 2010 and estimated 2030 scenarios to estimate impervious surface runoff, and the difference in impervious surface runoff between the alternative scenario and the other scenarios was our estimate of avoided runoff. Avoided runoff was valued at the national average of $0.008936/gallon based on the USFS' Community Tree Guide series, which estimates that value regionally based on stormwater treatment and management costs and fees (Hirabayashi, 2013).

2.3.4. Air temperature reductions

i-Tree Cool, which is based on the Physically based Analytical Spatial Air Temperature and Humidity model (Yang et al., 2013), was used to simulate the spatial distribution of air temperature for the Bronx for 2010 and 2030. i-Tree Cool calculates spatial solar radiation and heat storage based on semi-empirical functions and generates spatially distributed urban microclimate conditions based on inputs of topography, land cover, and weather data measured at a reference site (Yang et al., 2013). The La Guardia Airport weather station was used as a reference site for air temperature and humidity data for July 2010, the month with the highest temperatures in 2010. The NED, 2010 and 2030 land cover, percent impervious cover and percent tree canopy maps were resampled to a 300-m horizontal resolution and used as input data for this model. Heat index values in degrees Fahrenheit (°F) were calculated for each block group for 2010 and 2030 tree cover scenarios from the hourly 300-m i-Tree Cool air temperature and humidity output for the month of July using the US National Weather Service (US NWS) methodology (US NWS, 2018). The heat index, a human-perceived equivalent temperature, is a measure of how hot it really feels when relative humidity is factored in with the actual air temperature, and is widely used in environmental health research, including studies of air pollution exposures, outdoor temperature exposures, and the development of heat warning systems (Anderson et al., 2013; Rothfusz, 1990). Average reduction in heat index, considered an ecosystem service in this study, was calculated by subtracting the average block group heat index values for 2010 from 2030. This change in heat index was incorporated into a damage function that relates changes in heat index to health and productivity impacts (Voorhees et al., 2011; US EPA, 2017c):

$$\Delta y = y_0 \bullet (e^{\beta \bullet \Delta x} - 1) \bullet \text{Pop} \quad (1)$$

where Δy is the change in cardiovascular and respiratory related mortality, y_0 is the baseline incidence rate for the effect, Δx is the change in the heat index, β is a unitless coefficient derived from the relative risk associated with a change in exposure, and Pop is the exposed population. Here y_0 is estimated as 0.02304 based on 2010 cardiovascular and respiratory mortality for the population over 65 years old for the Bronx (Centers for Disease Control and Prevention, 2018). For β we used 0.013867 for the Northeastern US from Basu et al. (2005) based on their study of 1992 mean apparent temperature impacts on cardiovascular and respiratory mortality impacts for ages 65–99 in the 20 largest metropolitan areas of the US. Here Pop (the exposed population) is estimated at the census block group as all people older than 65 years in 2010 (US Census Bureau, 2010). This analysis used a conservative assumption of no change in population in the Bronx between 2010 and 2030 so that all changes in services and benefits are due to trees. To estimate the monetary benefit of reduced mortality we applied the Value of Statistical Life of $8.7 million, which is also used by the EPA in BenMap for changes in air pollution benefits (US EPA, 2017c)

3. Results

The aim of this study is to assess the current and future ecosystem services and benefits of urban tree cover at the census block group level in the Bronx, NY. The following sections present the projected 2030 tree cover and the estimated ecosystem services and benefits from this tree cover.

3.1. Tree cover

Block group tree cover percentages for the Bronx in 2010 and for the different 2030 tree mortality growth scenarios are illustrated in Fig. 2. The Bronx had 22.7% tree cover in 2010, and tree cover is estimated to increase to 24.9% in 2030 based on the high tree mortality growth scenario, 26.2% in 2030 using the average mortality growth scenario and 27.4% in 2030 using the low tree mortality growth scenarios (Fig. 2). Tree cover varies both spatially and temporally at the block group level, with tree cover ranging from 0.18%–69% in 2010 and from 0.18%–89% in 2030. The maximum tree cover (89%) is the maximum that can be achieved in that block group without converting impervious surfaces to tree cover.

3.2. Ecosystem services

All the ecosystem services and benefits (air pollutant removal, carbon storage and sequestration, runoff reduction and air temperature decreases) are estimated at the block group level. There are both spatial and temporal variations ecosystem services and monetary benefits across different block groups in the Bronx as tree cover changes over time.

3.2.1. Air pollution removal

The overall monetary benefits of $PM_{2.5}$ removal per acre of tree cover at the block group level for the Bronx in 2010 and the increased benefits of $PM_{2.5}$ removal per acre of tree cover for 2030 are shown in Fig. 3. In 2010, the Bronx's 2,470 ha of tree cover is estimated to have removed 5.1 tons/yr of $PM_{2.5}$ pollutants, resulting in human health benefits valued at $6.9 million/yr (Fig. 3). For the 2030 high tree mortality scenario, $PM_{2.5}$ pollutant removal is expected to increase to 5.6 tons/yr ($7.2 million/yr); it will increase to 5.9 tons/yr ($7.3 million/yr) for the average mortality scenario, and increase to 6.2 tons/yr ($7.4 million/yr) for the low mortality scenario. These changes correspond to a 9.8% increase in air pollutant removal for the high mortality scenario, a 15.7% increase for the average mortality scenario, and a 21.6% increase for the low mortality scenario. In 2010, block group $PM_{2.5}$ removal ranged between 0 – 0.8 tons/yr, in 2030 (high mortality) 0–1.1 tons/yr, in 2030 (average mortality) 0–1.2 tons/yr, and in 2030 (low mortality) 0–1.3 tons/yr.

3.2.2. Carbon storage and sequestration

Increases in carbon storage and sequestration services and benefits over time are proportional to tree cover increases. The block group estimates of carbon storage and sequestration benefits per acre of tree cover in the Bronx in 2010 as well as the increase in these benefits for different 2030 scenarios are shown in Fig. 4. In the individual block groups, carbon storage peaks at 29,900, 37,300, 42,000 and 45,600 tons, with sequestration peaking at 1,600, 2,000, 2,200 and 2,400 tons/yr for 2010, 2030 high tree mortality, 2030 average tree mortality, and 2030 low tree mortality scenarios, respectively. In 2010, total carbon sequestration was 10,300 tons/yr ($1.3 million) and carbon storage was 195,500 tons ($25.4 million). For the 2030 high tree mortality scenario, carbon sequestration is expected to increase to 11,400 tons/yr ($1.5 million/yr) while carbon storage is expected to increase to 215,000 tons ($27.9 million). Carbon sequestration will increase to 12,000 tons/yr ($1.6 million/yr) and carbon storage to 225,600 tons ($29.3 million) for the average mortality scenario, and carbon sequestration is expected to increase to 12,500 tons/yr ($1.6 million/yr) and carbon storage to 237,000 tons ($30.7 million) for the low mortality scenario. These changes from 2010 correspond to a 10% increase for the high mortality scenario, a 16% increase for the average mortality scenario, and a 21% increase for the low mortality scenario.

3.2.3. Runoff reduction

Increasing tree cover reduces total surface runoff in the Bronx (Fig. 5). During the simulation period of 2010–2012, the 2010 tree cover scenario resulted in 2.5 billion ft^3/yr total runoff and 60 million ft^3/yr (9830 ft^3 per acre of tree cover) net avoided runoff by trees (a 2.4% reduction), a service valued at $4 million/yr. Fig. 5 illustrates avoided runoff reduction monetary benefits for block groups in the Bronx per acre of tree cover in 2010 as well as increases in these benefits for 2030 scenarios. The 2030 tree cover generated from the high tree mortality scenario increases this avoided runoff by 1.2 million ft^3/yr ($82,200/yr). Runoff is reduced by 2 million ft^3/yr ($135,200/yr) based on the 2030 tree cover from the average mortality scenario.

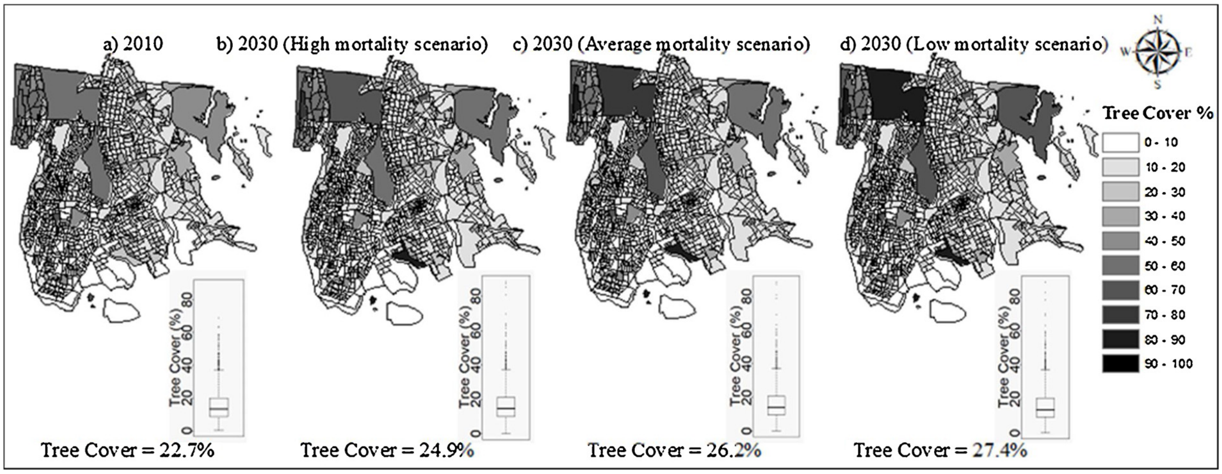

Fig. 2. Block group tree cover estimates for the Bronx, NY for a) 2010, b) 2030 with high tree mortality, c) 2030 with average tree mortality, and d) 2030 with low tree mortality.

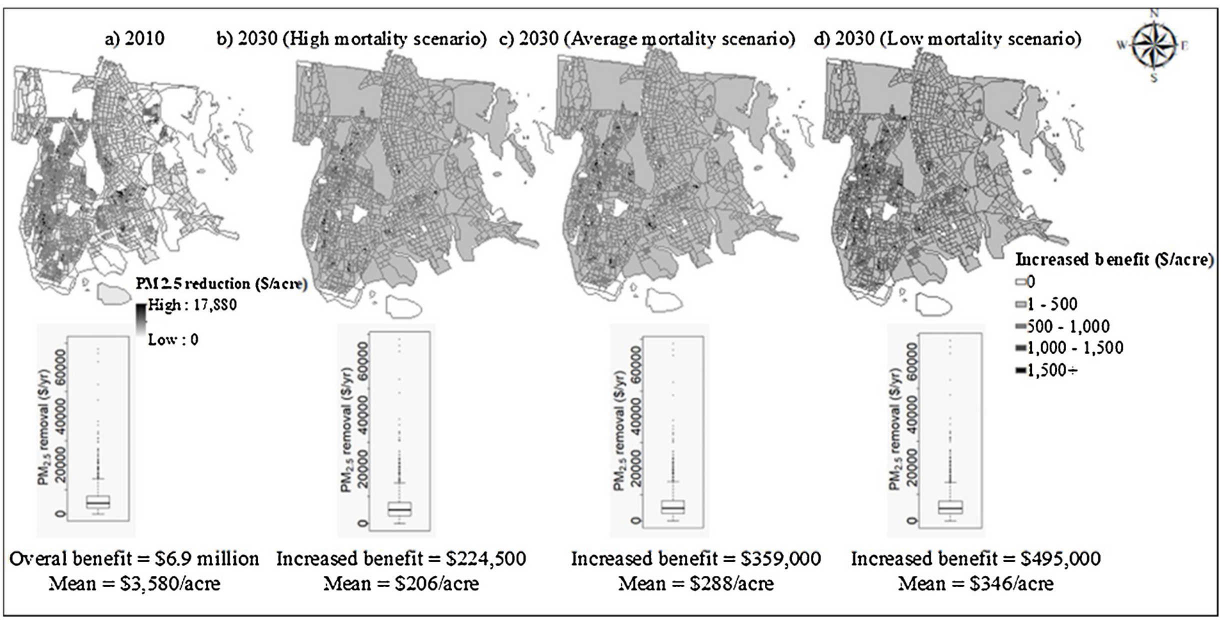

Fig. 3. a) Estimated 2010 $PM_{2.5}$ removal monetary benefits, increased $PM_{2.5}$ removal monetary benefits in b) 2030 (high mortality), c) 2030 (average mortality), and d) 2030 (low mortality). Box plots illustrate the distribution of $PM_{2.5}$ removal monetary benefits for each analysis scenario.

Under the 2030 no mortality scenario, runoff is reduced by 3 million ft^3/yr ($197,500/yr). In any given block group, the increase in avoided runoff is a maximum of 184,000 ft^3/yr in 2030 based on the high tree mortality scenario, 303,000 ft^3/yr in 2030 based on the average tree mortality scenario, and a maximum of 391,100 ft^3/yr in 2030 based on the low tree mortality scenario.

3.2.4. Air temperature reduction

Reductions in heat index values are desirable to reduce heat stress, especially for vulnerable and susceptible populations such as children and the elderly. However, in the Bronx, the estimated 2%–5% increases in tree cover is predicted to have a minimal impact on both air temperature and heat index reduction. Fig. 6 depicts the block group mean temperature and heat index values in the Bronx in 2010. The average temperature across all scenarios is 87.5 °F, while the heat index is 91.1 °F. The maximum heat index reduction in any given block group was estimated as 0.06 °F based on the high tree mortality scenario, 0.10 °F based on the average tree mortality scenario and 0.17 °F under the low tree mortality scenario. Changes in temperature are only observed in 1 block group using the high tree mortality scenario, 2 block groups based on the average tree mortality scenario and 3 block groups using the low tree mortality scenario. Heat index values change in 3 block groups under the high and average tree mortality scenarios and in 4 block groups under the low tree mortality scenarios. In terms of changes in mortality due to reductions in the heat index as a result of increasing tree cover, we did not estimate any reduction in cardiovascular and pulmonary related mortality cases for any tree mortality scenario.

4. Discussion

This analysis has illustrated a tree grow-out scenario under varying mortality rates and a spatially distributed implementation of i-Tree tools to estimate current and potential future tree cover and resultant ecosystem services and benefits in the Bronx, NY. Our results show that high amounts of tree cover are expected in large block groups that mostly consist of parks and playgrounds (Fig. 2). Landscaped parks and other natural areas are also where most of the new trees were planted in

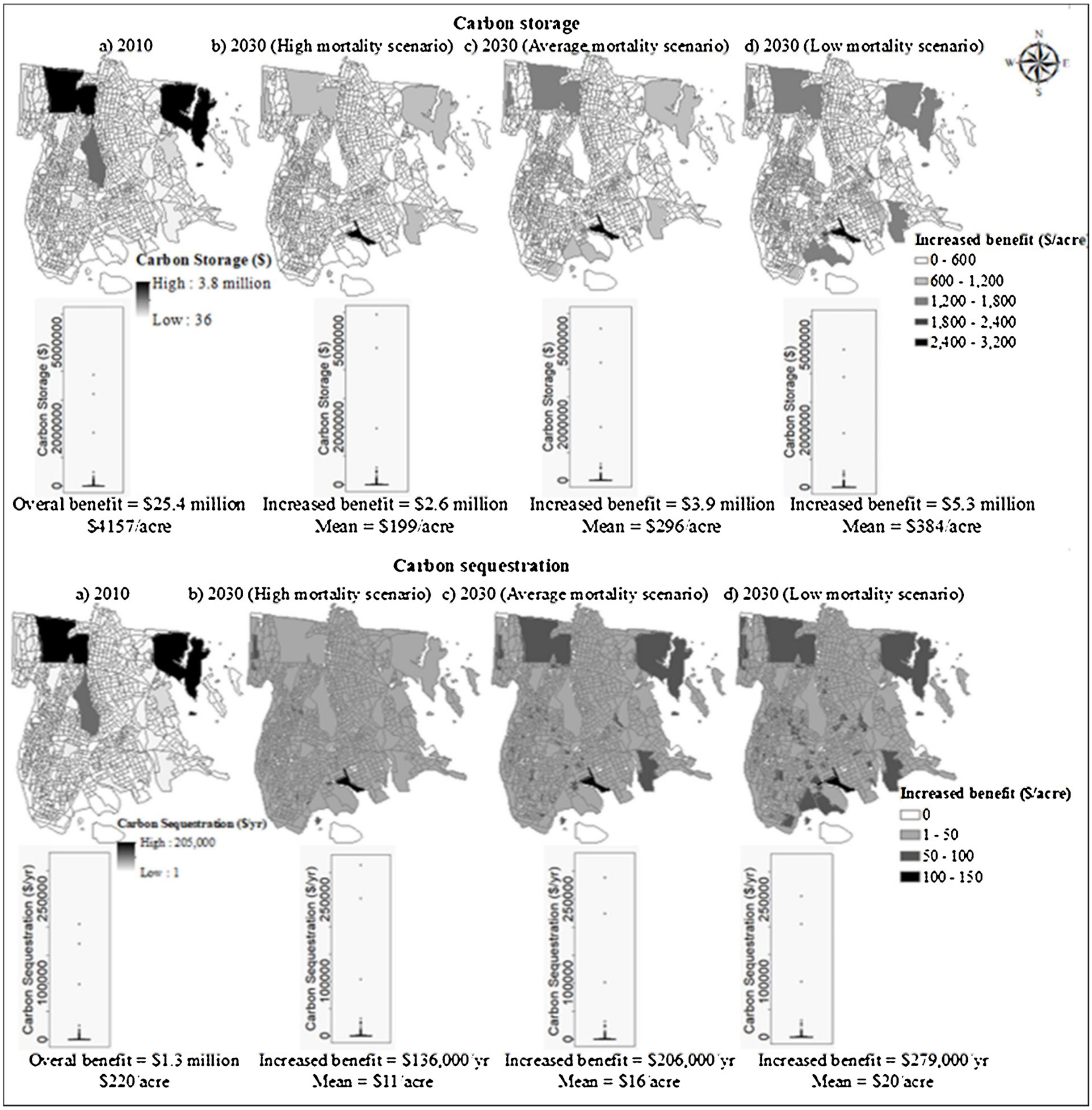

Fig. 4. a) Estimated 2010 carbon storage and sequestration monetary benefits, increased carbon storage and sequestration monetary benefits in b) 2030 (high mortality), c) 2030 (average mortality), and d) 2030 (low mortality). Box plots illustrate the distribution of carbon storage and sequestration monetary benefits for each analysis scenario.

the Bronx under MTNYC (NYC Parks and Recreation, 2017a, b). This is not surprising considering that tree planting is usually in areas where there is more plantable space, mostly large properties including urban parks and natural areas owned and managed by the Department of Parks and Recreation. Smaller block groups are typically in commercial districts that are primarily impervious surfaces (e.g. roads and buildings) and have relatively few trees and few opportunities to expand tree canopy (O'Neil-Dunne, 2012). Our projections of future tree cover using the low, average, and high mortality scenarios illustrate how tree mortality affects tree cover and subsequent tree benefits. Numerous factors affect planting, regeneration and mortality through time, so management plans and urban forest monitoring are needed to ensure local management goals are met (Morani et al., 2011). This also has implications for sustainable development discussions with regards to tree cover amounts needed to sustain future populations.

Vegetation improves air quality, but to what level depends on the local situation (Bolund and Hunhammar, 1999). Our results have shown that in general, the greater the tree cover, the greater the pollutant removal; the greater the pollutant removal and population density, the greater the monetary value of this benefit (Nowak et al., 2014). This is evident in the Bronx where pollutant removal across all scenarios varies with block group size and tree cover percentages; parks and forested areas with high tree cover typically have the greatest pollutant removal. In addition to tree cover amounts, removal rates by trees will vary locally based on factors that include pollutant concentration, length of growing season, percent evergreen leaf area and meteorological conditions (Nowak et al., 2014; Hirabayashi and Nowak, 2016). However, due to the minimal spatial variation in the weather and pollutant concentration employed in the Bronx, total tree cover will be the main driving cause of removal rates. Nowak et al. (2014) highlight that due to the limited number of weather and pollutant monitors nationally, use of the closest weather and pollutant data might not be representative of the area being analyzed. While the removal gradients follow a distribution similar to the tree cover

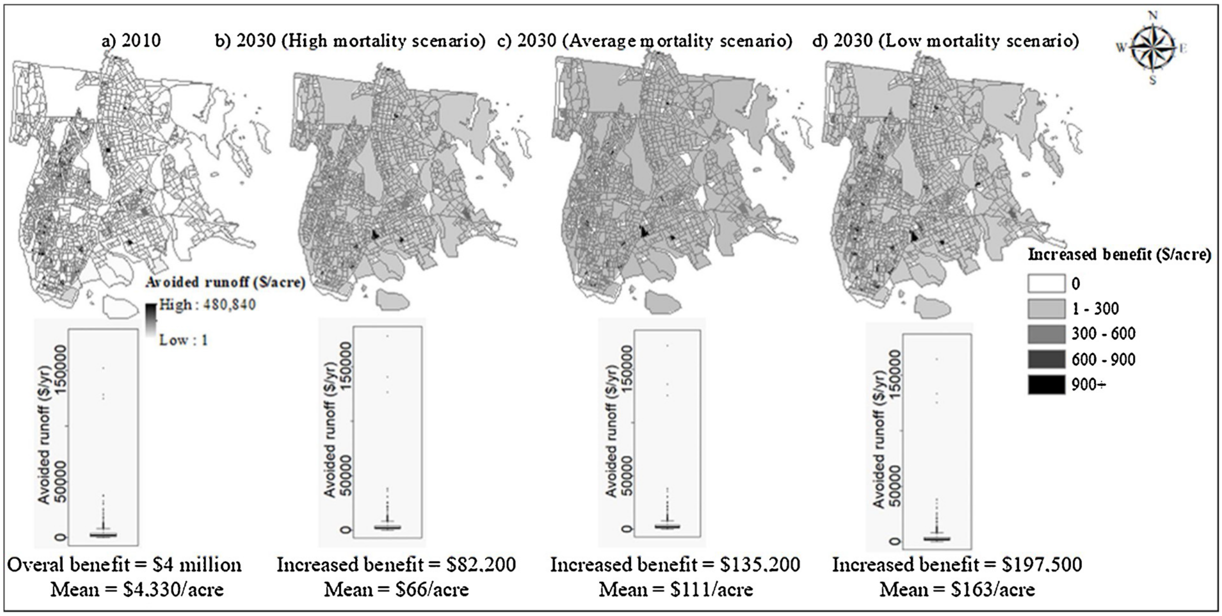

Fig. 5. a) Estimated 2010 runoff reduction monetary benefits, increased runoff reduction monetary benefits in b) 2030 (high mortality), c) 2030 (average mortality), and d) 2030 (low mortality). The distribution of runoff reduction monetary benefits for each analysis scenario is shown in the box plots.

distribution (Fig. 2), the monetary benefit of this service (Fig. 3) shows a different pattern and is influenced by population demographics. BenMap's economic valuation is driven by modeled air quality changes, population demographics and baseline incidence rates (US EPA, 2017c). It then follows that areas with high population and incidence rates will have a higher monetary benefit from pollutant removal than areas with high tree cover alone. To overcome uncertainties associated with estimating tree LAI, we calculated block group specific averages using data from all the newly planted trees in each block group. Our average LAI is 3.6, a value slightly lower than the 4.8 (standard error = 1) value Nowak and Greenfield (2018) found based on field samples from 34 US cities and urban areas within the conterminous US. The LAI of 3.6 is for newly planted trees, and thus should be smaller than the average LAI in cities across the US.

Carbon storage and sequestration are strongly impacted by the total amount of tree cover (Nowak et al., 2013a). In general, block groups with higher total tree cover will have greater forest carbon storage and sequestration (darker shades in Fig. 4). Nowak and Crane (2002) argue that urban forests take up a small portion of all annual carbon emissions. They note that while increasing the number of trees can potentially slow the accumulation of atmospheric carbon, tree care practices release carbon back to the atmosphere by fossil-fuel emissions from maintenance equipment. Thus, some of the carbon gains from tree growth are offset by carbon losses to the atmosphere via fossil fuels used in maintenance activities. Our results indicate that trees have some effect, although minimal to offset some of the carbon emissions that contribute to greenhouse gas formation. Numerous studies have quantified carbon sequestration and its economic value. In Hangzhou,

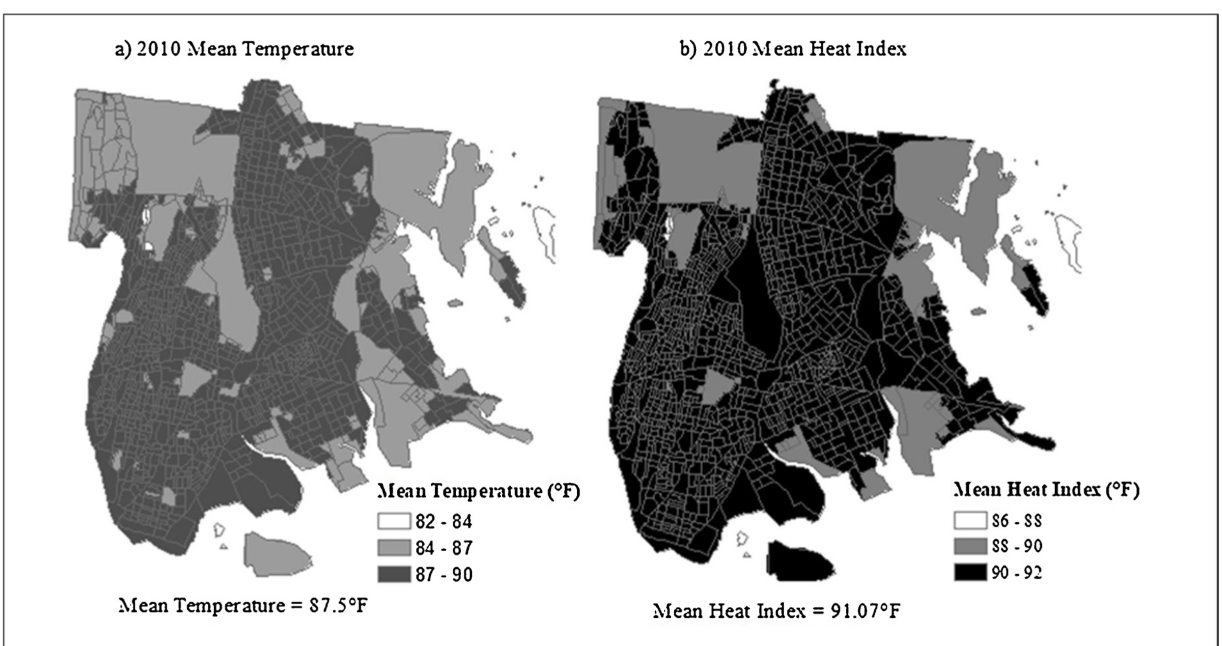

Fig. 6. a) Estimated 2010 temperature, b) estimated 2010 heat index.

China, Zhao et al. (2010) found that sequestration of carbon by urban forests was comparable to carbon emissions from several industrial sectors and offset urban industrial carbon emission by 18%. Morani et al. (2011) estimated that new trees planted in NYC will sequester an average of 7,000 tons of carbon per year. Nowak and Crane (2002) note that after a tree is removed, the tree eventually decomposes, and the carbon stored in that tree is emitted back to the atmosphere, though a fraction of the carbon may be retained in the soil. In addition, all the carbon sequestered by subsequent trees grown on that same site will be offset by carbon emissions due to decomposition of the tree previously on the site. Another important element to consider is the placement of trees; for example, trees strategically located around buildings can reduce building energy use and consequently lower carbon emissions from fossil-fuel-burning power plants (Nowak and Crane, 2002).

Studies have reported stormwater runoff reductions of 2%–7% (Vargas et al., 2008). In Phoenix, AZ, 22,146-acres of tree canopy is estimated to have reduced stormwater runoff by 91.7 million ft^3 (4,140 ft^3 per acre of tree cover), with an estimated value of $6.1 million (Davey Resource Group, 2014). NYC's street trees are estimated to reduce stormwater runoff by 890.6 million gallons annually, with a value of $35.6 million (MillionTrees NYC, 2017). Larger amounts of pervious surfaces such as grass and soil under trees allow water to infiltrate into the ground, unlike impervious surfaces that enhance runoff. In addition, vegetated areas allow water to infiltrate and be held in pore spaces, allowing direct evaporation of this water and transpiration through the vegetation (Bolund and Hunhammar, 1999), as well as increased interception (Freeborn, 2011). Urban trees have the potential to reduce surface water runoff and help motivate greening initiatives in cities to reduce the risk of flooding. For example, NYC dedicated $2.4 billion to increasing and improving urban green infrastructure for stormwater absorption (McPhearson et al., 2014).

Studies have documented reductions in temperature by trees. Scott et al. (1999) found that trees in a Davis, CA parking lot reduced air temperatures by 1–3 °F. Rosenzweig et al. (2009) found that increasing tree cover from 22% in the Fordham neighborhood of the Bronx to 31% by planting in open spaces reduces air temperature by 0.1 °C, while increasing tree cover to 32% by planting street trees reduces it by 0.2 °C. Luley and Bond (2002) report that replacing all urban grass with trees in NYC reduced surface air temperature by up to 1 °C on a summer afternoon. Our result is not surprising considering that the amount of tree cover added is too little to have an impact on temperature. It is also important to consider that the configuration and placement of newly planted trees was not necessarily done in a manner that maximizes the cooling effect of trees. Nowak (2002) highlights that in areas with scattered tree canopies, radiation can reach and heat ground surfaces; at the same time, the canopy may reduce atmospheric mixing such that cooler air is prevented from reaching the area. Previous epidemiologic studies examining the relationship between temperature and mortality report changes in mortality for much higher temperature changes than we are seeing in the Bronx. For example, Basu and Ostro (2008) report a 2.6% percent increase in cardiovascular mortality for each 10 °F increase in mean daily heat index. Our finding of no reduced mortality due to a reduction in heat is due to our minimal predicted changes in temperature (about 0.1 °F) and the small value of the unitless coefficient β in Eq. (1) ($\beta = 0.013867$), which was obtained from Basu et al. (2005) for the Northeastern US.

Where our study differs from previous studies and i-Tree assessments is in utilizing a spatially explicit modelling methodology utilizing a growing body of spatial biophysical data and i-Tree Tools as opposed to using traditional lumped models. We also explored a tree grow-out scenario under varying mortality rates to estimate future canopy conditions. While our findings may not be surprising, it is important to note that carbon related services and benefits, avoided runoff benefits and services, and $PM_{2.5}$ removal services differ significantly (at $p = 0.05$) from ecosystem services and benefits estimated obtained from employing lumped versions of i-Tree tools. This was based on a Wilcoxon paired signed rank test, a non-parametric statistical hypothesis test (McCrum-Gardner, 2008; Rosner et al., 2006), which concluded that ecosystem services and benefits estimated from our spatially distributed implementation of i-Tree models are significantly different from those estimated from the lumped implementation of i-Tree models used in i-Tree Landscape. The mean services and benefits from carbon storage and sequestration as well as avoided runoff from the spatially distributed models were greater than those from the lumped model, while $PM_{2.5}$ removal and monetary services from the lumped model were higher than those from the spatially distributed model. These differences have implications on what block groups to target for future plantings.

Future work will build on this work (in the Bronx as well as other cities) and seek to improve on the spatial variability in the data as well as incorporate social and demographic data to highlight inequities and promote tree plantings that are equitable across different socio-demographic populations. This will culminate in a body of work that is applicable at large spatial scales (such as entire cities) and in different locations to inform decision-making processes, policy options and management measures for urban forests.

5. Conclusion

This study quantifies current and future ecosystem services and benefits provided by trees at the block group level in the Bronx, NY using spatially explicit i-Tree Tools. Results show spatially and temporally varying gradients of different ecosystem services and benefits (pollutant removal, stormwater runoff reduction, air temperature reduction as well as carbon storage and sequestration) due to estimated increases in tree cover from 2010 to 2030. We have shown how cover and benefits can be enhanced by ensuring the long-term survival of newly planted trees (reducing tree mortality). Our results have illustrated how new tree plantings have the potential to increase 2010 ecosystem benefits by $6.3 million if trees are maintained to full maturity (and current policies and planning strategies persist), $4.7 million if new trees are lost at an annual rate of 4%/yr and $3.1 million if new trees are lost at an annual rate of 8%/yr. Management plans should enhance the protection and maintenance of existing trees in addition to planting new trees or natural regeneration. Spatially distributed modeling approaches such as ours provide more spatially refined service and benefit estimates and have the potential to guide more local and fine scale decision making regarding where to improve or protect tree cover and maximize the services and benefits of trees. However, more accurate and spatially distributed weather inputs, pollutant concentrations, and species and age specific mortality rates are needed to develop improved results. Regardless, this analysis develops a methodology to estimate the potential range of ecosystem services and benefits due to increased tree cover in the Bronx in 2030. Clearly trees provide a myriad of services and benefits to urban inhabitants and maintaining and expanding existing canopy cover should be a priority in urban settings.

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