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Implementing and managing urban forests: A much needed conservation strategy to increase ecosystem services and urban wellbeing

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ABSTRACT

Megacities contain at least 10 million people whose wellbeing largely depends on ecosystem services provided by remote natural areas. What is, however, most often disregarded is that nature conservation in the city can also contribute to human wellbeing benefits. The most common mind set separates cities from the rest of nature, as if they were not special kinds of natural habitats. Instead, awareness that urban systems are also nature and do host biodiversity and ecosystem services opportunities, should push urban people towards increased urban forest conservation and implementation strategies. This research estimated existing and potential, tree cover, and its contribution to ecosystem services in 10 megacity metropolitan areas, across 5 different continents and biomes. We developed estimates for each megacity using local data to transform i-Tree Eco estimates of tree cover benefits to reductions in air pollution, stormwater, building energy, and carbon emissions for London, UK. The transformation used biophysical scaling equations based on local megacity tree cover, human population, air pollution, climate, energy use, and purchasing power parity. The megacity metropolitan areas ranged from 1173 to 18,720 sq km (median value 2530 sq km), with median tree cover 21%, and potential tree cover another 19% of the city. Megacities had a median tree cover density of 39 m^2/capita, much smaller than the global average value of 7800 m^2/capita, with density lower in desert and tropical biomes, and higher in temperate biomes. The present median benefit value from urban trees in all 10 megacities can be estimated as $482 million/yr due to reductions in CO, NO_2, SO_2, PM10, and PM2.5, $11 million/yr due to avoided stormwater processing by wastewater facilities, $0.5 million/yr due to building energy heating and cooling savings, and $8 million/yr due to CO_2 sequestration. Planting more trees in potential tree cover areas could nearly double the benefits provided by the urban forest. In 2016 there were 40 megacities, totaling 722 million residents, nearly 10% of the human population, who would benefit from nature conservation plans where they work and live. Nature conservation strategies in megacities should work to sustain and grow the benefits of the urban forest, and improve accounting methods to include additional ecosystem services provided by the urban forest.

1. Introduction

Megacities are densely populated, containing at least 10 million people, yet these urban systems still contain parts of nature that deserve an accounting of their benefits and nature conservation strategies. The human livelihoods in these megacities, unfortunately, are adversely impacted by urban pollution (Gurjar et al., 2008), climate change (Dasgupta et al., 2013; Mourshed, 2011), and constrained budgets that prohibit needed investments in education (Bunar, 2010; Maitra and Rao, 2015; Ngware et al., 2011) and healthcare (Loganathan et al., 2015; Vuong, 2015). Conserving and enhancing natural systems to solve or reduce pollution problems is one of the main functional applications of the field of ecological engineering. As such, ecological engineering recognizes the strategic importance of coupling urban areas and natural areas in order to convert urban pollution into ecosystem resources, in such a way that benefits human wellbeing and biodiversity (Mitsch and Jorgensen, 2003). Efforts to improve the condition of human livelihoods are the focus of the United Nations Sustainability Development Goals (Chin and Jacobsson, 2016; United Nations, 2016a),

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Table 1
Megacity name, area, human population (N_{Pop}), purchasing power parity conversion (PPP), annual average air pollutant concentration (C_{TSP} is total suspended particles, C_{SO2} sulfur dioxide, C_{NO2} nitrous dioxide), growing season ($N_{GrowDay}$), precipitation depth (D_{Ppt}), electricity use ($W_{Electricity}$), energy use (J_{Energy}), and inversion potential (F*Inversion*). Superscript [a] denotes data from Gurjar et al. (2008), except for Istanbul and Mumbai, which were estimated based on the Gurjar data, [b] is from Kennedy et al. (2015).

City	Area (sq km)	N_{Pop} (–)	PPP L£/$	C_{TSP}[a] (ug/m3)	C_{SO2}[a] (ug/m3)	C_{NO2}[a] (ug/m3)	$N_{GrowDay}$ (day)	D_{Ppt}[b] (mm)	$W_{Electricity}$[b] (GWh)	J_{Energy}[b] (TJ)	$F_{Inversion}$ (–)
Beijing	2742	2.1E+7	3.52	377	90	122	251	721	80686	652343	1.1
Buenos Aires	2941	1.4E+7	2.66	185	20	20	273	1195	34170	449961	1.0
Cairo	1173	1.6E+7	2.22	593	37	59	365	26	30897	250964	1.0
Istanbul	1990	1.3E+7	1.16	668	13	30	350	852	38249	286315	1.0
London	2906	1.0E+7	0.70	34	19	71	246	601	39946	386643	1.0
Los Angeles	6612	1.5E+7	1.00	39	9	66	365	379	63898	508755	1.1
Mexico City	2219	2.0E+7	7.93	201	47	56	365	697	13667	119262	1.1
Moscow	2318	1.6E+7	21.26	150	15	170	166	698	51954	1236353	1.0
Mumbai	1358	1.8E+7	17.00	405	18	36	365	3225	12952	29005	1.1
Tokyo	18720	3.8E+7	104.72	40	19	55	312	1480	240783	1047599	1.0

which call for additional tree cover in cities in order to provide needed environmental, economic, and social ecosystem services (Bolund and Hunhammar, 1999; Gauthier, 2003; United Nations, 2016b). The objective of this work is to advance these UN goals by applying accounting models of urban tree benefits, and thereby establish a rationale for the development of more advanced nature conservation strategies for megacities.

Urban tree cover delivers an array of ecosystem services, including: air pollutant reduction (Baró et al., 2014; Jim and Chen, 2008); stormwater runoff reduction (Coutts et al., 2013; Inkilainen et al., 2013; Soares et al., 2011); building energy savings from reduced heating and cooling costs, and the associated avoided carbon emissions from reduced energy use (Akbari, 2002; Kulak et al., 2013; Sawka et al., 2013; Wang et al., 2016); and carbon dioxide sequestration (Lwasa et al., 2015; Nowak et al., 2013). A benefit of providing these services with trees is the low energy cost due to solar radiation, via the process of photosynthesis, powering tree structure and function. The additional energy inputs needed for tree management is a real cost, but something that can be incorporated into green jobs, education, and outreach programs (Beck and Villarroel Walker, 2013; Gauthier, 2003).

Estimates of tree cover are used by some ecological models when accounting for the ecosystem services provided from trees. A set of widely applied, tested, and free models are collectively known as i-Tree tools (www.itreetools.org), which include computer programs that were been developed to help communities inventory their tree cover and estimate the associated ecosystem services. The i-Tree Eco tool uses input data of tree structure, air pollution, weather, buildings, and economic pricing to estimate the tree-based ecosystem services of air pollutant reduction, stormwater runoff reduction, building energy savings and avoided carbon emissions, and carbon dioxide sequestration (i-Tree, 2016b). To estimate ecosystem services for an entire city, the tree structure input data are typically obtained from a survey of 200 or more plots, each 0.04 ha in area, which requires approximately 5 person-hours per plot for trained staff (i-Tree, 2016a). While 10 s of cities have invested in these tree structure surveys and the subsequent i-Tree Eco analyses, surveys in megacities have been limited to London, Los Angeles, and New York City, and these analyses did not include their entire metropolitan areas. The preparation, implementation, and post-processing of field surveys for megacities can take months to years and 10 s to 100 s of thousands of dollars, limiting the implementation of such surveys for the 40 megacities known to exist worldwide.

A more rapid, lower cost approach is needed to obtain estimates of tree cover and associated ecosystem services in megacities. One approach is to start with the i-Tree Canopy tool, which provides a relatively rapid estimate of canopy cover without the need for field based plot surveys (i-Tree, 2011). The i-Tree Canopy tool uses human photo-interpretation of land cover captured in Google Earth aerial photography to determine percent tree canopy cover, which is the projected area of canopy on the surface, and is typically larger than the tree stem area. The accuracy of tree canopy estimates by human photo-interpretation have been shown to be higher than multi-spectral auto-classification, which tends to underestimate urban tree cover (Greenfield et al., 2009). The i-Tree Canopy tool can use tree canopy cover to generate estimates of ecosystem services, based on accessing a database of per canopy cover benefits generated by prior i-Tree Eco simulations in representative cities; the cities are representative based on vegetation, air pollution levels, weather, building energy usage, and human population. The i-Tree Canopy database of ecosystem services is only provided for US cities. In this manuscript we develop scaling equations that convert i-Tree Canopy estimates of canopy cover in international megacities to access i-Tree Eco estimates of ecosystem services.

Inherent in an accounting of nature across a set of megacities is that the investigated cities are located in very different geographical and climatic areas, with different characteristics spanning from concentration and typology of pollutants, tree species and growth rate, population density, season cycling, among others. Further, such a wide study will encounter data that are applicable to some cities but may not fully fit other ones. However, the methods used for such a study of ecosystem service benefits are able to provide at least a reliable estimate of the extent managing urban forests may provide wellbeing and economic benefits; moreover, the methods are such that they can easily be improved when new data become available. As stated above, implementing detailed ecosystem inventories and modeling is costly and urban administrations are reluctant to invest in something that does not seem to be directly linked to the urban daily life. This study aims to contribute to the awareness that managing urban forests is a way to provide wellbeing and economic benefits, as other kinds of investments in productive sectors do. New and more accurate estimates may emerge as a follow up of this study.

2. Methods

We selected ten megacities for the inventory of tree cover and estimation of the associated value in ecosystem services. The megacities were: Beijing, China; Buenos Aires, Argentina; Cairo, Egypt; Istanbul, Turkey; London; Great Britain; Los Angeles, United States; Mexico City, Mexico; Moscow, Russia; Mumbai, India; Tokyo, Japan. These megacities are distributed across five continents, and represent five different biomes. The biomes were defined by megacity annual average precipitation, maximum and minimum average temperatures, and their native vegetation density and types. The human population and area of each megacity (Table 1) was defined based on a combination of functional and physical definitions of the city, extending beyond the core area and political boundary to include the greater or metropolitan area, using

Table 2
Value per unit tree-based ecosystem service, for London, UK, in purchasing power parity adjusted dollars.

Value	Ecosystem Service from Tree
$1,238.03	/metric ton of CO removed
$8,718.32	/metric ton O_3 removed
$86,281.68	/metric ton NO_2 removed
$2,180.91	/metric ton SO_2 removed
$238,320.66	/metric ton PM2.5 removed
$9,992.41	/metric ton PM10 removed
$1.08	/m^3 Stormwater avoided
$199.26	/kWh Electricity avoided
$18.78	/Mbtu Energy avoided
$0.08	/kg CO_2 sequestered

the most recent census data compiled in a 2015 global database (Demographia, 2015). The megacity metropolitan area was delineated by Natural Earth polygon boundary files that extended to the edge of remotely sensed intensive land use, sampled by the moderate-resolution imaging spectroradiometer (Schneider et al., 2010). In cases where the boundary polygon excluded an internal polygon of low density land use, called a donut-hole, the internal polygon was removed to include that area as influencing the megacity.

The i-Tree Canopy model was used as a supervised classification tool to obtain a detailed inventory of land cover types within the 10 megacities, sampling within the Natural Earth polygon file. The i-Tree Canopy photo-interpretation automatically retrieves the most recent aerial imagery and for our study used 2016 Digital Globe aerial imagery for all cities except London, which used October 2015 data, at approximately 0.30 m resolution. For each megacity, 500 points were randomly selected for survey, and categorized as tree canopy, potential tree canopy, or another class such as herbaceous, shrub, agricultural, water, impervious and pervious areas with no potential for tree canopy. The potential tree canopy was defined as impervious or pervious sidewalks, parking lots, and plaza areas, where the canopy would extend above the human occupied pedestrian or parking area, and the stem would be positioned to allow for pedestrian passage or parking; herbaceous park areas were not identified for planting. Standard error, *SE*, was calculated to quantify the uncertainty in the i-Tree Canopy land cover classification, with *SE* calculation based on the number of points, n, in a land cover category. In cases when $n < 10$, $SE = \sqrt{n}/N$, where N is the total number of survey points, e.g., 500, and when $n \geq 10$ $SE = \sqrt{(p \cdot q)/N}$, where $p = n/N$ and $q = 1 - p$; for all tree cover and potential tree cover counts, $n > 10$.

We then used a detailed i-Tree Eco study from London, UK that simulated the mechanistic relationship between forest structure and ecosystem services. The i-Tree Eco London study invested several months into an urban forest inventory of the greater London area, using 724 plots of 0.04 ha, which included species and size distribution data (Rogers et al., 2015). The survey determined the London tree size distribution, measured as diameter at breast height (DBH), approximated the ideal distribution of a managed urban forest, with 75% smaller than 30 cm DBH, 15% between 30 and 45 cm DBH, and 10% larger than 45 cm (Rogers et al., 2015). The London i-Tree Eco study determined a unit benefit value for air pollutant removal (e.g., \$/ton), stormwater treatment avoidance (e.g., \$/m^3), energy conservation (e.g., \$/kWh), and carbon sequestration (e.g., \$/kg) that could be associated with services provided by trees (Table 2). The i-Tree Eco model was run with these benefit values, local pollution data, weather data, and the tree data, to estimate the total benefit of trees on reductions in air pollution, stormwater runoff, energy use, and carbon sequestration. The results are referred to as i-Tree Eco London estimates of ecosystem services.

Within megacity scaling was performed for London to scale London i-Tree Eco estimates of ecosystem services to i-Tree Canopy estimates of ecosystem services. The within megacity scaling was based on differences in tree canopy cover area, human population size, and city area between the two studies. In The i-Tree Eco estimated tree cover at 223 km^2 in the 1594 km^2 surveyed area (Rogers et al., 2015), which was considered the greater London area and based on 2015 census data was estimated to have a population of 8.5E + 06 people (Wikipedia, 2016). Our i-Tree Canopy photo-interpretation estimated tree canopy cover at 593 km^2 for the 2906 km^2 metropolitan London area, with an estimated metropolitan population of 10.2E + 06 people (Wikipedia, 2016).

The load of air pollution removed was scaled as,

$$L^{L}_{AirP} = L^{L\_Eco}_{AirP} \cdot \frac{A^{L}_{Tree}}{A^{L\_Eco}_{Tree}} \tag{1}$$

where superscript L = our London megacity value, and superscript L_Eco = London i-Tree Eco value, L_{AirP} = load of air pollution removed (kg) for pollutants of CO (carbon monoxide), O_3 (ozone), NO_2 (nitrous dioxide), SO_2 (sulfur dioxide), PM10 (particulate matter of 10 μm or smaller), PM2.5 (particulate matter of 2.5 μm or smaller), and A_{Tree} = tree canopy area (km^2). This load based scaling relationship was only applied in London, with all other megacities using local air pollution monitor data to scale the air pollution load. The load of air pollution removed was converted to a price benefit value,

$$P^{L}_{AirP} = P^{L\_Eco}_{AirP} \cdot \frac{L^{L}_{AirP}}{L^{L\_Eco}_{AirP}} \cdot \frac{N^{L}_{Pop}}{N^{L\_Eco}_{Pop}} \tag{2}$$

where P_{AirP} is price of benefit value for air pollution removed, N_{Pop} is number of people in population for megacity area. This scaling relationship assumed the benefit value is related to changes in load of air pollution removed and population exposed to air pollution, which varied between the i-Tree Eco and i-Tree Canopy London studies due to different sample areas.

The volume of stormwater avoided at wastewater plants due to tree canopy interception was scaled as,

$$V^{L}_{Water} = V^{L\_Eco}_{Water} \cdot \frac{A^{L}_{Tree}}{A^{L\_Eco}_{Tree}} \tag{3}$$

where V_{Water} is stormwater volume avoided (m^3). The volume of stormwater avoided was converted to a price benefit value,

$$P^{L}_{Water} = P^{L\_Eco}_{Water} \cdot \frac{V^{L}_{Water}}{V^{L\_Eco}_{Water}} \cdot \frac{N^{L}_{Pop}}{N^{L\_Eco}_{Pop}} \tag{4}$$

which assumed the benefit value is related to changes in volume of stormwater avoided and population exposed to stormwater. The load and price benefit value of carbon dioxide sequestered per year in trees, L_{CO_2} and P_{CO_2}, were scaled as,

$$L^{L}_{CO_2} = L^{L\_Eco}_{CO_2} \cdot \frac{A^{L}_{Tree}}{A^{L\_Eco}_{Tree}} \tag{5}$$

$$P^{L}_{CO_2} = P^{L\_Eco}_{CO_2} \cdot \frac{L^{L}_{CO_2}}{L^{L\_Eco}_{CO_2}} \tag{6}$$

which assumed that CO_2 concentration, uptake rate, and value per unit uptake were identical between the two studies and these values were only controlled by differences in tree canopy cover. The energy saved for buildings by tree canopy cover, P_{Energy}, was scaled as,

$$P^{L}_{Energy} = P^{L\_Eco}_{Energy} \cdot \frac{A^{L}_{Tree}}{A^{L\_Eco}_{Tree}} \cdot \frac{N^{L}_{Pop}}{N^{L\_Eco}_{Pop}} \tag{7}$$

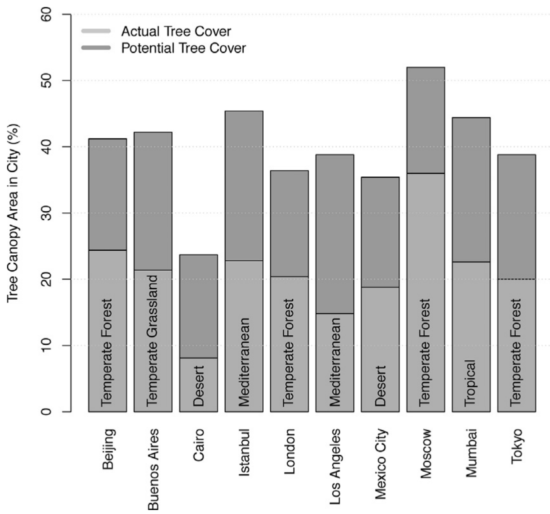

Fig. 1. Tree canopy area (%) in each megacity, showing existing cover and potential cover in a stacked bar, noting the biome type for each megacity.

which assumed that savings were determined by differences in tree cover as well as by building energy use, and that use was controlled by differences in human population. The carbon emissions during energy production avoided due to building energy efficiency, $P_{Emissions}$, was scaled as,

$$P^{L}_{Emissions} = P^{L\_Eco}_{Emissions} \cdot \frac{A^{L}_{Tree}}{A^{L\_Eco}_{Tree}} \cdot \frac{N^{L}_{Pop}}{N^{L\_Eco}_{Pop}} \quad (8)$$

which made the same scaling relationship as in Eq. (7), noting the influence of tree canopy and human population driving energy production demand.

Between megacity scaling was performed between London and all other megacities to obtain i-Tree Canopy estimates of ecosystem services. The between megacity scaling was based on annual average differences in biophysical data such as measured air pollution, weather, energy use, tree canopy cover area, human population size, and city area (Table 1). The London i-Tree Canopy estimates for ecosystem services were generated by Eqs. (1)–(8). The megacity estimate of annual average air quality data for total suspended particulates (TSP), sulfor dioxide (SO_2), and nitrous dioxide (NO_2), were provided by Gurjar et al. (2008), and were considered the best available data for inter-comparisons between megacities. Air quality data from Gurjar et al. (2008) were missing for Mumbai and Istanbul, so these values were set equal to values for Delhi and Karachi, respectively, based the World Health Organization (WHO) 1992 air quality database (WHO, 1992). The WHO 1992 database reported that Karachi and Istanbul had comparable air quality, and Delhi and Mumbai had comparable air quality; unfortunately this WHO 1992 report remains one fo the most recent cross-comparison databases. Precipitation and electricity and energy use in buildings data were obtained from Kennedy et al. (2015). All monetary values were converted to US dollars using World Bank 2014 purchasing power parity (PPP) values (http://data.worldbank.org/indicator/PA.NUS.PPP) to account for healthcare and other cost differences; for London the PPP was \$1.43 per British Pound. The i-Tree Canopy survey provided distinct estimates of tree canopy area for each megacity. The distribution of tree sizes within each megacity were not measured, but were assumed to be equivalent with London and the ideal for a managed urban forest. This assumption was based on the London size distribution approximating the ideal size distribution of an urban forest, with a greater number of young small trees that will steadily diminish due to mortality as they grow into mature larger trees (Rogers et al., 2015).

The mass of air pollution removed in each megacity was estimated using a scaling factor based on the ratio of the megacity's air pollution to London's air pollution,

$$L^{M}_{AirP} = L^{L}_{AirP} \cdot \frac{A^{M}_{Tree}}{A^{L}_{Tree}} \cdot \frac{\log\left(C^{M}_{TSP} + C^{M}_{SO_2} + C^{M}_{NO_2}\right)}{\log\left(C^{L}_{TSP} + C^{L}_{SO_2} + C^{L}_{NO_2}\right)} \cdot \frac{N^{M}_{GrowDay}}{N^{L}_{GrowDay}} \cdot \frac{F^{M}_{Inversion}}{F^{L}_{Inversion}} \quad (9)$$

where the superscript M = the megacity value, L = the London value estimated in Eqs. (1)–(8), C_{TSP} = the air pollution concentration for total suspended particles ($\mu g/m^3$), C_{SO_2} = the air pollution concentration for sulfur dioxide ($\mu g/m^3$), C_{NO_2} = the air pollution concentration for nitrogen dioxide ($\mu g/m^3$), $N_{GrowDay}$ = the growing season (days), and $F_{Inversion}$ = a function for inversion strength relative to London, taking values of 1 or 1,1, where 1 is same strength as London. While C_{TSP} is not a surrogate for PM 2.5, it was used in this study as the only available air pollutant data for particulate matter. The megacity air pollution concentration, growing season, and inversion strength values were obtained from Table 1. The difference between each megacity and London for the load of air pollution removed was assumed to scale with city specific values of: tree canopy, which absorbs pollutants; air pollution concentrations, which were log transformed to reduce the magnitude of differences; the growing season, which regulates the fraction of the year where tree-based removal is active; and the inversion strength, which affects the pollutant concentration vertical distribution in the atmosphere. The price benefit value of air pollution removed scaled as,

$$P^{M}_{AirP} = P^{L}_{AirP} \cdot \frac{L^{M}_{AirP}}{L^{L}_{AirP}} \cdot \frac{N^{M}_{Pop}}{N^{L}_{Pop}} \quad (10)$$

which assumed the value was controlled by load of air pollution removed and human population exposed to air pollution, and did not consider harder to measure influences such as population behavior (e.g., respiratory air pollution masks) and vulnerability (e.g., population demographics, genetics).

The mass of volume of stormwater avoided scaled between London and other megacities in the i-Tree Canopy study as,

$$V^{M}_{Water} = V^{L}_{Water} \cdot \frac{A^{M}_{Tree}}{A^{L}_{Tree}} \cdot \frac{D^{M}_{Ppt}}{D^{L}_{Ppt}} \quad (11)$$

where D_{Ppt} = depth of annual average precipitation (mm), from Table 1. This scaling relationship assumed the stormwater avoided volume is controlled by the differences in tree cover and precipitation between megacities. The price benefit value of stormwater avoided was scaled as,

$$P^{M}_{Water} = P^{L}_{Water} \cdot \frac{V^{M}_{Water}}{V^{L}_{Water}} \cdot \frac{N^{L}_{Pop}}{N^{L\_Eco}_{Pop}} \quad (12)$$

which assumed the scaling relationship was controlled by stormwater avoided volumetric differences and human population exposed to avoided stormwater, and did not consider harder to measure influences such as differences in stormwater discharge locations or stormwater conveyance technologies. The load and price benefit value of CO_2 sequestered in urban trees were scaled as,

$$L^{M}_{CO_2} = L^{L}_{CO_2} \cdot \frac{A^{M}_{Tree}}{A^{L}_{Tree}} \cdot \frac{N^{M}_{GrowDay}}{N^{L}_{GrowDay}} \quad (13)$$

$$P^{M}_{CO_2} = P^{L}_{CO_2} \cdot \frac{L^{M}_{CO_2}}{L^{L}_{CO_2}} \quad (14)$$

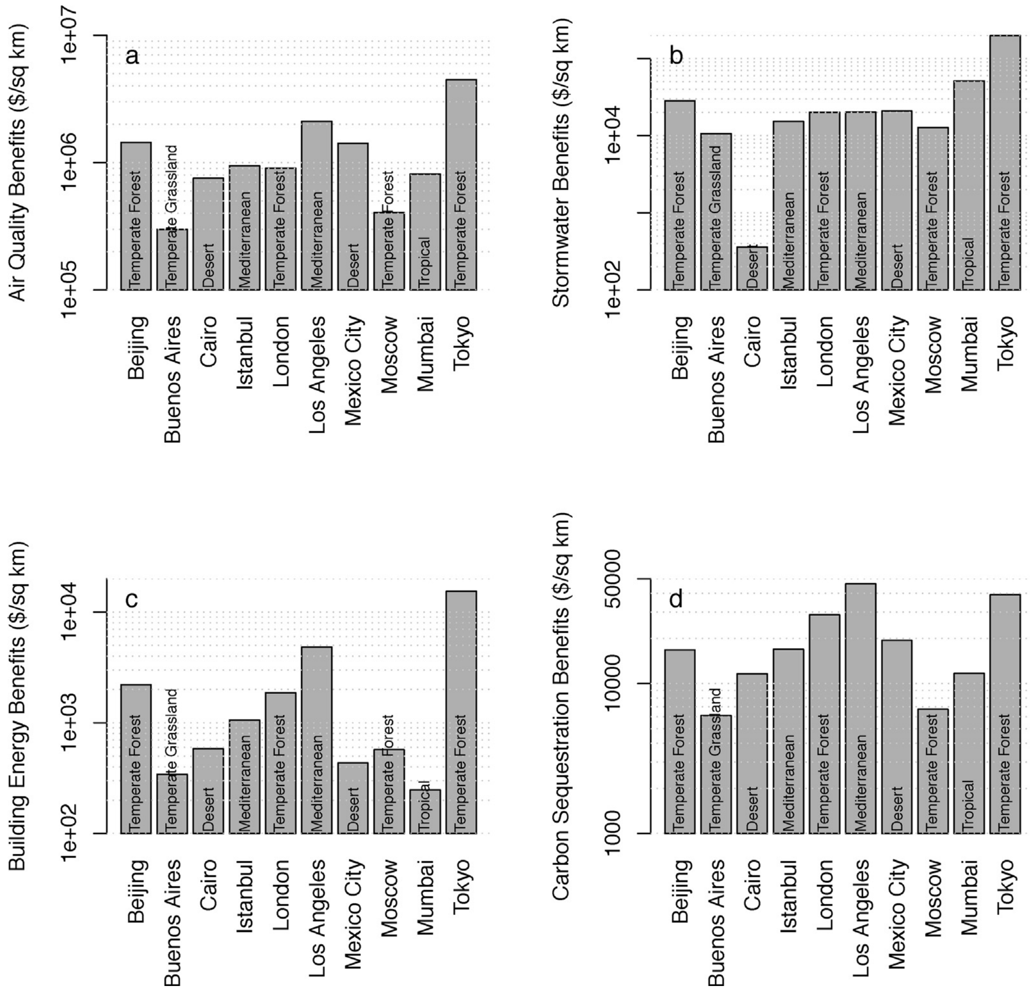

Fig. 2. **a.** Tree based air quality benefits normalized for tree canopy area in each megacity, noting the biome type for each megacity. **b.** Tree based stormwater avoided benefits normalized for tree canopy area, noting the biome type for each megacity. **c.** Tree based building energy saving benefits normalized for tree canopy area, noting the biome type for each megacity. **d.** Tree based carbon sequestration benefits normalized for tree canopy area, noting the biome type for each megacity.

which assumed the sequestration load scaling relationship was controlled by differences in tree cover and growing season. The building energy use price benefit value was scaled as,

$$P^{M}_{Energy} = P^{L}_{Energy} \cdot \frac{A^{M}_{Tree}}{A^{L}_{Tree}} \cdot \frac{N^{M}_{Pop}}{N^{L}_{Pop}} \cdot \frac{N^{M}_{GrowDay}}{N^{L}_{GrowDay}} \cdot \frac{W^{M}_{Electricity}}{W^{L}_{Electricity}} \quad (15)$$

where $W_{Electricity}$ is the gigawatt hours of electricity use for the megacity, from Table 1. This equation assumed the scaling relationship was controlled by differences in tree cover, human population size using the buildings, growing season, and building electricity usage in the city. The growing season was included to capture the influence of daylight and temperature on electricity for lighting and electric heating and cooling. The building avoided CO_2 was scaled as,

$$P^{M}_{Emissions} = P^{L}_{Emissions} \cdot \frac{A^{M}_{Tree}}{A^{L}_{Tree}} \cdot \frac{N^{M}_{Pop}}{N^{L}_{Pop}} \cdot \frac{N^{M}_{GrowDay}}{N^{L}_{GrowDay}} \cdot \frac{J^{M}_{Energy}}{J^{L}_{Energy}} \quad (16)$$

where J_{Energy} is the terajoule of energy use for the megacity, from Table 1. This equation assumed the scaling relationship was controlled differences in tree cover, human population size using the buildings, growing season, and building energy usage in the city. The growing season was included to capture the influence of temperature on energy use for heating and cooling.

The prediction results of Eqs. (9)–(16) were tested with available data. After the tree-based ecosystem services were predicted, their accuracy was examined for the city of Los Angeles, using independent estimates obtained from a 2009 Los Angeles i-Tree Eco model study (Nowak et al., 2010). This comparison was for all services but stormwater avoided, which was not estimated by the 2009 i-Tree Eco study. The predicted values from Eqs. (9)–(16) were also normalized to megacity tree cover area in order to remove the influence of megacity total area on cumulative magnitude of ecosystem services. The megacity areas ranged by an order of magnitude, from the smallest megacity Cairo, at 1173 km^2, to the largest megacity of Tokyo, at 18,720 km^2, with a median megacity area of 2530 km^2. The spatial extent of these metropolitan areas exceeded the municipal political boundaries, in order to capture the functional urban area containing the developed land and associated population connected to the urban center. The large Tokyo area was independently confirmed using Google Earth imagery and measurements.

3. Results and discussion

Existing tree canopy cover based on i-Tree Canopy surveys ranged from 8.1% of metropolitan area, in Cairo, to 36%, in Moscow, with a median value of 20.9% (Fig. 1). This percent urban tree cover is comparable to the 24% tree cover found in an assessment of Canadian urban areas (Pasher et al., 2014). Our tree canopy estimates had a standard error of less than 2%, in keeping with Parmehr et al. (2016) who demonstrated that i-Tree Canopy random point estimates of urban tree cover are highly accurate, and also noted

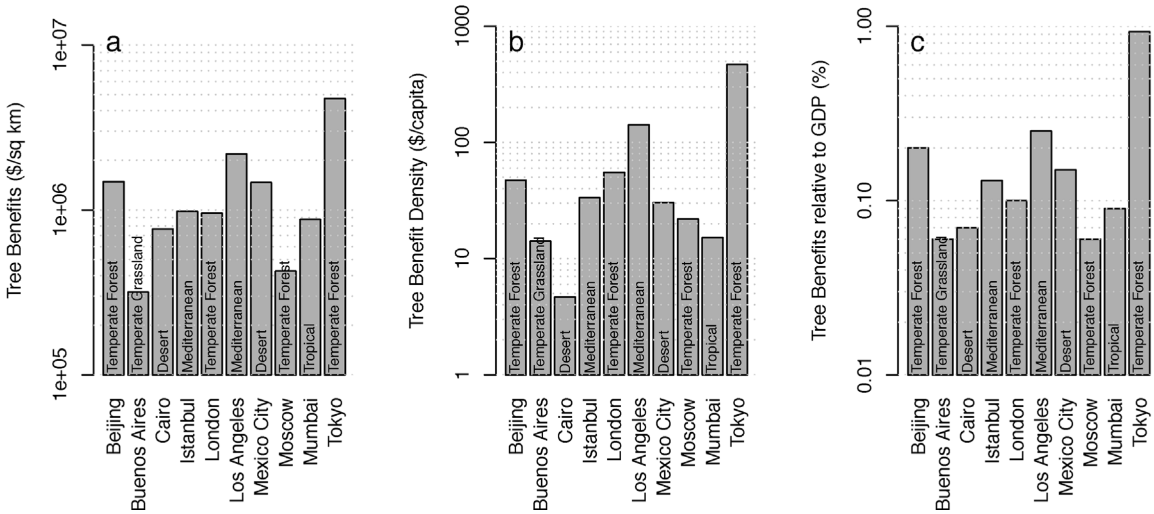

Fig. 3. **a.** Tree based total benefits from air quality, stormwater, building energy, and carbon sequestration ecosystem services in each megacity, normalized for tree canopy area, noting the biome type for each megacity. **b.** Tree based total benefits, per capita, noting the biome type for each megacity. **c.** Tree canopy total benefits as percentage of gross domestic product in each megacity, noting the biome type for each megacity.

they are within 1% of estimates made using Light Detection and Ranging maps of urban tree canopy cover. comparable The potential additional tree canopy cover for the megacities ranged 15.6% of metropolitan area, in Cairo, to 24%, in Los Angeles (which suffered significant forest loss during 2009 forest fires), with a median value of 17.8% (Fig. 1). Planting trees in this potential tree canopy cover area would increase tree cover by 85%, on average. The tree canopy cover per person in the megacity was smallest for Cairo, at 6.1 m^2/capita, largest for Tokyo at 98.9 m^2/capita, and had a median value of 39 m^2/person (Fig. 2). These megacity tree canopy densities are within the same order of magnitude as green space density (e.g., open and park space) estimated for smaller cities in Latin America (255 m^2/capita), Africa (74 m^2/capita), and Asia (39 m^2/capita), as reported in the Green City Index (Economist Intelligence Unit and Siemens, 2012). The megacity median tree canopy density was 2 orders of magnitude smaller than the global average, of 7756 m^2/capita (Crowther et al., 2015). When examined by biome, the tree area as percent of city area and as area per capita, was smallest in the desert biome, and next smallest in the Mediterranean biome, with these biomes perhaps exerting a water availability limitation.

Air pollution reduction benefits of tree cover in megacities had median annual value of $482 million, and when normalized by tree cover area, this median value was $0.93 million/km^2 (Fig. 2**a**). The largest contributor to these air pollution benefits were largest was the $259,000/ton for PM2.5 removal (Table 2), which is supported by research showing PM2.5 exposure is the pollutant most likely to lead to human sickness and death (Pope and Dockery, 2006; Pope et al., 2009). The other air pollutants are of concern, and contribute to the value of trees; O_3 and other air pollutants exert a direct and adverse impact on human health (Cohen et al., 2005; Jerrett et al., 2009). While this research adjusted costs based on purchasing power parity, the healthcare costs were otherwise uniform across all megacities, allowing each person to receive the same value of healthcare. Use of the uniform cost facilitates future conversion of these findings that might account for cost differences between megacities.

Megacity tree cover provided a median annual value of $11.3 million in avoided stormwater processing by wastewater facilities, and when normalized by tree cover area, this median value was $20,000/km^2 (Fig. 2**b**). The lowest benefit value of avoided stormwater was in Cairo, which had the least precipitation (see Table 1). The megacity tree cover provided a median annual value of $1.2 million in building energy heating and cooling savings, and when normalized by tree cover area, this median value was $820/km^2 (Fig. 2**c**), with the lowest benefit in Mumbai due to its low energy expenditures (see Table 1). The megacity tree cover provided a median annual value of $107,000 in avoided carbon emissions. The median annual value of CO_2 sequestered by megacity tree cover was $7.9 million, and when normalized by tree cover area, this median value was $17,000/km^2 (Fig. 2**d**), with the greatest benefit in Los Angeles, due to the long growing season. Integrating across all years of CO_2 storage in the megacity trees, the total CO_2 stored was valued at $242 million. The sum of all annual services provided by the megacity trees had a median annual value of $505 million. These normalized total annual benefits provide a median value of $967,000/km^2 of tree cover (Fig. 3**a**). The benefits of these megacity trees have a median value of $32/capita (Fig. 3**b**), referred to as the tree canopy benefit density, and this is comparable to the $29/capita value estimated for street trees in California (McPherson et al., 2016). The sum of all annual ecosystem service benefits had a median contribution of 0.12% of 2014 megacity gross domestic product, GDP, (Fig. 3**c**) where all values were adjusted for purchasing power parity (Institute, 2014). Examining value as% of GDP allows for cross-comparison of relative impact between megacities.

Estimates of model accuracy are limited to the validation test, where the model estimated ecosystem services were within 2% of the independently generated 2009 i-Tree Eco estimates for Los Angeles for air pollution, CO_2 sequestered, and building avoided CO_2 emissions. The predictive accuracy was judged using the ratio of tree cover in Los Angeles between the two studies, which was 133.7 km^2 in the 2009 i-Tree Eco study, 11.1% of the surveyed area of 1204 km^2 (Nowak et al., 2010), and 13.6% of the value estimated using i-Tree Canopy in our larger metropolitan Los Angeles city area. For air pollution services, the i-Tree Eco study estimated 1.7E + 06 kg/yr of air pollutants removed, which is 12.3% of the removal value we estimated, and within 2% of the 13.6% difference in forest areas. For CO_2 sequestration services, the i-Tree Eco study estimated 6.9E + 07 kg/yr, which is 13.7% of the CO_2 sequestration value we estimated, and within 0.1% of the 13.6% difference in forest areas. For building avoided CO_2 emissions, the i-Tree Eco study estimated $7.3E + 03 per yr, which is 1.3% of the value we estimated, and within 0.6% of the 13.6% difference in forest areas. For the $ values of air pollutant removal, the i-Tree Eco values used $8/kg of removal, which was 10% of the value we used (Table 2), with the differences perhaps attributed to new data on the health costs. The model application was limited to annual average analysis due to the difficulty in obtaining accurate, higher temporal resolution samples, such as annual, seasonal or daily. The next steps in model development should include extended sensitivity tests and model accuracy and uncertainty analysis.

The ecosystem service value of megacity trees is significant. Delphin et al. (2016) have similarly modeled the ecosystem service value for smaller cities, showing how urbanization and tree removal led to a 21% reduction in carbon storage and a 4% loss in stormwater retention. In megacities, the impact of tree services per person will be more significant. Tokyo, the largest city area and largest population, had the largest magnitude of ecosystem service benefits, although it had a percent tree canopy cover equivalent to other megacities. The median value of half a billion dollars per year of ecosystem services provided by these trees is an accounting of how nature improves human livelihoods. The cost of these services does not need to paid in full by their fiscal budgets, but rather is primarily provided using solar radiation as the energy input. If the potential tree cover area were converted to tree canopy, the annual benefits would increase to a total of $1 billion/yr. There are some biophysical limits with urban tree growth, with water and heat in some biomes, such as desert and Mediterranean biomes, constraining tree growth (Allen et al., 2010). There are also trade-offs with tree cover, and as one example deciduous as well as evergreen trees can limit insolation into buildings which in some cases will increase winter heating costs in cold climates (McPherson et al., 1994). Another trade off, although rare, is PM2.5 filtered by trees when the boundary layer height is high can be re-suspended and increase the concentration and human exposure if the boundary layer height becomes very low. A conversation with megacity stakeholders about the benefits, limits, and potential trade-offs of urban trees is a necessary step in developing the management plans to implement the UN Sustainable Development Goals. This will then advance the establishment and conservation of nature in urban areas to improve human livelihoods. The field of ecological engineering intentionally designs connections between human and natural systems in order to benefit both nature and humans. As such this nature conservation plans for urban areas must consider how to improve biodiversity and other nature benefits.

4. Conclusions

This research determined the area in tree canopy cover in 10 megacities and provided a scoping level accounting of the value of these trees in order to contribute to nature conservation planning where it is greatly needed. The research methods adjusted detailed i-Tree Eco model estimates of magnitude and value of tree ecosystem services to the other megacities via scaling relations between pollution, biophysical, and resource flow data. In a validation assessment of the scaling equations, they were found to be within 2% of i-Tree Eco estimates. The accounting considered tree-based reductions in CO, NO_2, SO_2, PM10, and PM2.5, avoided stormwater processing by wastewater facilities, reduced building energy heating and cooling costs, avoided CO_2 emissions, and CO_2 sequestration. The relative area of megacities in tree cover was smallest in desert and Mediterranean biomes, which included Cairo and Istanbul, and was largest in Tokyo, which was also the largest city area. The tree-based ecosystem benefits had a median annual value of $505 million in total benefits, equivalent to $1.2 million/km^2 of trees, or $35/capita for the megacity resident, and 0.12% of the megacity GDP. Megacities can increase these benefits on average by 85% by establishing trees in their potential tree cover area, which would serve to filter the pollutants of urban metabolism, and improve human livelihoods as well as other living members of the urban natural area.

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