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Under one canopy? Assessing the distributional environmental justice implications of street tree benefits in Barcelona

Francesc Baró[a,b,*], Amalia Calderón-Argelich[a], Johannes Langemeyer[a,b], James J.T. Connolly[a,b]

[a] Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Edifici Z (ICTA-ICP), Carrer de les Columnes s/n, Campus de la UAB, 08193 Cerdanyola del Vallès, Spain

[b] Hospital del Mar Medical Research Institute (IMIM), Carrer Doctor Aiguader 88, 08003 Barcelona, Spain

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ABSTRACT

Street trees are an important component of green infrastructure in cities, providing multiple ecosystem services (ES) and hence contributing to urban resilience, sustainability and livability. Still, access to these benefits may display an uneven distribution across the urban fabric, potentially leading to socio-environmental inequalities. Some studies have analyzed the distributional justice implications of street tree spatial patterns, but generally without quantifying the associated ES provision. This research estimated the amount of air purification, runoff mitigation and temperature regulation provided by circa 200,000 street trees in Barcelona, Spain, using the i-Tree Eco tool. Results were aggregated at neighborhood (n = 73) and census tract (n = 1068) levels to detect associations with the distribution of five demographic variables indicating social vulnerability, namely: income, residents from the Global South, residents with low educational attainment, elderly residents, and children. Associations were evaluated using bivariate, multivariate and cluster analyses, including a spatial autoregressive model. Unlike previous studies, we found no evidence of a significant and positive association between the distribution of low income or Global South residents and a lower amount of street tree benefits in Barcelona. Rather, higher ES provision by street trees was associated with certain types of vulnerable populations, especially elderly citizens. Our results also suggest that street trees can play an important redistributive role in relation to the local provision of regulating ES due to the generally uneven and patchy distribution of other urban green infrastructure components such as urban forests, parks or gardens in compact cities such as Barcelona. In the light of these findings, we contend that just green infrastructure planning should carefully consider the distributive implications associated with street tree benefits.

1. Introduction

Cities around the world are facing pressing environmental challenges and climate change-related risks, including air pollution, heat stress and extreme precipitation (Revi et al., 2014; Elmqvist et al., 2018). Moreover, exposure and vulnerability to these environmental burdens and climate hazards are generally unequally distributed across neighborhoods and socioeconomic population groups (see, for instance, Harlan et al., 2006; Moreno-Jiménez et al., 2016; Tonne et al., 2018). The notion of urban environmental justice is hence expanding beyond accessibility to environmental and community resources to include the local experience of climate change and how vulnerable communities can adapt to its impacts (Schlosberg, 2013). In this context, an international call for safer, more inclusive, resilient and sustainable cities was issued by the UN through the Sustainable Development Goal (SDG) eleven[1] in the framework of the 2030 Agenda for Sustainable Development.

Urban green infrastructure (UGI) can play a pivotal role in the achievement of this goal by mitigating environmental burdens, contributing to climate change adaptation, increasing public health and social cohesion, and ultimately, creating more livable cities (Tzoulas et al., 2007; EEA, 2011; EC, 2012; Demuzere et al., 2014). The definition of UGI as a “strategically planned network of green and blue spaces in urban areas, designed and managed to deliver a wide range of ecosystem services (ES) and other benefits at various spatial scales” (Hansen et al., 2017) reflects the idea that different green (and blue) elements, such as urban parks, gardens, green roofs, and street trees, can be part of a multifunctional and interconnected ecological system

* Corresponding author at: Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Edifici Z (ICTA-ICP), Carrer de les Columnes s/n, Campus de la UAB, 08193 Cerdanyola del Vallès, Spain.

E-mail address: francesc.baro@uab.cat (F. Baró).

[1] See https://sustainabledevelopment.un.org/sdg11

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within the urban landscape. But, while city-scale benefits flow from this systemic aspect, the actual provision of many ES depends on being near the area of demand, i.e., where beneficiaries live and spend most of their time (Baró et al., 2016; Kabisch et al., 2016; Larondelle and Lauf, 2016). For instance, city trees regulate temperature and mitigate the urban heat island effect where they directly provide shade, create humidity and block wind (Bowler et al., 2010).

Recent literature has pointed towards a stronger consideration of ES (including potential disservices and trade-offs) within the urban environmental justice framework for better informed decision-making in cities (Ernstson, 2013; Wolch et al., 2014; Marshall and Gonzalez-Meler, 2016). In this paper, we focus on the distributive dimension of urban environmental justice and ES, i.e., who benefits most and who remains excluded from access to the benefits of UGI in cities (Ernstson, 2013; Aragão et al, 2016), and more specifically, on the socio-spatial inequalities related to the provision of regulating ES by street trees.

Street trees are a critical component of UGI, providing multiple ES such as runoff control, temperature regulation, air purification, noise reduction and habitat for biodiversity, among others (Bowler et al., 2010; Soares et al., 2011; Gillner et al., 2015; Livesley et al., 2016; Salmond et al., 2016; Willis and Petrokofsky, 2017). Street trees can also provide socio-cultural benefits by contributing to the physical and mental health of citizens, improving cognitive development and favoring a sense of belonging and aesthetic appreciation (Roy et al., 2012; Fisher et al., 2015; Nesbitt et al., 2017). An important characteristic of street trees is their integration with cities' grey infrastructure, namely the transport network. This is particularly important in compact cities, where the availability of land for the implementation of larger UGI components such as parks or gardens is generally limited (Jim, 2004; Artmann et al., 2017). However, street trees are often overlooked in urban ES assessments, as these tend to focus on other UGI components with a more defined spatial delimitation and associated land use (Luederitz et al., 2015).

Several authors have analyzed urban trees' distribution from an environmental justice perspective, mostly in the US context, with results generally indicating spatial inequities associated with residential segregation by factors such as race/ethnicity, education level, homeownership, and income (Heynen et al., 2006; Landry and Chakraborty, 2009; Danford et al., 2014; Duncan et al., 2014; Schwarz et al., 2015; Pham et al., 2017). However, few have explicitly considered the ES provided by trees (but see Flocks et al., 2011 and Escobedo et al., 2015) and their role in terms of environmental (in)equalities considering the overall UGI distribution across the urban fabric, especially in highly compact cities. The consideration of the pattern of urban tree ES, rather than simple tree distribution, is relevant in this context since ES provision can substantially vary across tree species and tree structural traits (Graça et al., 2017; Vogt et al., 2017).

Given the trajectory of the literature on urban tree distribution, the main goal of this study is to analyze the spatial pattern of ES provided by street trees in a highly compact city and to understand their role in terms of distributional environmental justice. The specific objectives are the following: 1) to quantify three locally relevant regulating ES provided by a complete inventory of street trees, namely: air purification, runoff mitigation and urban temperature regulation (following the nomenclature of urban ES by Gómez-Baggethun and Barton, 2013); 2) to compare the spatial distribution of these three ES in relation to five socio-demographic variables indicating vulnerability, namely: income, residents from the Global South, residents with low educational attainment, elderly and children residents; and 3) to assess the role of street trees in terms of ES inequalities considering the overall UGI distribution across the case study area. The municipality of Barcelona (Spain) was selected as case study due to the high compactness of its urban fabric and the availability of a large and up-to-date inventory of street trees.

2. Material and methods

2.1. Description of the case study area and street tree data

Barcelona, located in the North-East part of the Iberian Peninsula on the Mediterranean Sea, is the second largest city in Spain. The municipality covers a total area of 10,216 ha with a population of 1.62 million inhabitants (Barcelona City Council Statistical Yearbook, 2018). Due to its compactness and population density (greater than 400 inhabitants per ha in some neighborhoods), Barcelona has a low ratio of green space coverage per capita compared to other large European cities (Fuller and Gaston, 2009), namely 7.0 m^2 of public green space area per inhabitant, increasing to 17.6 m^2 if the periurban natural park of Collserola is considered (Barcelona City Council Statistical Yearbook, 2018). However, these figures do not include the high ratio of street trees in Barcelona (> 120 trees per 1000 inhabitants) compared to the average range of 50–80 trees per 1000 inhabitants in other European cities (Pauleit et al., 2002).

The complete inventory of Barcelona street trees was retrieved in April 2018 from the municipal open data portal[2] . The database considers trees and palm trees located on streets, squares and promenades (but excludes trees in parks and other green spaces). It contained information on 201,226 street trees, including geographic coordinates, species name, and several structural and tree-condition variables such as total tree height or tree vitality (Fig. 1). Among the circa 300 different tree species included in the inventory, the four most abundant (> 5% of all specimens) are *Platanus x acerifolia* (23.2%), *Celtis australis* (10.5%), *Sophora japonica* (5.3%) and *Tipuana tipu* (5.2%). Street trees show a widespread though uneven distribution across the urban fabric (Fig. 1).

The Master Plan for Barcelona's Trees 2017–2037 (Barcelona City Council, 2017a) aims to increase the city's tree cover by 5% before 2037 and maximize its ES provision in terms of environmental, social and economic benefits. It seeks, as well, to ensure that a substantial share of tree species (at least 40%) are adapted to future climate changes. However, there is no explicit reference to distributional nor procedural justice aspects in any of the 10 strategic lines and 50 actions proposed in the Plan. This remains a blindspot in the City's strategy for urban trees and points toward the urgency of our study. Further, Barcelona has recently developed an ambitious climate action plan for the period 2018–2030 (Barcelona City Council, 2018) which includes a flagship adaptation measure based on UGI: increasing urban green space by 1 m^2 per inhabitant (i.e., 1.6 km^2 in total). The Plan identifies four main climate change challenges for the city: rising temperatures, reduced availability of water, increased flooding, and shrinking beaches due to sea level rise. Moreover, Barcelona has faced serious air quality problems in recent decades, mostly due to exceeding nitrogen dioxide and particulate matter levels from traffic emissions (Moreno-Jiménez et al., 2016).

2.2. Selection and quantification of ecosystem services

The three ES quantified in this study were selected due to their potential contribution to mitigate the above-mentioned local urban environmental and climate threats for Barcelona, namely air pollution, heat stress (including heatwaves) and stormwater runoff (including flooding) at the neighborhood or smaller spatial scale (Demuzere et al., 2014; Marshall and Gonzalez-Meler, 2016). These three ES are classified as "*in situ*" or "*local proximal*" because their benefits are realized in the same location of provision or their immediate surroundings (Costanza, 2008; Fisher et al., 2009) and hence are among the most relevant in terms of urban distributional justice. Other regulating ES provided by street trees, such as carbon sequestration, were not

[2] See http://opendata-ajuntament.barcelona.cat/

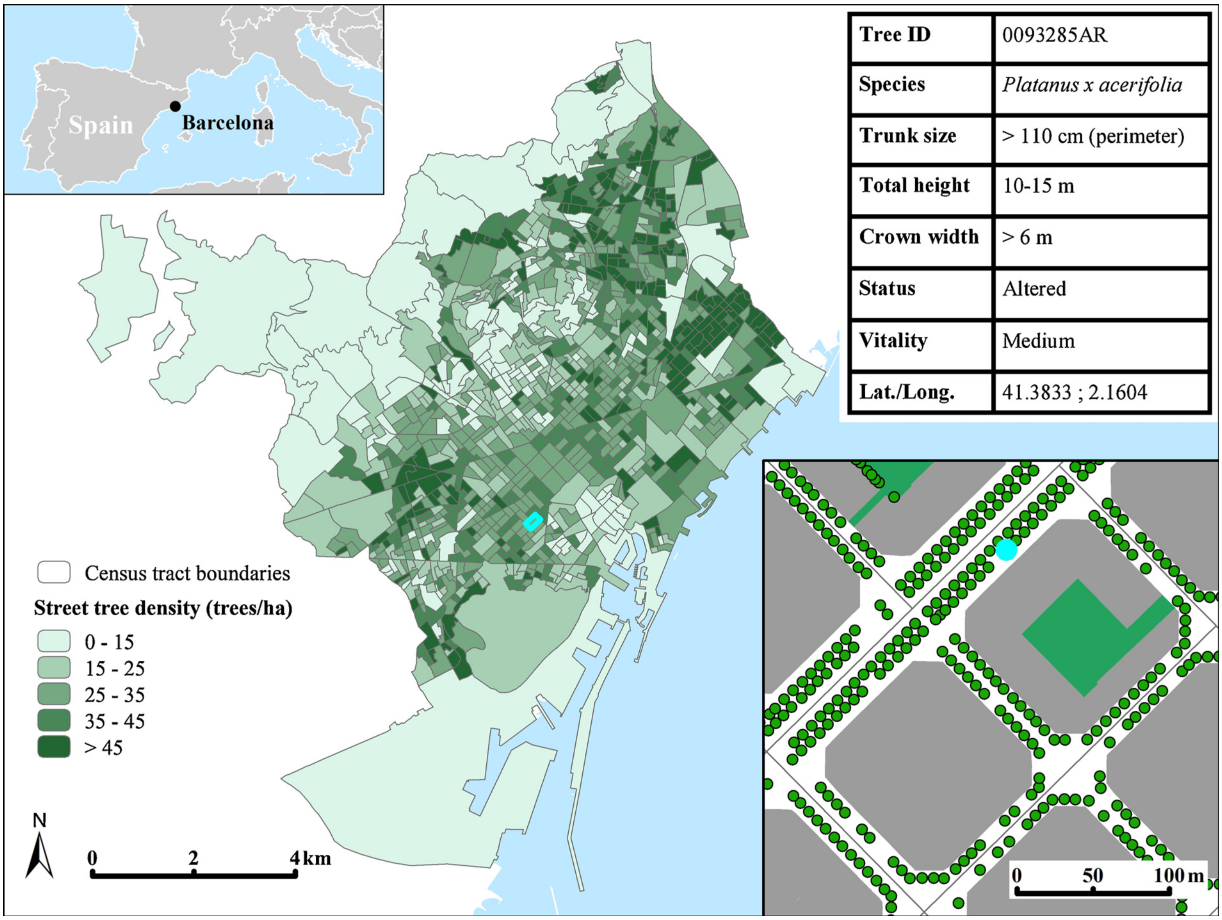

Fig. 1. Barcelona municipality displaying street tree density at the census tract level. The zoom-in map corresponds to the census tract highlighted in turquoise color in the city map (each green dot represents a street tree). The table with tree data corresponds to the street tree highlighted in turquoise color. Source: own elaboration based on Barcelona City Council datasets.

considered in the assessment because their benefits and distributional justice implications only make sense at larger spatial scales (Syrbe and Walz, 2012).

ES indicators were quantified using i-Tree Eco (version 6)[3] . This tool contains various process-based models that estimate several ES provided by UGI (Nowak et al., 2008). Despite being originally developed for the US context, i-Tree Eco has been adapted to support non-US cases (e.g. Selmi et al., 2016; Graça et al., 2017). An i-Tree Eco assessment of a complete tree inventory requires individual tree data comprising at least scientific species name, diameter at breast height (DBH), total tree height, crown size and crown health (% missing and % dieback) and geographic coordinates. From the inventory of Barcelona (originally containing 201,226 street trees) some trees were discarded due to missing location (357), species name (85), or because they were registered as stubs, empty tree pits or trees to be removed (5387), resulting in a total of 195,397 street trees assessed. Furthermore, the inventory did not contain the exact measurement of the required structural variables, thus several assumptions were made following recommendations of four street tree managers from the City Council (see **Tables A1, A2** and **A3** in Appendix A for all the estimates). As additional input to the model, local hourly precipitation (in m) and air pollution data (in µg/m^3) were collected from official public sources (Meteorological Service of Catalonia and Public Health Agency of Barcelona respectively). Due to limitations of i-Tree Eco, pollutant concentrations and precipitation had to correspond to 2015 as most recent year and be derived from one single station or aggregated values from several stations. Therefore, average values were calculated from seven air quality monitoring stations and three meteorological stations respectively in order to consider the heterogeneity of pollutant concentrations and precipitation across the urban fabric. Air pollutants processed by i-Tree Eco include: nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ground-level ozone (O_3), carbon monoxide (CO) and particulate matter of less than 2.5 µm ($PM_{2.5}$).

Indicators defined by i-Tree Eco to quantify the three ES are presented in Table 1. Air purification is estimated from dry deposition of air pollutants (see Nowak et al., 2008 for more details). Runoff mitigation is estimated as the avoided runoff considering rainfall infiltration, evaporation and water intercepted by the tree canopy (USDA Forest Service, 2018). Urban temperature regulation is estimated considering tree transpiration as a proxy indicator due to its cooling effect on air temperature (Bowler et al., 2010). Furthermore, an aggregated ES index value was created to show the ES performance of each tree in a single metric. To this end, the indicators were normalized in a 0–100 range using minimum and maximum values and then aggregated by a non-weighted linear summation. The resulting value was also rescaled in a 0–100 range.

All the indicators and the ES index were estimated at the individual tree level and also aggregated at the census tract (n = 1068), neighborhood (n = 73) and district (n = 10) levels for the sake of results visualization and to allow the statistical analyses with the socio-demographic variables.

[3] See https://www.itreetools.org/

Table 1
ES indicators quantified by i-Tree Eco and ES index considered in the assessment of street trees.

ES	Indicators	Unit
Air purification	Pollution removal, as sum of: NO_2 removal SO_2 removal O_3 removal CO removal $PM_{2.5}$ removal	g/ha year
Runoff mitigation	Avoided runoff	m^3/ha year
Urban temperature regulation	Transpiration	m^3/ha year
ES index	Rescaled sum of previous	Value 0 - 100

Table 2
Socio-demographic and UGI indicators considered in the assessment.

Indicators	Unit
Children (residents under 14 years old)	% of total population
Elderly (residents over 65 years old)	% of total population
Income (household disposable income index)	Numerical value where 100 is the city average
Low educational attainment (residents with primary education or no studies)	% of population over 16 years old
Immigrants from the Global South (residents whose nationality is from the Global South)	% of total population
Overall UGI cover (area of canopy cover based on NDVI map)	% of total area

2.3. Selection and spatial distribution of social vulnerability and overall green infrastructure indicators

The selected socio-demographic variables (see Table 2) that indicate vulnerabilities include aspects related to age (children and elders), socioeconomic status (income and level of educational attainment) and risk of social exclusion (immigrants from the Global South). These or similar variables have been used in previous environmental justice assessments in Barcelona (e.g., Moreno-Jiménez et al., 2016; Anguelovski et al., 2018) as they indicate vulnerable social groups which are generally assumed to have higher needs in terms of access to UGI benefits due to exposure to environmental burdens, health status and/or socioeconomic circumstances (e.g., housing condition) (Heynen et al., 2006). All the variables were collected from the Barcelona City Council Statistical Department[4] both at the census tract and neighborhood level (except for the household income index which was only available at the latter level). We used 2015 data as the corresponding year to match with i-Tree Eco results. The household income index is a good indicator of wealth disparities across neighborhoods since it is adjusted based on various socioeconomic variables such as housing prices. The index is given relative to the total mean of Barcelona (for which the value is 100). Following Anguelovski et al. (2018), immigrants from the Global South were identified as those residents whose nationality is from all African, Asian and Latin American countries, except Japan. Despite their broad differences in geographical and social origins, communities from these countries tend to be more segregated than other social groups, and they generally face more adverse socioeconomic and environmental conditions (Anguelovski, 2013; Moreno-Jiménez et al., 2016; Lagonigro et al., 2018). The spatial distribution of all the socio-demographic variables is shown in **Fig. A1** (Appendix A).

In order to assess the role of street trees in terms of ES inequalities considering the overall UGI distribution in Barcelona, we used a publicly available high-resolution map of plant canopy cover based on a Normalized Difference Vegetation Index (NDVI) analysis (see Barcelona Regional, 2015). NDVI is a radiometric measure of greenness (Garbulsky et al., 2011) widely used as a proxy of UGI in urban studies (e.g., Apparicio et al., 2008; Li et al., 2015; Triguero-Mas et al., 2015). Despite having some limitations as a measure of urban vegetation complexity or structure, it currently represents the best high-resolution spatial delimitation of Barcelona's UGI available, as it includes all green spaces and other vegetation (both in public and private land). The spatial distribution of percent canopy cover at the census tract level is shown in **Fig. A2** (Appendix A).

2.4. Statistical analyses

Following the approach of other studies examining the distributional equity of urban trees (Landry and Chakraborty, 2009; Duncan et al., 2014; Schwarz et al., 2015), our data was analyzed using bivariate and multivariate techniques considering the census tract as the unit of analysis (n = 1068). In addition, a cluster analysis (Raudsepp-Hearne et al., 2010) was applied in order to identify groups of neighborhoods (n = 73) with similar socio-demographic characteristics, ES index, and overall UGI cover. As a preliminary step, we also tested the spatial autocorrelation of the variables using Global Moran's I in ArcGIS v. 10 (ESRI). All variables showed a significantly clustered spatial pattern (z-scores > 3; see **Fig. A1** and **Fig. A2** in Appendix A).

As our study variables displayed a non-normal distribution and heteroscedasticity, we first employed non-parametric Spearman correlations for bivariate analysis using RStudio software. As a second step, we used multivariate analysis in order to model the distribution of the street tree ES index (dependent variable) in relation to the socio-demographic variables (independent variables). We compared an ordinary least squares (OLS) linear model, a generalized linear model (GLM) following gamma distribution and a spatial lag model (SLAG), with R squared and Akaike Information Criterion (AIC) values. Spatial autoregressive modeling accounts for the spatial autocorrelation of the variables, addressing the violation of the assumption of independent observations (i.e. uncorrelated errors) generally associated with socio-environmental data (see Anselin and Bera, 1998). We developed our SLAG regression model using the open-source software tool GeoDa (Anselin, 2005) and considering maximum likelihood estimation and a first order Rook contiguity-based spatial weight matrix in order to capture the highly localized clusters of data. The control variable of "percent of street area" was added to regression models to account for the space limitation associated with street tree planting. The variable was derived from a high-resolution land use zoning dataset developed by the Barcelona City Council (year 2016) and available online[5] . The same models were developed using the percent of UGI coverage in each tract as a dependent variable to assess the role of street trees relative to other UGI in terms of socio-environmental inequalities. In the UGI models, "total population density" (inhabitant/ha.) was used as a control variable as one would expect density to limit the capacity for UGI in an area. Finally, we classified neighborhoods into clusters based on similar combinations of street tree ES index, UGI cover and socio-demographic variables using a k-means clustering algorithm contained in R statistical software (R Core Team, 2018). The appropriate number of clusters was determined by interpreting the meaning of different clustering outputs with the support of dendrograms and scree plots. Each cluster was illustrated with the average standardized indicator values shown in star plots and their spatial distribution was mapped using ArcGIS v.10.

3. Results

3.1. Street tree benefits across the urban fabric

Total air purification, runoff mitigation and urban temperature

[4] See http://www.bcn.cat/estadistica/angles/index.htm

[5] See http://w20.bcn.cat/cartobcn/

Table 3
ES values and ES index by district (street trees of the municipality of Barcelona, year 2015). Note: neighborhoods are ranked based on the ES index.

District	Air purification			Runoff mitigation			Urban temp. regulation			ES index
	$kg\ yr^{-1}$	$kg\ yr^{-1}\ ha^{-1}$	$g\ yr^{-1}\ tree^{-1}$	$m^3\ yr^{-1}$	$m^3\ yr^{-1}\ ha^{-1}$	$l\ yr^{-1}\ tree^{-1}$	$m^3\ yr^{-1}$	$m^3\ yr^{-1}\ ha^{-1}$	$l\ yr^{-1}\ tree^{-1}$	Average value
Eixample	4878	6.52	200	9380	12.55	385	146,383	195.79	6014	15.60
Sant Martí	5747	5.46	156	10,735	10.20	292	172,481	163.90	4686	12.04
Sants-Montjuïc	3569	1.56	150	6776	2.95	285	106,883	46.59	4494	11.62
Nou Barris	3140	3.90	147	5836	7.26	274	94,159	117.09	4414	11.33
Les Corts	2273	3.78	134	4253	7.07	251	68,163	113.27	4021	10.34
Ciutat Vella	897	2.05	126	1672	3.83	234	26,911	61.60	3771	9.68
Sant Andreu	2563	3.90	124	4772	7.27	231	76,828	117.02	3726	9.57
Horta-Guinardó	2342	1.96	115	4349	3.64	214	70,204	58.76	3457	8.87
Sarrià-Sant Gervasi	1772	0.88	112	3323	1.65	209	53,124	26.44	3343	8.60
Gràcia	842	2.01	102	1571	3.75	191	25,273	60.38	3073	7.89
Barcelona (total/*avg.)	28,023	*2.74	*143	52,668	*5.16	*270	840,408	*82.26	*4301	*10.55

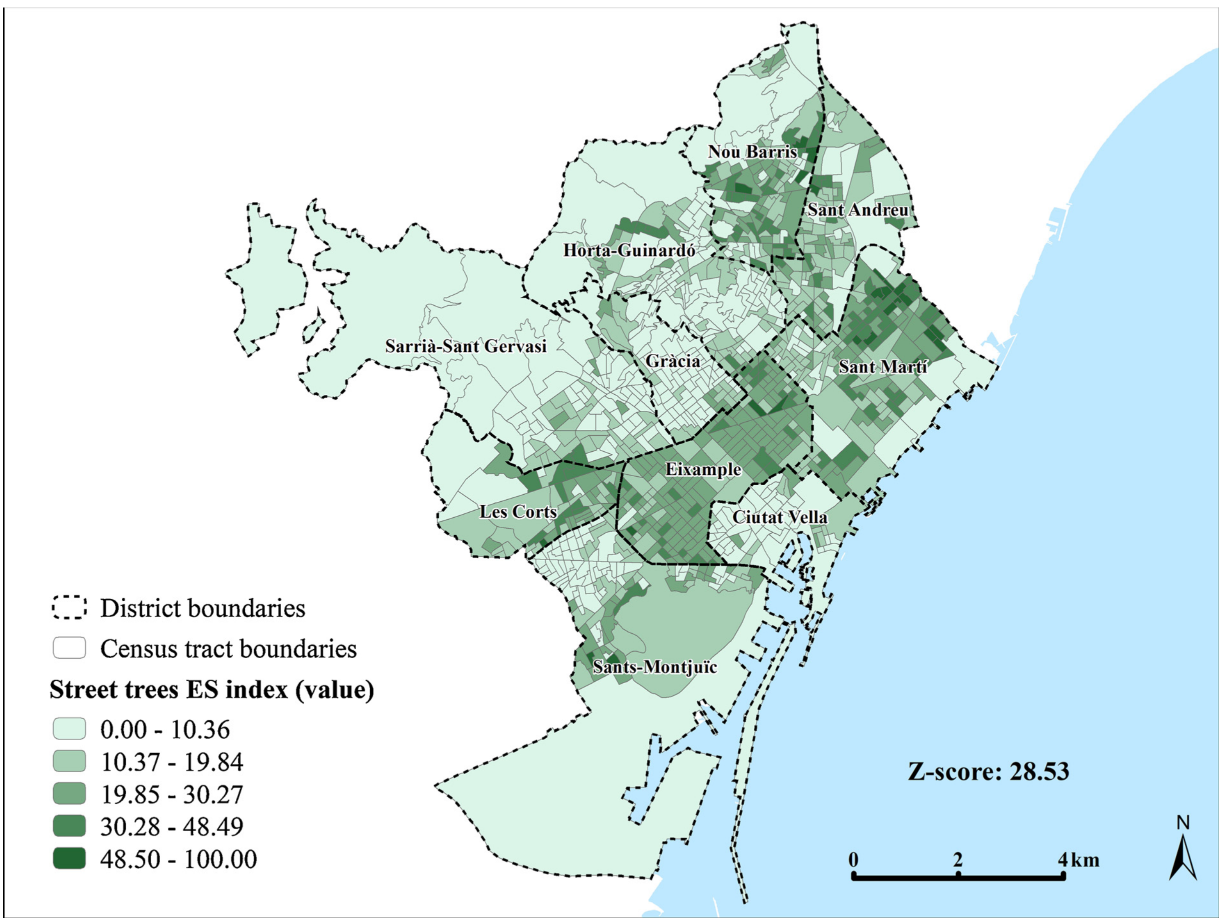

Fig. 2. Spatial patterns of ES index (street trees) at the census tract level. Index values classified using the natural breaks (Jenks) method. The variable is spatially autocorrelated (z-score > 3). Source: own elaboration based on i-Tree Eco results and Barcelona City Council data.

regulation by street trees in Barcelona during 2015 are estimated at 28,023 kg of removed air pollutants, 52,668 m^3 of avoided runoff and 840,408 m^3 of transpired water respectively (see Table 3). Obviously, the spatial patterns of these ES (see **Fig. A3** in Appendix A) largely follow the distribution of street tree density in the city. The dense central district of Eixample and the nearby postindustrial district of Sant Martí (see Fig. 2) prominently show the highest provision of all ES, both in absolute and relative terms (i.e., ES supply normalized by area). On the other hand, the historical districts of Ciutat Vella and Gràcia show the lowest total ES amounts, and the southern and western peripheral areas of Sants-Montjuïc and Sarrià-Sant Gervasi have the lowest values per hectare (see Table 3). In the case of Sants-Montjuïc, this is mainly due to the presence of "Zona Franca" within its boundaries, an almost treeless industrial park of about 600 ha, whereas in the case of Sarrià-Sant Gervasi a large portion of the district is covered by the periurban natural park of Collserola (mostly a forest area, but with few street trees). Interestingly, Eixample and Sant Martí are also the two districts with the highest average ES values per tree. For example, on average a street tree in Eixample almost doubles the amount of air pollutants removed or the runoff avoided relative to a tree in Gràcia (see Table 3). This disparity is also reflected in the ES index average values which are the highest in Eixample (15.60) and Sant Martí (12.04) and lowest in Gràcia (7.89) and Sarrià-Sant Gervasi (8.60). The spatial distribution of street tree ES index is shown in Fig. 2 at the census tract level.

Table 4
Spearman's correlation results between ES index, socio-demographic variables and total UGI cover at the census tract level ($n = 1068$).

	ES index (street trees)	Children	Elderly	Income	Low education	Global South	Total UGI cover
ES index (street trees)	1						
Children	**−0.11	1					
Elderly	**0.18	**−0.27	1				
Income	*−0.07	0.03	−0.04	1			
Low education	0.04	−0.06	0.04	**−0.87	1		
Global South	0.02	**−0.24	**−0.31	**−0.34	**0.46	1	
Total UGI cover	**0.37	**0.17	*0.07	**0.23	**−0.18	**−0.30	1

Note: *p-value < 0.05; **p-value < 0.01.

3.2. Bivariate and multivariate associations

Bivariate analysis (Table 4) reveals that the ES index is strongly positively correlated with elderly residents and moderately negatively correlated with children. The other vulnerability indicators do not show a significant bivariate relationship with street tree ES index. In contrast, the overall UGI cover shows positive and significant relationships with children and income, but a significant negative correlation with residents with low educational attainment and residents from the Global South. The correlation results between socio-demographic variables also show some significant associations. As expected, income is negatively correlated with low educational attainment and residents from the Global South, whereas the relationship between the two latter variables is positive and significant. Elderly population is negatively associated with Global South residents supporting the fact that immigrant residents from these countries are predominantly young (their average age is 32 years according to Barcelona Statistical Yearbook 2018). Finally, children show a significant negative relationship with elderly and Global South residents.

The multivariate regression results (Table 5) show that, when we control for all measured factors (including the added control variables), some of the relationships seen in the bivariate analysis are altered. Diagnostic tests revealed that GLM fits better than OLS with our data and that the SLAG model provides more robust results as evidenced by higher R-square and lower AIC values – as a result, we primarily interpret multivariate relationships based on SLAG results. All models indicate significant and positive associations between the ES index and the age and education attainment variables, but income and Global South do not show clear relationships in the same or opposite direction. The control variable added in the models (percent street area) is, as expected, strongly associated with the street tree ES index. The results of the multivariate analyses using total UGI cover as dependent variable show a different picture. This SLAG model only indicates a positive association with elderly population. In contrast, the OLS and GLM models show significantly positive relationships with all socio-demographic variables except for Global South residents, where only GLM does. This difference indicates that there is a strong spatial lag within the UGI variable, which reduces the strength of linear models that do not account for this lag.

3.3. Cluster analysis outputs

The non-spatial cluster analysis reveals four meaningful groups of neighborhoods ($n = 73$) based on the distributional patterns of the seven variables considered in the study (Fig. 3). All groups are also highly spatially clustered (z-score of Moran's I statistic = 6.82). Cluster 1 includes more than half of the neighborhoods of Barcelona ($n = 40$), mostly from the districts of Eixample, Sant Martí and Nou Barris, among others. This cluster probably reflects the area of the city where the benefits of street trees are more relevant since the ES index mean value is highest, but the overall UGI cover is lowest. Cluster 1 is characterized by intermediate socio-demographic values, but with a high share of elderly residents and a relatively low share of children compared to clusters 2 and 3. Cluster 2 ($n = 13$) clearly contains the neighborhoods of Barcelona with the most vulnerable population in terms of low income, low educational attainment and residents from the Global South. Most of these neighborhoods are located in the district of Nou Barris, a historically deprived area of Barcelona (Anguelovski et al., 2018), but it also includes neighborhoods such as el Raval (Ciutat Vella) and la Marina del Prat Vermell (Sants-Montjuïc) characterized by the highest percent of residents from the Global South and residents with low or no educational attainment respectively. This cluster also shows the second highest mean value for percent of children in the population, but the lowest for elderly. In regard to ES index and overall UGI cover, the cluster shows intermediate values due to the fact that some neighborhoods (mostly in Nou Barris) comprise a high amount of street trees and/or other green spaces (e.g., the urban park of Montjuïc and the periurban park of Collserola, see **Fig. A2** in Appendix A), but others (e.g., el Raval, la Marina del Prat Vermell) stand out for the opposite condition. Cluster 3 ($n = 9$) groups the wealthiest neighborhoods of

Table 5
Ordinary least squares (OLS), generalized linear model (GLM) and spatial lag model (SLAG) results for ES index (street trees) and percent UGI cover as dependent variables at the census tract level ($n = 1068$).

	ES index (street trees)			Total UGI cover		
	OLS	GLM	SLAG	OLS	GLM	SLAG
Children	**0.39	*0.02	*0.24	**0.52	**0.02	0.12
Elderly	**0.41	**0.02	**0.28	*0.19	*0.01	*0.13
Income	0.00	−0.00	0.02	**0.08	**0.00	0.02
Low education	**0.20	*0.01	**0.14	**0.31	**0.01	0.08
Global South	−0.01	−0.00	0.00	−0.13	*−0.01	−0.01
Street area	**0.63	**0.04	**0.37	NA	NA	NA
Population density	NA	NA	NA	**−0.02	**−0.00	**−0.02
Constant	*−21.32*	*0.54*	*−18.78*	*1.91*	*2.22*	*3.81*
R-squared	*0.28*	*0.24*	*0.53*	*0.30*	*0.31*	*0.60*
Lag coeff.	*NA*	*NA*	*0.62*	*NA*	*NA*	*0.66*
AIC	*8082.9*	*7750.9*	*7730.9*	*8105.1*	*7388.7*	*7628.6*

Note: *p-value < 0.05; **p-value < 0.01.

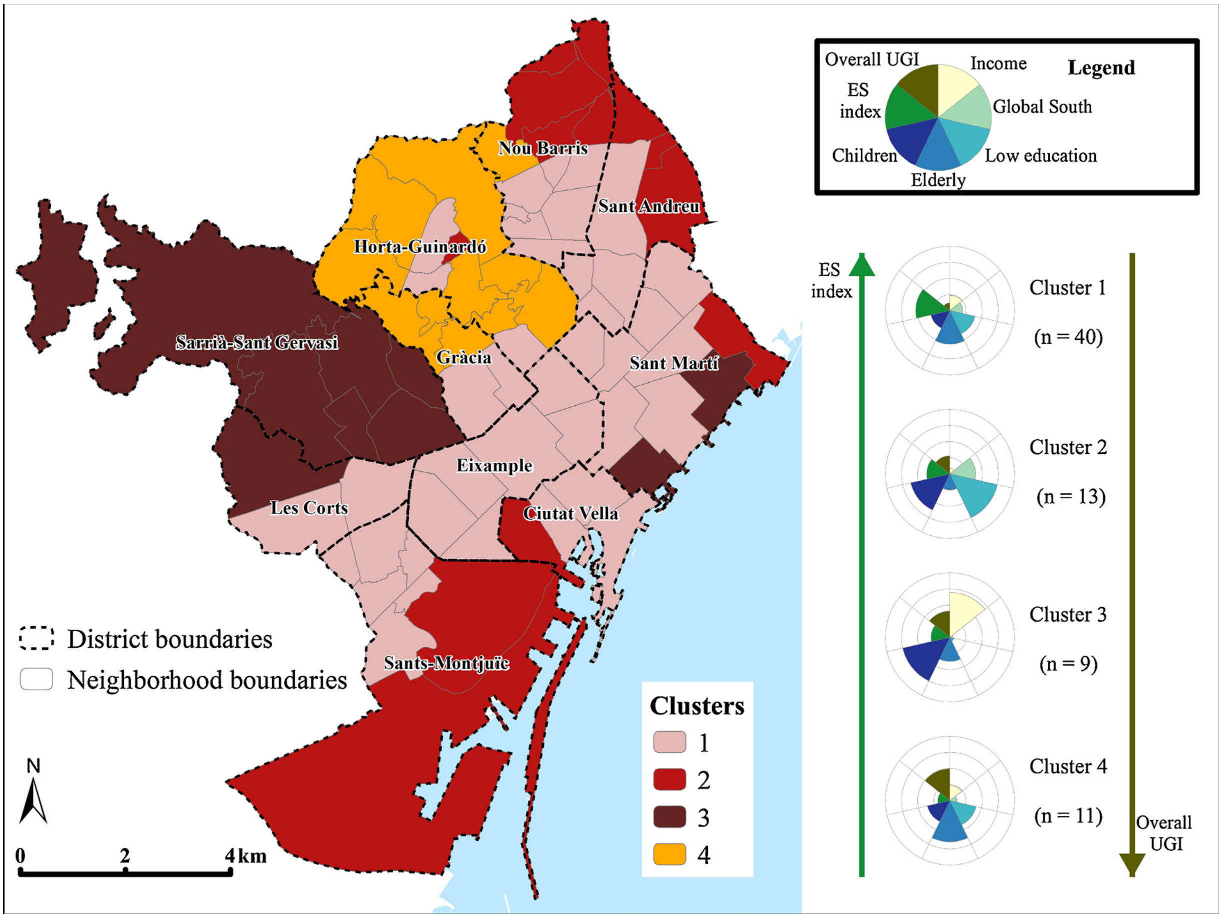

Fig. 3. Spatial distribution of neighborhood clusters and standardized mean indicator values for each cluster (represented in the star plots). The number of neighborhoods per cluster is indicated with *n*. Source: own elaboration based on i-Tree Eco results and Barcelona City Council data.

Barcelona, mainly located in the districts of Sarrià-Sant Gervasi and Les Corts (Fig. 3). This cluster clearly shows the highest mean values in terms of income and the lowest for residents from the Global South and residents with low educational attainment. It is also the cluster with the highest share of percent of children in the population. Interestingly, the cluster displays high values of overall UGI cover due to the large share located in the periurban park of Collserola and also likely due to a high presence of private green space, but a relatively low street tree ES index mean value. Finally, Cluster 4 ($n = 11$) is very similar to cluster 1 in terms of socio-demographic characteristics, but the role of street trees is likely minor because the ES index mean value is lowest and the overall UGI cover is highest. This cluster mostly includes neighborhoods from the districts of Horta-Guinardó and Gràcia, which contain several large green spaces (e.g., Collserola or the urban forest of Tres Turons, see **Fig. A2** in Appendix A), but in some cases also very compact urban forms and narrow streets (especially in Gràcia).

4. Discussion

4.1. The role of street tree benefits in distributional environmental justice

Previous environmental justice studies have called for quantification of the ES provided by urban trees beyond the mere distribution of trees (Schwarz et al., 2015). Our results show that this is a pertinent appeal because the local provision of street tree benefits can be extremely uneven, not only at the single tree level (the most "productive" tree in Barcelona removes almost 290 times more air pollutants or avoids 24 times more runoff than the least productive), but also at the district level (a street tree in Eixample almost doubles, on average, the amount of air pollutants removed or the runoff avoided by a tree in Gràcia, see Table 3). Trees providing more benefits have generally larger DBH, leaf area and crown size and present better health condition according to the i-Tree Eco model outputs.

Our results also indicate that the role of street trees in a highly compact European city such as Barcelona is substantially different in terms of distributional environmental justice than what previous research suggested, especially in comparison with the context of the US. In most of these studies, the findings support the inequity hypothesis, i.e., the proportion of street tree canopy cover is significantly lower in low-income neighborhoods or those with a higher proportion of racial/ethnic minority residents (Landry and Chakraborty, 2009; Flocks et al., 2011; Danford et al., 2014; Schwarz et al., 2015). In Barcelona, we found that the provision of ES by street trees is neither significantly associated with income nor with residents from the Global South. Rather, the spatial regression model reveals a strong positive relationship between the street tree ES index, elderly residents and residents with low educational attainment. This shows that street trees ES do not produce direct inequities for vulnerable populations – the ethnicity and income results are not significant and the elderly and low education results show a tendency toward higher ES Index for these vulnerable groups.

Moreover, cluster analysis shows that the most affluent neighborhoods of the city (and those with a lower proportion of Global South immigrants) generally display intermediate to low ES index values, whereas the most disadvantaged neighborhoods generally show intermediate to high values (with some exceptions such as El Raval in the Old Town). These findings suggest that the reasons usually alleged to explain distributional street tree inequalities might not apply in such a direct way to the case of Barcelona and possibly other similar, compact Southern European cities (see also Graça et al., 2018). Yet, this case does make clear that street tree ES are not evenly distributed and do play an important role in shaping the local environment of vulnerable residents. More empirical research is needed in order to consistently compare the distributional patterns and (in)equalities of street tree benefits across cities and the associated underlying drivers.

The motives that drive street tree inequity in the US cases generally include incentives for wealthy residents (often homeowners) to live in (and lobby for) greener neighborhoods to increase their property values (Landry and Chakraborty, 2009; Schwarz et al., 2015). In contrast, residents in disadvantaged neighborhoods (usually renters) might resist street tree-planting programs because their perceptions of trees mainly focus on potential negative impacts or disservices (e.g., maintenance or nuisance concerns, associated rising rents due to gentrification processes, etc., see Carmichael and McDonough, 2019). Understanding residents' perceptions of street trees in Barcelona goes beyond the scope of this research, however a potential explanation for our results might relate to the fact that, unlike many US cases, UGI is not apparently associated with gentrification in several historically deprived neighborhoods of the city according to a recent assessment by Anguelovski et al. (2018). Moreover, the assumption that wealthy residents are homeowners and poor residents are renters is probably weakly supported in Barcelona because a substantial share of disadvantaged neighborhoods are inhabited by homeowners (Barcelona Metropolitan Housing Observatory, 2019).

Our results also show that percent of street area, added as a control variable in the regression models, plays an essential role in the provision of ES by street trees. This variable, a key aspect of urban form, is highly determined by the distinct historical processes of urban development and expansion in European cities like Barcelona. For instance, the Eixample and Sant Martí districts were largely built following the square-gridded urban form designed by the 19th century urbanist Ildefons Cerdà (Neuman, 2011). Despite their compactness, the neighborhoods located in these areas (mostly from Cluster 1) are characterized by substantially wider streets (at least 20 m) than most parts of the historical neighborhoods of the city such as those in Ciutat Vella (Old Town), Gràcia or Sants-Montjuïc. This fact physically allowed the planting and growth of larger street trees (mostly *Platanus x acerifolia*) with a higher potential to provide ES. In contrast, the narrow street canyons of the historical 'old towns' (in some cases less than 5 m) remain as a clear barrier for street tree planting and associated ES provision. This physical unavailability of tree planting sites, combined with historical processes, has also been observed in other cities and highlighted as a major limitation to increase the equity of urban tree cover (Danford et al., 2014).

Our findings also suggest that street trees can have a relevant redistributive impact in the provision of regulating ES considering the whole UGI distribution in compact cities. In Barcelona, this role is especially relevant in neighborhoods located in Cluster 1 and, to a lesser extent, in Cluster 2 (see Fig. 3). In contrast, neighborhoods with a higher proportion of overall UGI cover (mostly from Cluster 4 and Cluster 3) have lower street tree ES index values. However, this redistributive role might not apply to other ES that have not been assessed in this study. For example, cultural ES such as outdoor recreational opportunities are generally associated with parks, periurban forests or urban gardens and can hardly be provided by street trees alone (Cvejić et al., 2015). This fact suggests potential inequalities related to the diversity of obtained benefits, as affluent neighborhoods (mostly from Cluster 3) may benefit from a wider variety of UGI components and derived ES, while other neighborhoods rely heavily on street trees.

4.2. Limitations and caveats

The advantages and limitations of i-Tree Eco models have been widely discussed in the scientific literature (Nowak et al., 2008; Pataki et al., 2011). While most parts of i-Tree Eco assessments rely on sample data and hence have an associated standard error, our case study is backed by a complete municipal inventory of street trees. Cities with similar available information in relation to their street tree inventory can easily adapt our methodological approach to their context thanks to the international support provided by i-Tree Eco. A key advantage of this tool is that it can provide ES estimates at the individual tree level. Thus, distributional equity assessments can be performed at any urban spatial scale (neighborhood, census tract or even smaller units). However, the assumptions related to the tree structural data described in the methods section and other assumptions directly linked to the models (e.g., homogeneity of air pollution and precipitation distribution) entail a degree of uncertainty in the ES estimates.

Probably the highest uncertainty is attached to the ES estimates of air purification. The links between urban trees and air quality are extremely complex (Eisenman et al., 2019). In this study, we have only considered the air pollution removal estimates from the i-Tree Eco dry deposition model, which may have a positive but very low effect on air quality and therefore on human health (Baró et al., 2014). However, street trees can also reduce air quality through the emission of BVOCs (biogenic volatile organic compounds) and allergenic pollen. Even though BVOC emissions are estimated by i-Tree Eco, the model does not quantify the subsequent harmful O_3 formation due to the complexity associated with this chemical process (Calfapietra et al., 2013). Allergenic pollen is also commonly highlighted as an ecosystem disservice associated with urban trees (von Döhren and Haase, 2015), even if pollen levels (and the associated health impacts) can substantially vary across the urban fabric, both spatially and temporally (Weinberger et al., 2015). Further, trees in urban street canyons can concentrate local air pollution by reducing air dispersion according to various modeling studies (Wania et al., 2012; Vos et al., 2013; Jin et al., 2014). This effect can be especially relevant in street canyons where the height of buildings at least doubles street width (i.e., aspect ratio $\geq$ 0.5) based on a recent review (Abhijith et al., 2017).

4.3. Lessons for urban green infrastructure policy and practice

Many cities around the world are fostering city tree planting programs and other greening initiatives (e.g., Young, 2011; Connolly et al., 2018), but generally the justice implications of these policies are not carefully assessed (Haase et al., 2017). Our assessment suggests that a careful selection and distribution of street trees can contribute to environmental and climate justice in compact cities such as Barcelona. Urban planners and tree managers can use street tree planting strategies to address certain ES mismatches (imbalance between ES provision and demand) derived from the generally unequal and patchy distribution of other UGI components such as urban forests, parks or gardens (Nielsen et al., 2017). In Barcelona, historical legacies related to urban form have likely determined to a large extent the distribution of street trees and their ability to provide ES. However, even if the expansion of street trees can face physical barriers in very compact neighborhoods, the transformation of the street network and the wider transport system can provide new opportunities for additional tree planting or at least for other greening alternatives. For example, the *superilles* (superblocks) program aims to drastically restrict car traffic within these blocks so street public area can be repurposed as pedestrian-friendly spaces and green promenades (see Barcelona City Council, 2016).

Street tree selection criteria should include ES performance, but also consider disservices (e.g., BVOC emissions, pollen allergenicity, damage by roots), tolerance or sensitivity to current local threats (e.g., drought, heat, air pollution, flooding, pests), and capacity to adapt to future conditions in a context of climate change (McPhearson et al., 2015). Online tools and databases such as Citree[6] (Vogt et al., 2017) can

[6] See https://citree.de/

support tree officers in this challenging multicriteria decision-making process. Management of street streets can also optimize the provision of ES and minimize potential risks. For instance, Jin et al. (2014) suggested adequate pruning of street tree canopies to minimize their negative effect on air pollution dispersion.

Further, consideration of procedural environmental justice, i.e., the legitimation and transparency of the process through which environmental decisions are made and by whom (Aragão et al., 2016; Graham and Barnett, 2017), has also been pointed to as an important step towards street tree planting acceptance, especially in historically deprived neighborhoods (Graça et al., 2018). Participatory processes related to street tree planting programs or strategies would allow for a deeper understanding of how different population groups in different neighborhoods value street trees. Co-management approaches such as the recent initiative related to the sowing of herbaceous plants in street tree pits by citizens in Barcelona (Barcelona City Council, 2017b) can also contribute to a greater acceptance and engagement with urban renaturing strategies.

5. Conclusion

The findings of this research suggest that street trees can play an important redistributive role in relation to the local provision of regulating ES in compact cities. This case study underscores the importance of considering and quantifying street tree ES beyond the mere distribution of trees in environmental justice assessments. Our methodological approach based on the i-Tree Eco tool can be easily adapted to other cities with available (street) tree data.

Unlike what previous studies suggested, we found no evidence of a significant and positive association between the distribution of poorer, less educated or Global South residents and a lower amount of street tree benefits in Barcelona. Rather, ES provided by street trees in Barcelona seem to most directly benefit certain types of vulnerable populations, especially elderly citizens. Yet, more cross-city comparative research is needed in order to understand the drivers associated with the distributional equity of street tree benefits.

In light of our results, we contend that street tree planting can be an important greening strategy for compact cities to address ES inequities derived from the generally uneven and patchy distribution of other UGI components such as urban forests, parks or gardens. Street trees can be easily integrated and increased in the grey infrastructure and public spaces of compact cities, especially if pedestrian-friendly streets and other sustainable mobility measures are encouraged. Urban tree managers and planners should carefully select and manage street trees in order to enhance equity in the provision of ES while minimizing potential disservices such as BVOC, pollen emissions or other negative effects on air quality and human health, especially in a context of rising temperatures and weather extremes due to climate change. To this end, more empirical studies are needed to quantify and value ES (and disservices) from street trees and how these benefits contribute to a wider multi-functional UGI network for all urban dwellers. Further, awareness-raising and participatory initiatives on the potential multiple benefits of urban trees to make compact cities more resilient, healthy and just can change or enhance citizens' perceptions and values, especially in historically deprived neighborhoods.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2019.08.016.

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