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Benefits and costs of street trees in Lisbon, Portugal

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ABSTRACT

It is well known that urban trees produce various types of benefits and costs. The computer tool i-Tree STRATUM helps quantify tree structure and function, as well as the value of some of these tree services in different municipalities. This study describes one of the first applications of STRATUM outside the U.S. Lisbon's street trees are dominated by *Celtis australis* L., *Tilia* spp., and *Jacaranda mimosifolia* D. Don, which together account for 40% of the 41,247 trees. These trees provide services valued at $8.4 million annually, while $1.9 million is spent in their maintenance. For every $1 invested in tree management, residents receive $4.48 in benefits. The value of energy savings ($6.20/tree), CO_2 reduction ($0.33/tree) and air pollutant deposition ($5.40/tree) were comparable to several other U.S. cities. The large values associated with stormwater runoff reduction ($47.80/tree) and increased real estate value ($144.70/tree) were substantially greater than values obtained in U.S. cities. Unique aspects of Lisbon's urban morphology and improvement programs are partially responsible for these differences.

Introduction

More than two thirds of Europe's population lives in urban areas (Forrest et al., 1999). The same trend is also observed in Portugal where the Metropolitan Area of Lisbon, covering only 3.3% of the area of the country, has around 3 million inhabitants, about 30% of the total. Although population growth and urbanization have resulted in economic growth and opportunity, they have also adversely impacted the environment and quality of life in cities.

Urban landscapes planted with trees can minimize many of the environmental impacts of urban growth by improving the chemical and physical environment: moderating urban heat islands; improving urban hydrology and air quality; reducing noise levels and the energy requirements of the city (Pauleit and Duhme, 2000; Fang and Ling, 2005; Konijnendijk et al., 2005). Trees in the urban context can increase biodiversity and afford numerous other benefits of an aesthetic, psychological and socio-economic nature (Schoeder and Cannon, 1983; Ulrich, 1985; Kaplan and Kaplan, 1989; Huang et al., 1992; Kaplan, 1992; McPherson et al., 1994; Sullivan and Kuo, 1996; Wolf, 1999; Nowak, 2001).

Trees provide a host of environmental, social, economic, aesthetic, and health benefits that are often disregarded because their monetary worth is unknown (Konijnendijk, 2008). Conversely, pressures on municipal budgets drive management decisions aimed at reducing expenditures. Sometimes trees are prematurely removed, not replaced, and inadequately maintained because controlling costs outweighs management aimed at increasing their health and the ecosystem services they provide over the long term (Carreiro et al., 2008). A computer program called STRATUM (Street Tree Resource Analysis Tool for Urban forest Managers) quantifies urban forest structure, function, management needs, and benefits as well as management costs. Released in 2006 by the USDA Forest Service as part of the i-Tree software suite, STRATUM has been used to value tree services in many U.S. cities. For example, the cities of Fort Collins, CO, Cheyenne, WY, Bismarck, ND, Berkeley, CA, and Glendale, AZ spent US$13–65 annually per tree, while benefits ranged from $31 to $89/tree (McPherson et al., 2005). For every dollar invested in management, benefits returned annually ranged from $1.37 to $3.09. New York City, Boise, Minneapolis and many other cities found that monetizing the value of their municipal forest service's led to increased appreciation of trees and tangible program enhancements.

This paper describes application of i-Tree STRATUM in Lisbon, Portugal. The goal of this study is to generate objective data on the value of services provided by Lisbon's street trees as a foundation for assessing return on investment in their management. Results for Lisbon are compared with several U.S. cities and limitations to applying i-Tree STRATUM in cities outside the U.S are discussed. Directions for future research to spur municipal forest benefit–cost assessments in Europe are suggested.

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Methods

The city of Lisbon

Lisbon, the capital city of Portugal, occupies an area of 8477 ha with a resident population of 564,000 as reported for 2001 by the Portuguese National Statistical Institute. Various parts of the centre of the capital have lost population while at the same time there has been considerable population growth in suburban areas. Large numbers of people commute to and from Lisbon every day. As a consequence, Lisbon suffers from traffic jams and atmospheric pollution, which take their toll on the residents' quality of life. In these circumstances, urban green spaces and street trees have a particularly important role to play, as they can make a major contribution to mitigating these adverse impacts.

STRATUM reference cities

Application of STRATUM in European cities is not straightforward because data requirements are intensive and developed for U.S. cities. STRATUM's benefit calculations are based on tree growth, geographic, and economic data for 16 different U.S. reference cities. Each reference city represents a region wherein climate and the types of tree species are relatively similar. The 16 U.S. regions were aggregated from 45 Sunset climate zones (Brenzel, 2001). The reference city in each region had an updated computer inventory of street trees for sampling and reliable information on program expenditures. A sample of approximately 30–70 randomly selected trees from each of the most abundant species was surveyed in each reference city to (1) establish relations between tree age, size, leaf area and biomass, (2) estimate growth rates, and (3) collect other data on tree health, site conditions, and sidewalk damage. At the same time, geographic and economic information were collected as input to numerical models of tree benefits.

Resources were available to sample Lisbon's street tree population, but not sufficient to conduct a full reference city analysis for Lisbon. For example, data were not available to determine the age of sampled street trees. Without tree age information it is difficult to develop growth curves for each species. One option was to use STRATUM data for the U.S. region and reference city most similar to Lisbon. This approach had the virtue of being easiest to implement, but results would be first-order approximations. Also, criteria for determining which U.S. reference city to use would need to be developed. For example, should the U.S. city be selected based on similar tree species to Lisbon, air temperatures, precipitation patterns, or other criteria?

Another approach was to use tree growth data from U.S. reference cities, but Lisbon data as input to the numerical models that calculate tree benefits. While more labor intensive than the first approach, this tact produces more accurate results because data on climate, buildings, air pollutant concentrations, and rainfall patterns are specific to Lisbon instead of its U.S. surrogate. In this study the second approach is applied to quantify benefits and costs of Lisbon's street tree population.

Collecting tree data

The population of interest is all street trees in the city of Lisbon. An inventory of all 33,232 trees was completed in 2003 under supervision of the Gardens Department of the Municipality of Lisbon. Because this inventory did not contain detailed information required by the STRATUM analysis, the population was sampled in 2006 following protocols published in the STRATUM User Manual (CUFR, 2006).

First, four management zones were identified corresponding to different groups of parishes (*freguesias*) in Lisbon (Fig. 1). Zone 1 consisted of parishes with the lowest density of street trees, including older areas with few trees and modern areas where street trees are fully integrated within the geometric grid of the city.

Zone 2 included a series of parishes that were developed in the second half of the 20th century according to a town planning system in which street trees were set into a residential fabric. In this zone, green areas, ranging from squares and parks to private gardens, are relatively large.

Zone 3 had the highest density of trees. It consisted of parishes that collectively represent the transition between the old city (zone 4) and the areas occupied from the time of the Great Lisbon Earthquake (1755) until the 20th century.

Zone 4 was composed of old city parishes with similar tree density and species profile; organic urban layout (of Medieval origin); narrow streets with few spaces for plantings and no geometric pattern. They also had a similar topography – south-facing with steep

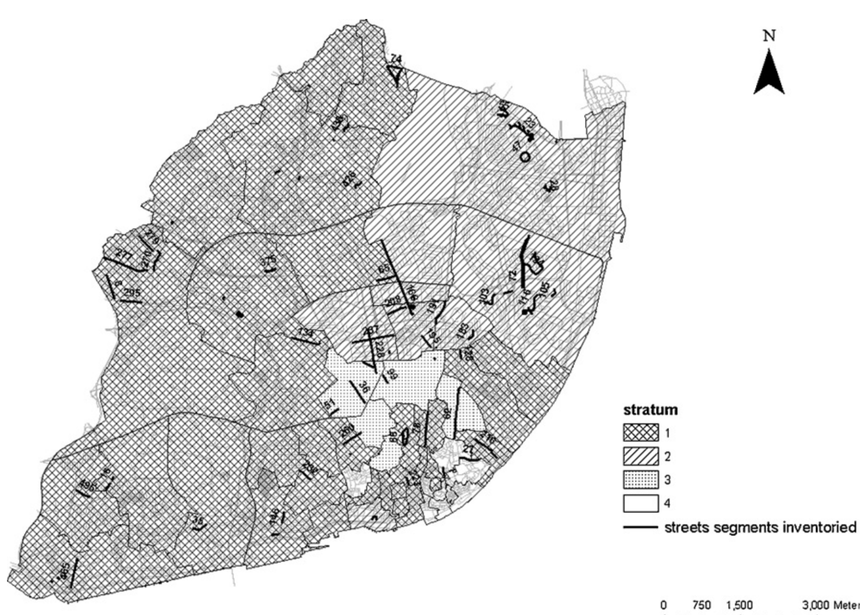

Fig. 1. Location of street segments inventoried in the city of Lisbon (summer 2005), and the four strata are represented.

slopes. Although overall tree density was minimal, there were some very old trees.

Second, the i-Tree sampling utility was used to randomly locate 65 street segments with a goal of sampling a minimum of 2300 trees, as suggested by Jaenson et al. (1992). There were 35, 20, 8, and 2 street segments to sample in zones 1, 2, 3, and 4, respectively. The distribution of the selected segments in Lisbon is shown in Fig. 1. During summer 2004, 3033 trees were sampled. Data recorded for each tree included species name, diameter at breast height (DBH), tree condition and location, severity of pruning, management needs, and other related attributes described in the STRATUM.v3.0 Manual (2006).

Assigning surrogate species using dimensional data

Lacking growth curves for Lisbon tree species, U.S. tree species were assigned to each species in Lisbon based on a comparison of crown and DBH dimensions. Selecting which U.S. reference city tree species' dimensions best matched its Lisbon counterpart was a three-step process. First, more tree measurements were required from Lisbon trees because DBH data from the STRATUM sample alone were not sufficient for comparative purposes. With this in mind additional data were recorded on total tree height, height of the crown, and crown diameter for the ten most abundant species. All trees belonging to these ten species account for approximately 73% of the entire street tree population in Lisbon based on the 2003 inventory. The sample was stratified to include five or more individuals in every DBH class whenever possible. A total of 322 trees were sampled, with 28 or more individuals sampled in every species except *Acer pseudoplatanus* L., with only 18 measured. The small sample size for this species was due to the absence of large trees in the population.

The second-step of the process involved an ocular comparison of fitted Lowess curves for species measured in U.S. cities to scatterplots of the raw crown height and crown diameter measurements for like species in Lisbon. The selection process is shown for *Celtis australis* L. and *Jacaranda mimosifolia* D. Don in Fig. 2.

Of the species measured, some were closely matched by the same U.S. species: *J. mimosifolia*, *Gleditsia triacanthos* L., *Prunus cerasifera* Ehrh., and *Koelreuteria paniculata* Laxm. Genera-based surrogates were found to be the best match for three additional species (*Celtis occidentalis* L. for *C. australis*, *Platanus racemosa* Nutt. ex Audubon for *Platanus* spp., *Acer saccharum* Marschall for *Acer negundo* L.), *Cornus florida* L. was used for *Cercis siliquastrum* L. because it was the only small tree with a similar growth habit measured in U.S. reference cities.

The final step required assignment of U.S. reference city species to the remaining species in Lisbon. This was accomplished using a taxonomic approach, first matching at the species level, and if not available then at the genus level. When faced with several options, U.S. species from Mediterranean climates were selected (Table 1).

Annual benefits and costs

Data collected to calculate annual benefits and costs followed i-Tree STRATUM protocols to facilitate comparisons with other cities. Results are reported in U.S. dollars. Economic data collected in euros were converted to U.S. dollars using an exchange rate of 1 U.S. dollar to 0.78 euros.

Numerical modeling techniques in the computer program i-Tree STRATUM were used to calculate annual benefits and have been described in previous publications (Peper et al., 2001a,b; McPherson et al., 2005; Maco et al., 2005); therefore, this paper summarizes the most salient points. Total value of annual benefits (B) was computed by summing the different estimated benefits

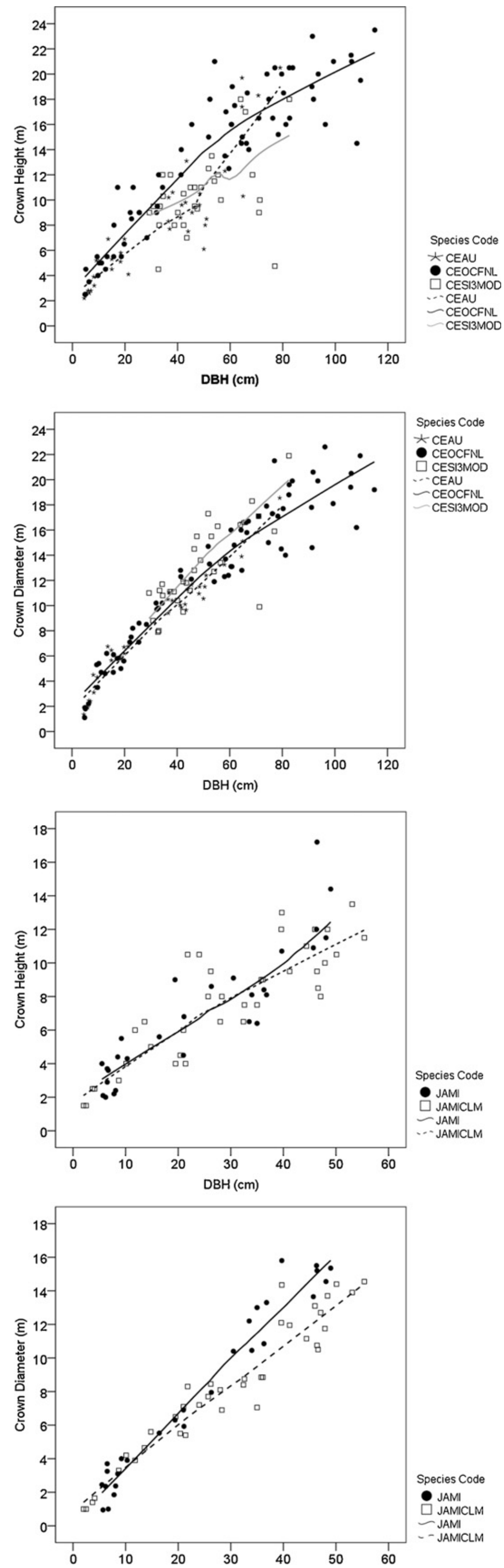

Fig. 2. Comparison of growth curves based on the relationships of diameter at breast height (DBH) with crown height (CRNHT) on the left side and DBH with crown diameter (CDIA) on the right. The top graphs compare *Celtis australis* in Lisbon (CEAU) with *Celtis sinensis* in Modesto (CESI3MOD) and *Celtis occidentalis* in Fort Collins (CEOCFNL). CEOCFNL shows a closer match to CEAU than does CESI3MOD. The bottom graphs compare *Jacaranda mimosifolia* in Lisbon (JAMI) with *Jacaranda mimosifolia* in Claremont (JAMICLM), and shows a close match.

Table 1
Tree species from US reference cities assigned to each of the predominant species in the Lisbon inventory. The i-Tree STRATUM software requires at least one species per tree type, where tree type is based on life form and mature size.

Lisbon species	Tree type	Assigned species	Reference city
Acer negundo L.	BDL	*Acer saccharum* Marschall	Longview, WA
Brachychiton populneu (Schott & Endl.) R. Br.	BEM	*Brachychiton populneum* (Schott & Endl.) R. Br.	Glendale, AZ
Celtis australis L.	BDL	*Celtis occidentalis* L.	Fort Collins, CO
Cercis siliquastrum L.	BDS	*Cornus florida* L.	Charlotte, NC
Fraxinus angustifolia Vahl.	BDM	*Fraxinus velutina* Torr.	Berkeley, CA
Jacaranda mimosifolia D. Don	BDM	*Jacaranda mimosifolia* D. Don	Claremont, CA
Koelreuteria paniculata Laxm.	BDM	*Koelreuteria paniculata* Laxm.	Modesto, CA
Magnolia grandiflora L.	BEL	*Magnolia grandiflora* L.	Charlotte, NC
Phoenix canariensis Chabaud	PEL	*Phoenix canariensis* Chabaud	Santa Monica,CA
Phoenix dactylifera L.	PEM	*Phoenix dactylifera* L.	Glendale, AZ
Pinus pinea L.	CEL	*Pinus halepensis* Miller	Glendale, AZ
Platanus L.	BDL	*Platanus racemosa* Nutt. ex Audubon	Claremont, CA
Populus alba L.	BDL	*Populus deltoides* W. Bartram ex Marshall	Fort Collins, CO
Prunus cerasifera Ehrh.	BDS	*Prunus cerasifera* Ehrh.	Berkeley, CA
Robinia pseudoacacia L.	BDM	*Robinia pseudoacacia* L.	Berkeley, CA
Schinus terebinthifolius Raddi	BES	*Schinus terebinthifolius* Raddi	Claremont, CA
Tilia L.	BDL	*Tilia cordata* Mill	Fort Collins, CO
Washingtonia robusta H. Wendl.	PES	*Washingtonia robusta* H. Wendl.	Santa Monica, CA
Zelkova serrata (thumb.) Makino	BDL	*Zelkova serrata* (thumb.) Makino	New York City, NY

Tree types: BDL = broadleaf deciduous large, BDM = broadleaf deciduous medium, BDS = broadleaf deciduous small, BEL = broadleaf evergreen large, BEM = broadleaf evergreen medium, BES = broadleaf evergreen small, CEL = coniferous evergreen, large, CEM = coniferous evergreen medium, CES = coniferous evergreen small, PEL = palm evergreen large, PEM = palm evergreen medium, and PES = palm evergreen small.

(McPherson and Simpson, 2002):

$$B = E + AQ + CO_2 + H_2O + PV$$

where E = net annual energy savings (cooling and heating); AQ = annual value of air quality improvement; CO_2 = annual value of carbon dioxide reduction; H_2O = annual value of stormwater runoff reduction; PV = annual increase in property value.

Energy savings

Street trees can reduce summer air conditioning loads by shading buildings and, if tree canopy is sufficient, lowering air temperatures. During winter tree shade can increase heating loads, but by reducing wind speeds trees can decrease heating loads. The effects of street trees on building energy performance in Lisbon were based on computer simulations that incorporated building, climate, and shading effects (McPherson and Simpson, 1999). The distribution of street trees with respect to buildings was based on the STRATUM field sample in Lisbon. Climate data were provided by the National Weather Services. Building information (i.e., age distribution, type of construction, size and HVAC saturations) was obtained from 2001 Census data from the Portuguese National Statistical Institute. Energy consumption and associated costs for Lisbon were provided by the Municipal Agency for Energy for 2002 (Tirone, 2005). The value of electrical energy and natural gas was \$35.81 and \$23.03/GJ, respectively based on marginal electricity and natural gas prices.

Air quality benefits

The hourly pollutant dry deposition per tree was expressed as the product of deposition velocity $V_d = 1/(R_a + R_b + R_c)$, pollutant concentration C, canopy projection area CPA, and a time step, where R_a, R_b and R_c are aerodynamic, boundary layer, and stomatal resistances, respectively. Hourly deposition velocities for ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter of <10 μm diameter (PM_{10}) were calculated using estimates for the resistances R_a, R_b, and R_c for each hour throughout a "base year" (Scott et al., 1998; Nowak et al., 2002). Hourly pollutant concentrations were obtained from the Praça de Entrecampos monitoring station in central Lisbon for the year 2004, when pollutant concentrations were near average (Department of Environmental Monitoring of the Commission for Coordination and Development of the Region of Lisbon and the Tagus Valley). Hourly meteorological data (i.e., air temperature, wind speed, relative humidity, solar radiation and precipitation) for 2004 in Lisbon was provided by the National Weather Services for the monitoring station in Gago Coutinho (latitude: 38°46′N, longitude: 09°09′W, elevation: 104 m).

Energy savings result in reduced emissions of criteria air pollutants (volatile organic hydrocarbons [VOCs], NO_2, SO_2, PM_{10}) from power plants and space-heating equipment. These avoided emissions were calculated using utility-specific emission factors for electricity and heating fuels in Lisbon.

Emission of biogenic volatile organic carbons (BVOCs) was included in the analysis because of concerns about their impact on ozone formation. The hourly emissions of carbon as isoprene and monoterpene were expressed as products of base emission factors and leaf biomass factors adjusted for temperature (monoterpene) or for sunlight and temperature (isoprene) (Scott et al., 1998). This approach did not account for the benefit associated with lowered summertime air temperatures and the resulting reduced hydrocarbon emissions from anthropogenic and biogenic sources (Donovan et al., 2005).

The monetary value of tree effects on air quality should reflect the value that society places on clean air, as indicated by its willingness to pay for pollutant reductions. In this study air quality benefits were calculated as damage values using regression relationships between emission values, pollutant concentrations, and population numbers (Wang and Santini, 1995).

Atmospheric carbon dioxide reductions

Sequestration, the net rate of CO_2 storage in above- and belowground biomass over the course of one growing season, was calculated with tree growth data and biomass equations for urban trees (Pillsbury and Thompson, 1998; McHale et al., 2009). Carbon dioxide released through decomposition of dead woody biomass was based on annual tree removal rates of 1% for young trees and 4% for adult trees (Hélder Dias, personal communication). To estimate CO_2 released by vehicles and equipment during tree maintenance activities, annual gasoline consumption of 120,000 l was multiplied by the emissions factor of 40 kg CO_2/l to convert into CO_2-equivalent emissions (Hélder Dias, personal communication).

Reductions in building energy use result in reduced emissions of CO_2 (Escobedo et al., 2010). Emission reductions were calculated as the product of energy savings and CO_2 emission factors for electricity and heating. Heating fuel was natural gas, while the fuel mix for electrical generation was 36% coal, 30% hydro, 19% oil, and 15% natural gas (Tirone, 2005) The value of CO_2 reductions was \$2.04/metric tonne CO_2 (Pearce, 2003).

Stormwater runoff reductions

A numerical interception model accounted for the amount of annual rainfall intercepted by trees, as well as through fall and stem flow (Xiao et al., 2000). The volume of water stored in tree crowns was calculated from crown projection area, leaf surface area, and water depth on canopy surfaces. Hourly meteorological and rainfall data for 2004 were used, when annual precipitation totaled 439 mm. This amount is considerably less than the historical average of 731 mm, so interception results are conservative.

Stormwater reduction benefits were priced by estimating costs of controlling stormwater runoff. Average annual expenditures totaled \$47.3 million based on scheduled maintenance and capital improvements. Lisbon spends about \$19.2 million annually to maintain 900 km of sewer pipes. Approximately 240 km of pipes are scheduled to be replaced and 60 km rehabilitated during the next 10 years at an average annual cost of \$28.1 million (José Monteiro, personal communication).

The hydrologic simulation model TR-55 (USDA, 1986) was used to determine the total amount of runoff from the city of Lisbon during 2004. Runoff curve numbers were applied based on land use data. The analysis assumed that 32% of Lisbon's 84,767 km^2 of area was park with a runoff curve number of 69, 34% was heavily urbanized with a curve number of 90, and 34% was residential with a curve number of 80. The soil, a sandy loam, had a high infiltration capacity. After eliminating small storm events (<2.5 mm) that do not generate runoff, total annual runoff was calculated as 4.51 million m^3.

The average annual expenditure of \$47.3 million was divided by the estimated volume of stormwater runoff to calculate the annual control cost of \$10.49/m^3. The stormwater runoff reduction benefit was the product of this price and the amount of annual rainfall interception attributed to the trees.

Property value benefits

Urban trees can increase the sales price of properties. European research comparing sales prices of residential properties with different numbers and sizes of trees suggests that people are willing to pay more for properties with ample trees versus few or no trees (Tyrväinen, 1999; Tyrväinen et al., 2005). A study in Athens, GA (Anderson and Cordell, 1988) found a large front-yard tree was associated with a 0.88% increase in average home sale prices. In this analysis, property value benefits (\$/tree/year) vary with the distribution of street trees among land uses, the number of property units they influence, and the growth rates of different trees. These relationships are expressed for a single street tree as:

$$\mathrm{PV} = \frac{T \times C \times L}{M}$$

where T = tree contribution to home sales price (\$/tree); C = tree location factor; L = annual increase in tree leaf area (m^2); M = tree leaf area (m^2).

The tree contribution to home sales price (T) was evaluated assuming that a 0.88% increase in property value due to a mature street tree is reasonable to apply to the city of Lisbon. The value of T in front of a typical apartment was thus estimated as \$1943/tree, obtained by multiplying 0.88% by \$220,336, the 2006 average median sale prices for apartments in Lisbon (Relatório de Mercado Área Metropolitana de Lisboa (SIR), 1st quarter of 2006).

The tree location factor (C) is used to depreciate the benefit for trees in non-residential sites and to appreciate their benefit if they influence multiple properties. The depreciation factors were: single family residential (1.00), multifamily residential (0.75), industrial/institutional/large commercial (0.50), park/vacant/other (0.50) and small commercial (0.66) (McPherson et al., 2001).

The appreciation factor is important for Lisbon because most buildings opposite street trees are multi-story, resulting in the value of several units influenced by the same tree. During a stratified random sample of 325 street trees in Lisbon, data were collected on the number of building units opposite each tree by occupation type. Overall, the sample of 325 trees was associated with 1883 units, an average of 5.8 units/tree. The value of (C) was 3.81 when weighted to account for the high number of property units per tree in Lisbon, as well as the depreciation factors.

The average annual leaf area increase (L) and the leaf surface area (M) are estimated for each tree. Assuming a typical value for L of 14.5 m^2, and a value of 675 m^2 for M (typical of a mature 40-year-old *C. australis*) and the values for C, T and M cited above, a typical large street tree in Lisbon is estimated to increase property values by \$159 annually ($159 = 14.5 \times (1943 \times 3.81)/675$).

Expenditures

Total annual municipal tree program expenditures (C) were based on information provided by the municipality of Lisbon for 2005 (Hélder Dias, personal communication):

$$C = \mathrm{TM} + \mathrm{ADM} + O$$

where TM = tree management (including planting, pruning, removals, control of pests and diseases and watering); ADM = administration costs (including inspections and other services); O = other costs (including infrastructure repairs, liability and claims).

Results

Tree numbers and species composition

Lisbon's street tree population was estimated to be 41,247, with a standard error of 6312 (Table 2). This estimate is 24% greater than the 2003 inventory total of 33,232. Given that this increase is greater than the standard error of the estimate, the street tree population has continued to grow. Earlier inventories reported that tree numbers were 21,822 (Câmara Municipal de Lisboa, 1929), 22,903 (Coutinho, 1939), and 21,671 (Andresen, 1982) and diversity of species used increased in recent years (Castel-Branco, 1995).

The number of street trees per capita was 0.16, well below the average of 0.37 calculated by McPherson and Rowntree for 22 U.S. cities (1989). Another measure of stocking level assumes full stocking occurs when there are two street trees along every 15 m of street length. Given Lisbon's 1423 km of streets, there were 29 trees/km of street frontage, and the stocking level was 22%. The mean stocking level for 22 U.S. cities was 38% (McPherson and Rowntree, 1989).

In this study seventy-eight different species of street trees were sampled, *Celtis* and *Tilia* were the most common street tree genera, each accounting for 16% of the population, while *J. mimosifolia* accounted for 10%. Other important species belonged to the *Platanus*, *Acer*, and *Populus* genera (Hélder Dias, personal communication).

From a management perspective, overreliance on *Celtis*, *Tilia*, and *Jacaranda* is of concern because of the possibility of heavy losses from outbreaks of pests and disease or other stressors that are specific to these genera.

Table 2
Predominant street tree species in Lisbon.

Species	% of total tree numbers	Total tree numbers
Celtis australis L.	16.1	6629
Tilia L.	15.9	6573
Jacaranda mimosifolia D. Don	10.3	4233
Platanus L.	8.6	3560
Acer negundo L.	6.9	2831
Tipuana tipu (Benth.) Kuntze	4.6	1906
Fraxinus angustifolia Vahl.	2.8	1177
Ligustrum lucidum Aiton fil.	2.8	1177
Koelreuteria paniculata Laxm.	2.4	981
Populus × *canadensis* Moench	2.3	953
Cercis siliquastrum L.	2.1	883
Populus nigra L.	2.0	813
Brachychiton populneum (Schott & Endl.) R. Br.	1.9	784
Populus alba L.	1.8	755
Aesculus hippocastanum L.	1.7	685
Celtis occidentalis L.	1.6	672
Melia azedarach L.	1.4	590
Robinia pseudoacacia L.	1.4	590
Prunus cerasifera Ehrh.	1.3	520
Grevillea robusta A. Cunn. Ex R. Br.	1.0	433
Aesculus × *carnea* Hayne	1.0	422
Catalpa bignonioides Walt.	1.0	421
Prunus avium L.	1.0	421
Other street trees	7.8	3238
Citywide total	100	41,247

Size distribution

Relative to the "ideal" size distribution as defined by Richards (1983), Lisbon's population has fewer small, new transplants, an abundance of maturing trees, and a deficit of large, old trees.

This distribution suggests that the population is dominated by trees planted between 1960 and 1995. Because of their age and size, these trees are providing substantial benefits. Small trees (<8 cm) are recent transplants that add diversity to the population. For example, *K. paniculata* is the most abundant small tree, but also present in larger size classes. It was abundant in 1929 and then heavily planted again after Expo 98 in Lisbon. *C. australis* has long occupied a dominant position among the trees of Lisbon and continues to be planted in large numbers because of its ability to withstand urban conditions. In contrast, *Tipuana tipu* (Benth.) Kuntze and *Populus* genera began to be planted in the 1980s (Fig. 3).

Annual costs

The Municipality of Lisbon spent approximately $1.9 million or $45.64/tree annually on tree management, administration, and other tree-related activities (Table 3). The largest expenditure was for tree management, which includes costs for planting, pruning, removals, control of pests and diseases and watering (64%). Administration expenditures accounted for 22% of the total and include inspection and other services. Other expenditures totaled 14% and were for repairing sidewalks and curbs damaged by tree roots, as well as payments for tree-related property damage or personal injury.

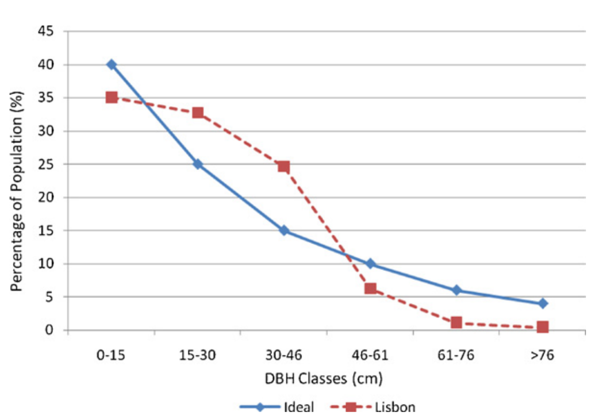

Fig. 3. Size distribution of Lisbon's street tree population compared to an "ideal" distribution with many small trees to offset high mortality rates.

Table 3
Annual management costs of all trees.

Costs	Total ($)	$/tree
Tree management (TM)	1,216,723	29.50
Administration (*A*)	409,600	9.93
Other costs (*O*)	256,000	6.20
Total costs	1,882,323	45.64

Table 4
Benefits, costs, and net benefits of Lisbon's street trees.

	Lisbon	
	Total ($)	Value/tree ($)
Benefits		
Energy	254,185	6.16
CO_2	13,701	0.33
Air quality	222,738	5.40
Stormwater	1,973,613	47.85
Property value	5,968,542	144.70
Total	8,432,779	204.45
Costs		
Total	1,882,323	45.64
Net benefit	6,550,456	159.00
Benefit–cost ratio	4.48	
Total trees	41,247	

Annual and net benefits

The total benefit of street trees to the city of Lisbon is $8,432,779 annually (Table 4). Tree services were unevenly distributed among species and benefit types (Table 5). For example, just five species accounted for 72% of all benefits, and increased property value represented 71% of total benefits. Relations among tree species benefit types, and benefit values are described in later sections of this paper.

Lisbon spent approximately $1.9 million ($45/tree) annually maintaining its municipal forest. Resident's received services from Lisbon's 41,247 street trees valued at $8.4 million ($204/tree) (Soares, 2006). The net benefit was $6.5 million ($159/tree). For every $1 invested in tree management, residents received $4.48 in benefits (Table 4).

Table 5
Distribution of benefits by species.

Species	Numbers of the main tree species (% of total)	Annual benefits (% of total)
Celtis australis L.	16.1	20.7
Tilia L.	15.9	15.1
Jacaranda mimosifolia D. Don	10.3	9.4
Platanus L.	8.6	16.2
Acer negundo L.	6.9	10.2
Other street trees	42.2	28.5
Citywide total	100	100

Table 6
Annual energy benefits by tree species.

Species	Total tree numbers	Total electricity (GJ)	Total natural gas (GJ)	Total ($)[a]	s.e.
Celtis australis L.	6.629	855	826	49,644	±13,505
Tilia L.	6.573	540	600	33,144	±10,148
Jacaranda mimosifolia D. Don	4.233	422	517	27,014	±14,575
Platanus L.	356	582	652	35,831	±9205
Acer negundo L.	2831	239	295	15,362	±7650
Tipuana tipu (Benth.) Kuntze	1.906	200	269	13,350	±10,122
Fraxinus angustifolia Vahl.	1.177	143	207	9872	±6134
Ligustrum lucidum Aiton fil.	1.177	43	59	2913	±1941
Koelreuteria paniculata Laxm.	981	23	37	1664	±1263
Populus × canadensis Moench	953	117	149	7617	±2264
Cercis siliquastrum L.	883	41	51	2654	±1411
Populus nigra L.	813	121	150	7774	±2473
Other species	12.735	749	891	47,345	
Citywide total	41.247	4.074	4.702	254,185	±38,898

[a]Based on the values of $35.81/GJ for electricity and $23.03/GJ for natural gas.

Energy

Energy savings due to shading and climate effects totaled $254,185 or $6.16/tree annually (Table 6). Electricity savings, largely for cooling, were about 30% greater than natural gas savings. Tree species that produced the greatest energy savings were large-stature deciduous trees, and many had large leaves (i.e., *Platanus* spp., *Populus nigra* L., *Fraxinus angustifolia* Vahl., *Populus × canadensis* Moench). Conversely, species that provided the least energy benefits had smaller mature sizes and smaller leaves (i.e., *K. paniculata*, *Ligustrum lucidum* Aiton fil., *C. siliquastrum*).

Carbon dioxide reduction

Lisbon's street tree population stored approximately 21,030 t of carbon dioxide that has accumulated over time in its biomass. Species that stored the most CO_2 by virtue of their numbers and size were *Platanus* spp., *A. negundo*, *T. tipu*, *P. nigra*, and *C. siliquastrum* (Table 7).

During the course of a single growing season the population was estimated to sequester 1776 t of CO_2 valued at $13,085. At the same time, energy savings produced by the trees reduced CO_2 emissions by 633 t, providing a total annual benefit of 2410 t ($17,743). Releases of CO_2 associated with tree maintenance activities and decomposition of removed biomass offset this benefit by 549 t ($4042). Therefore, the net annual CO_2 reduction benefit was 1861 t ($13,701 or $0.33/tree). Species that produced the greatest net benefit were *A. negundo*, *Platanus* spp., *P. nigra*, *Populus × canadensis*, and *F. angustifolia*. Species with the least attractive CO_2 balances include *K. paniculata* and *J. mimosifolia*.

Air quality effects

Air quality benefits include pollutant uptake by trees, decreased pollutant emissions from power plants as a consequence of energy savings, as well as the potential adverse impact of BVOC emissions from trees on ozone air quality. In net, Lisbon's street trees reduced air pollutants by approximately 25.6 t annually, valued at $222,738 or $5.40/tree (Table 8).

Deposition of pollutants to trees accounted for 93% of the net air quality benefit. Reduced emissions from energy savings were less important, equivalent to 14% of the deposition benefit. BVOC emissions amounted to 50% of reduced emissions from energy savings. The *T. tipu* alone accounted for 34% of total BVOC emissions. Species that provided the greatest benefits were: *Platanus* spp., *C. australis*, *F. angustifolia*, *J. mimosifolia* and *P. nigra*.

Stormwater runoff reduction

Lisbon's street trees intercepted approximately 186,773 m^3 of rainfall annually, and the associated storm water runoff reduction was valued at $1.97 million (Table 8). On average, each tree intercepted 4.5 m^3 annually and this service was valued at $48. This relatively large value reflects the large investment Lisbon is making to improve its stormwater management system over the next 10 years. Species that played a major role in rainfall interception were: *Platanus* spp., *C. australis*, *P. nigra*, *F. angustifolia*, and *Populus × canadensis*.

Property value benefits

The effects of trees on sales prices of properties were used as a proxy for all the intangible aesthetic, social, psychological, spiritual, and economic benefits of trees. As mentioned previously, it is

Table 7
Annual carbon dioxide reductions and releases.

Species	Total tree numbers	Total stored CO_2 (kg/year)	Sequestered (kg)	Decomposition release (kg)	Maintenance release (kg)	Avoided (kg)	Net total (kg)	Total ($)	s.e.
Celtis australis L.	6.629	3,638,947	278,415	−29,135	−68,716	132,784	313,348	2307	±628
Tilia L.	6.573	2,808,524	251,960	−22,560	−52,098	83,792	261,095	1923	±589
Jacaranda mimosifolia D. Don	4.233	1,003,267	86,430	−8401	−40,734	65,472	102,767	757	±408
Platanus L.	3.56	3,121,839	285,805	−25,218	−44,793	90,304	306,099	2254	±579
Acer negundo L.	2.831	2,351,032	277,645	−18,832	−28,837	37,108	267,084	1967	±979
Tipuana tipu (Benth.) Kuntze	1.906	1,567,161	59,077	−12,543	−23,475	31,068	54,127	399	±302
Fraxinus angustifolia Vahl.	1.177	567,844	47,596	−4543	−1794	22,142	63,402	467	±290
Ligustrum lucidum Aiton fil.	1.177	158,114	19,382	−1269	−7668	6711	17,156.30	126	±84
Koelreuteria paniculata Laxm.	981	99,475	8211	−815	−3503	3558	7451	55	±42
Populus × canadensis Moench	953	609,180	51,201	−4894	−12,154	18,194	52,346	385	±115
Cercis siliquastrum L.	883	626,113	44,370	−5009	−1346	6412	44,428	327	±174
Populus nigra L.	813	652,946	54,275	−5257	−11,791	18,777	56,003	412	±131
Other species	12.735	2,865,986	312,630	−30,708	−82,836	116,285	315,372	2322	
Citywide total	41.247	20,070,426	1,776,999	−169,183	−379,745	632,608	1,860,679	13,701	±2.097

Table 8
Annual air quality effects.

Species	Total tree numbers	Annual air quality effects					Stormwater runoff reduction			Property value	
		Deposition (kg)	Avoided (kg)	BVOC emissions (kg)	Total ($)[a]	s.e.	Total rainfall interception (m^3)	Total ($)	s.e.	Total ($)	s.e.
Celtis australis L.	6.629	5522	1.093	0	52.848	±14,377	43.349	458.061	±124,610	1,179,947	±320,990
Tilia L.	6.573	3200	693	0	31.018	±9497	26.249	277.369	±84,926	928.95	±284,431
Jacaranda mimosifolia D. Don	4.233	2288	545	0	22.816	±12,310	19.348	204.445	±110,305	537.247	±289,861
Platanus L.	3.56	3514	748	0	33.963	±8725	29.888	315.819	±81,139	974.11	±250,263
Acer negundo L.	2.831	1271	308	−250	11.483	±5719	8.201	86.659	±43,156	746.552	±371,783
Tipuana tipu (Benth.) Kuntze	1.906	1080	260	−1.572	4.469	±3388	7.471	78.947	±59,853	169.154	±128,243
Fraxinus angustifolia Vahl.	1.177	849	184	0	8.196	±5093	6.185	65.351	±40,608	112.457	±69,878
Ligustrum lucidum Aiton fil.	1.177	418	55	−81	3.551	±2365	2.109	22.287	±14,845	44.015	±29,318
Koelreuteria paniculata Laxm.	981	132	30	−124	791	±601	811	8.572	±6508	39.623	±30,083
Populus × *canadensis* Moench	953	562	152	−413	3.989	±1186	4.384	46.321	±13,767	133.677	±39,729
Cercis siliquastrum L.	883	308	53	0	2.902	±1543	1.328	14.03	±7459	31.526	±16,762
Populus nigra L.	813	574	157	−408	4.129	±1313	4.427	46.779	±14,879	116.561	±37,075
Other species	12.735	5186	965	−1.726	42.585		33.025	34.8974		954.723	
Citywide total	41.247	24,905	5.244	−4.576	222.738	±34,085	186.773	1,973,613	±302,020	5,968,542	±913,360

[a]Based on the reference values of CUFR.

difficult to quantify and assign a monetary value to these intangible benefits. In this analysis, the presence of street trees was estimated to add approximately $5.97 million annually to the value of property in Lisbon (Table 8). The mean annual benefit per tree was $145. Species that produced the greatest annual property value benefits were *Platanus* spp., *A. negundo*, *C. australis*, *P. nigra* and *Tilia* spp.

Discussion

Lisbon's street trees provide a high level of service to residents. However, maintaining that high level of net benefit may not be easy because those benefits depend on the health of so few species. The top five species (*C. australis*, *Platanus* spp., *Tilia* spp., *A. negundo*, *J. mimosifolia*) accounted for 58% of all street trees and produced 72% of total benefits (Table 5). Although these species have proven themselves to be tolerant to growing conditions, future threats from pests, disease, and drought represent a real risk to perpetuating the high level of services residents receive from their municipal trees. Maintaining the health and longevity of these trees is critical to sustaining a high level of benefits. Recent efforts to increase species diversity should be expanded to reduce the risk of catastrophic loss if one or more of these predominant species were to succumb.

Comparisons

Data from several U.S. cites with population sizes (Albuquerque, NM and Charlotte, NC) nearest to Lisbon's or Mediterranean climate (Berkeley and Santa Monica, CA) are presented as a basis for comparison (Table 9).

Street tree stocking in Lisbon is 22%, considerably less than Berkeley and Santa Monica, and more than Albuquerque and Charlotte. The number of trees per capita in Lisbon (0.07) is lower than other cities except Albuquerque. At first glance this result may be surprising given Lisbon's relatively higher stocking level. However, Lisbon's low number of trees per capita reflects its high population density (67/ha). For example, the population density of next the closest U.S. city is Santa Monica (43/ha), and Charlotte's is 9/ha. Lisbon's ratio of trees per capita matches the value reported for New York City (Peper et al., 2007).

Energy savings for Lisbon's street trees is similar to Santa Monica and Albuquerque on a per tree basis, but significantly lower than Berkeley, CA where energy prices range from 20% ($28/GJ for electricity) to nearly 40% ($49/GJ for natural gas) higher than Lisbon's. Carbon dioxide reductions are relatively low for Lisbon, perhaps due to dampened energy savings and reduced power plant emissions. Air quality benefits are large for Lisbon relative to all other cities except Santa Monica. This is influenced by high concentrations of air pollutants and large numbers of people in both cities, which increase deposition rates and damage costs. Lisbon's stormwater benefits exceed those of all other cities. On average, the Lisbon street tree intercepts 5 m^3 of rainfall annually, between rates found for Albuquerque (2 m^3) and Charlotte (9 m^3). Hence, the relatively large control cost attributed to stormwater management in Lisbon ($10.49/$m^3$) is responsible for the substantial per tree benefit. Control costs for other cities ranged from $0.54/$m^3$ to $2.62/$m^3$.

The most important benefit in all the cities is property value. The value in Lisbon is over twice as large as the value for Berkeley and Santa Monica where median sales prices for residential properties are quite high. The difference in these values may be primarily due to the different typologies of buildings in Lisbon compared to these U.S. cities. In Lisbon most buildings opposite street trees are multistory, resulting in increased sale prices for several units that are influenced by the same tree.

Table 9
General information and annual benefit and cost data (USD) for five cities.

	Lisbon	Albuquerque	Berkeley	Charlotte	Santa Monica
Total trees	41,247	21,519	36,485	85,146	29,229
City population	564,657	484,246	104,000	597,308	92,578
Stocking (%)[a]	22.1	1.3	66.3	16.0	82.8
Trees/capita	0.07	0.01	0.30	0.14	0.28
Annual benefit ($)					
Energy	254,185	170,422	553,061	914,001	141,032
Carbon dioxide	13,701	15,389	49,588	198,548	48,812
Air quality	222,738	23,855	−20,635	−36,270	171,782
Stormwater	1,973,613	55,830	215,645	2,077,392	110,486
Property value	5,968,592	295,282	2,449,884	2,757,217	1,894,758
Total benefits	8,432,779	560,778	3,247,543	5,910,888	2,366,870
Total costs	1,882,323	428,500	2,372,000	1,819,460	1,544,000
Net benefits	6,550,456	132,278	875,543	4,091,428	822,870
Benefit–cost ratio	4.48	1.31	1.37	3.25	1.53

[a] Shown as percentage of full stocking where full stocking is 2 trees every 15 m of street length.

On a per tree basis, tree management costs in Lisbon ($46) exceed the other cities except Berkeley ($65) and Santa Monica ($53), where infrastructure repair costs are particularly high. Despite relatively large expenditures on tree management in Lisbon, it has the highest benefit–cost ratio (4.48) of the five cities. Net benefits of $159/tree in Lisbon drive this result, especially when compared to net benefits in Berkeley ($24/tree), Santa Monica ($28/tree), and Charlotte ($48/tree).

Limitations and transferability

In this study, benefits were calculated based on dimensional data from surrogate U.S. species that provided the “best fit” to limited dimensional data for trees growing in Lisbon. This approach is preferred to using dimensional data from a single U.S. reference city because of the larger pool of growth curves from which to find the “best fit.” Also, incorporating measurements from local trees results in an improved “fit” compared to adopting uncalibrated growth curves from a single reference city. However, more accurate results are possible if the full complement of tree growth data existed for the most abundant species in Lisbon. One future direction for research is to develop growth curves for trees in Lisbon and other climate zones throughout Europe.

Reference city data collection includes information on benefit prices and other geographic factors. Some information on benefit prices, such as electricity and natural gas, were easily obtained and their application is clearly defined by customer service areas. However, the benefit price for rainfall interception was not readily available and required hydrologic calculations to estimate the volume of urban runoff. Furthermore, Lisbon’s sizable capital investment in improvement of its stormwater management infrastructure inflated the control cost value. The resulting benefit price, which was about five times greater than the next highest price, may be anomalous. Given the high level of uncertainty in runoff estimation and Lisbon’s unique capital improvement investment, other cities in the region should be cautious before adopting this benefit price. Other geographic data, such as building construction types, numbers and types of properties opposite street trees, saturation rates for air conditioning equipment, and utility fuel mixes were easily obtained and may be suitable for use by other cities in the region that are conducting similar analyses.

Calculating the influence of street trees on adjacent property values was a challenging issue in terms of data requirements and modeling. For instance, determining actual land use and property ownership boundaries during the field survey had a high level of uncertainty. More research is needed to determine relations between street trees and property features that contribute to sale price. For example, a recent study reported relations between several tree-related features and single family residential sales prices in Portland, OR (Donovan and Butry, 2008). However, these findings have limited application in Europe, where multi-story buildings are prevalent. Future research should examine the importance of tree characteristics that are thought to be associated with increased property sales prices, such as their shape, size, foliation and flowering characteristics, and longevity.

Conclusions

Lisbon’s 41,247 street trees are providing services valued at $8.4 million annually, while $1.9 million is spent maintaining these trees. For every $1 invested in tree management, residents receive $4.48 in energy savings, cleaner air, increased property values, reduced stormwater runoff and CO_2. However, 72% of total benefits are produced by the top five tree species, a rather perilous situation. To sustain this high level of benefits for future generations Lisbon should increase the diversity of its tree population, and increase stocking levels by planting more trees and prolonging the lifespan of its mature trees.

Compared to most U.S. cities, Lisbon’s benefit–cost ratio of 4.48:1 is high, but less than that reported for New York City (5.80:1) and Indianapolis (6.09:1) (Peper et al., 2007, 2008). Annual benefits for energy, CO_2, and air quality in Lisbon were reasonably close to those reported for similar U.S. cities on a per tree basis. However, benefits from rainfall interception and property values were substantially greater than found in comparable U.S. cities. Unique aspects of Lisbon’s urban morphology and capital improvement programs are partially responsible for these differences.

A serious limitation to applying i-Tree STRATUM was the absence of tree growth curves for the predominant species in Lisbon. Finding the “best fits” from U.S. reference cities was time consuming and a poor substitute for locally derived growth curves. Future research should strive to develop growth curves for trees in Lisbon and other climate zones throughout Europe. Most geographic data required as input to STRATUM’s numerical models were readily available. Exceptions were the difficulties in calculating benefit prices for rainfall interception and property value effects. Because of its important value special efforts should be focused for the influence of street trees on the real estate values.

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