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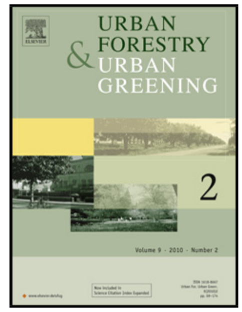

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The economic benefits and costs of trees in urban forest stewardship: A systematic review

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Highlights

Most studies were a "snapshot" of values for inventoried trees at a city-scale.
Costs were relatively understudied, and benefits were mostly limited to five types.
Benefits that drew most research interest did not necessarily provide greatest value.
A limited biogeographical scope reveals the need for more research in the tropics.
Comprehensive accounting and integration with decision-making frameworks are needed.

Abstract

Understanding the benefits provided by urban trees is important to justify investment and improve stewardship. Many studies have attempted to quantify the benefits of trees in monetary terms, though fewer have quantified the associated costs of planting and maintaining them. This systematic review examines the methods used to jointly analyse the costs and benefits of trees in the urban landscape, assesses the relative balance of benefits and costs, and attempts to understand the wide variation in economic values assigned in different studies. The benefits most frequently studied are those related to environmental regulation and property values, and the available data show that these usually outweigh the costs. Aesthetic, amenity, and shading benefits have also been shown to provide significant economic benefits, while benefits in terms of water regulation, carbon reduction and air quality are usually more modest. Variation in benefits and costs among studies is attributed largely to differences in the species composition and age structure of urban tree populations, though methodological differences also play a role. Comparison between studies is made difficult owing to differences in spatiotemporal scope, and in the way urban forest composition and demographic structure were reported. The overwhelming majority of studies concern deciduous trees in Northern America, and much less is known about urban forests in other regions, especially in the tropics. Future work should thus seek to fill these knowledge gaps, and standardise research protocols across cities. In light of ambitious goals in many cities to increase tree cover, ongoing advances in valuation methods need to provide a more comprehensive accounting of benefits and costs, and to better integrate economic assessment into the decision-making process.

(271 words)

Symbols and Abbreviations

BCR: Benefit-cost ratio

BCA: Benefit-cost analysis

CEA: Cost-effectiveness analysis

Keywords:
benefit-cost analysis; cost-effectiveness; ecosystem service valuation; forest resource; street tree; urban tree

Introduction

Over the past few decades, there have been intensive efforts to green cities, reflected in a surge of interest in innovations such as green roofs and green walls. However, the largest component of urban greenery in most cities remains the trees that grow in roadside verges, parks, gardens, remnant forest patches, and increasingly also on buildings (Feng and Tan, 2017; Jim, 2017). Recent studies demonstrate that these trees not only beautify the landscape, but often play a major role in moderating the environmental impact of urban settlements (Seamans, 2013).

The **benefits** considered in this paper arise through the "capacity of natural processes and components to provide goods and services that satisfy human needs" (De Groot et al., 2002). These benefits, referred to here as 'ecosystem goods and services', include a diverse range of economic, health, social and visual benefits, as well as services that indirectly sustain human life through the regulation of environmental processes (Roy et al., 2012). However, there are also costs to consider: in the case of urban trees, these include not only the direct costs of planting and maintenance (Vogt et al., 2015), but a long list of potential indirect costs, including damage to buildings and pavements by tree roots, damage and injury from falling trees, disruption to traffic during maintenance, carbon emissions through operating machinery, blockage of drains by leaf litter, and air pollution by volatile organic compounds emitted by foliage, to name but a few (Vogt et al., 2015).

Given this complex mix of benefits and costs, it is scarcely surprising that planting trees in urban environments can be politically controversial, with different interest groups emphasising either the positive or negative consequences. For this reason, it is important to be able to quantify the costs and benefits of urban trees, and know where the balance lies. In recent years, there have been many studies on this topic (Mullaney et al., 2015; Roy et al., 2012), though they vary greatly in their scope and the methods used. Our objective here is to synthesise the results of these studies with a view to drawing general conclusions about the benefits and costs of urban trees, and suggesting how the valuations can be improved. We believe that such a synthesis will be very valuable to urban policy makers in developing their strategies for green infrastructure.

Combining benefits and costs in urban tree valuation

The methods used to value the benefits and costs of trees vary greatly depending on the purpose of valuation, which can range from real estate assessment to damage claims evaluation (Cullen, 2007). A review by Roy et al. (2012) found that most studies valued urban trees using benefit-cost analysis (BCA, or CBA). This method often assigns a dollar value to individual benefits, thus allowing cumulative benefits to be calculated and used in decision-making. Having both benefits and costs expressed in monetary terms also allows the net benefit and benefit-cost ratio (BCR) of trees to be determined. Indeed, numerous cities have used BCA to calculate the value of their “forest resource” (examples include Peper et al., 2009; Vargas et al., 2006), thus helping to justify land use and investment into urban forests. Some benefits and costs prove difficult to quantify, however, and may not necessarily be best conveyed in monetary terms. As an alternative to BCA, some studies have used cost-effectiveness analysis (CEA), which uses data measured in different units to assess which tree-planting scenarios provide the greatest benefit at the lowest cost (Escobedo et al., 2008; Kovacs et al., 2013).

Roy et al. (2012) has reviewed the methods used to assess urban tree benefits and costs**,** and Mullaney et al. (2015) has provided information on the economic values of individual benefits of urban trees. However, we still lack a systematic understanding of whether these economic benefits outweigh the associated costs. For this reason, we conducted a systematic review of literature to (1) examine the methods used in studies that jointly analyse urban tree benefits and costs, (2) assess the variability in the economic value of benefits and compare them relative to the costs of urban trees, and (3) discuss management implications for urban forest stewardship and future research priorities.

Methods

Screening of relevant literature

Our systematic review followed the procedures recommended in the PRISMA statement (Moher et al., 2009). An initial screening of the literature was performed within five databases: Google Scholar, Web of Science, Scopus, Science Direct and ProQuest (on 1st Oct 2016). The literature was searched using the search phrase: "urban tree" OR "street tree" OR "urban forest" AND “cost” AND “benefit” OR "ecosystem service”. Papers were included if they met the following criteria: (1) were original research papers published in peer-reviewed English-language scientific journals, and (2) included an assessment of both benefits and costs of urban trees, using any measurement units. To limit the review to peer-reviewed, original research, we excluded books and ‘grey literature’. Review articles were only included if they contained original research. We also searched reference lists within review articles to ensure that all relevant papers were identified. The PRISMA flowchart summarising the search results and screening workflow is shown in Fig. 1. The final dataset consists of 34 original research papers published between 1992 and 2016.

<insert Fig. 1>

Data compilation and analysis

Information extracted from each of the 34 research papers included: (1) citation details, (2) spatio-temporal scope, (3) study location, (4) climate, (5), urban tree typology, (6) number of trees assessed, (7) urban forest structure, (8) type of valuation and assessment scenarios included, (9) benefits and costs, (10) tree growth and mortality.

The spatial scale of analysis for study locations within each paper were grouped into one of four levels: individual trees, project, urban forest, and city. The category "project" applied to the analysis of hypothetical tree-planting scenarios or simulations that did not have well-defined geographical boundaries; "urban forest" refers to local green spaces with a defined boundary (i.e. park, forest patch, nature reserve). Study locations were assigned to continent (Africa, Asia, Australia, Europe, North America, South America), and to a Köppen–Geiger climate zone based on the closest city (Peel et al., 2007).

The types of urban trees recognised were: street trees, trees in publicly managed green spaces, private residential lawn trees, and urban forests. Generic assessments that did not specify tree type were classified under the "urban forest" category. The presence of certain assessment scenarios was also noted. These included tree planting, tree removal, sensitivity analyses (i.e. for quantification of benefits and costs; varying discount rates), as well as hypothetical tree-planting simulations. Finally, it was noted whether analyses included a spatio-temporal differentiation of benefits and costs. Unless otherwise specified, assessment periods were assumed to be based on the year of publication.

We extracted the data on benefits and costs (and benefit-cost ratios) from each study (Refer to Supplementary Information for a detailed overview of assessments) and, when necessary, averaged them to give single values of benefit and cost for each location. If multiple scenarios were provided for sensitivity analyses of benefits, costs, growth or mortality rates, the "base" case scenario was used. Annual values per tree were used for comparison between studies. For studies that reported total benefits, costs and net present values over a longer duration, values were annualised based on the cumulative GDP deflator of the relevant country within the assessment time period. Annualised values were adjusted for inflation from their year of publication (or year of data collection) to 2015, based on annual GDP deflator figures (The World Bank, 2016). Finally, all currencies were converted to U.S. Dollars (USD) based on exchange rates on 31 Dec 2015 (OANDA, 2016). All dollar values reported in this study are in USD.

Of the 34 studies selected, two were excluded from further analysis because the methods used yielded estimates of costs or/and benefits that differed greatly from those in other studies. One of these was the study by Chaudhry (2011), which was the only one to use the Helliwell system to determine visual amenity. At $1,642 per tree, the annual economic benefit far exceeded the values reported in other studies, which typically ranged from $7 to $165. The second study investigated five trees planted in poor locations, where annual costs exceeded $3000, largely because of the need to repair damaged infrastructure (McPherson, 2007). All statistical analyses were performed using R 3.3.2 (2016).

Results

Geographical, taxonomic and temporal scope

Most of the 34 studies on the benefits and costs of urban trees were performed in North America, and most conclusions were presented at the city level (Fig. 2). Locations with a Mediterranean or semi-arid climate characterised by a hot, dry summer were the most frequent; very few locations had either a tropical or boreal climate (Table 1). Of the 34 studies, seven included locations in different climatic zones, or compared results across climatic zones.

<insert Fig. 2 & Table 1>

The scope of the assessments, both in terms of the types of trees and the methods used, varied widely (Table 2). The majority assessed street trees, followed by those in green spaces and private gardens (Table 2). Thus, they focused mainly on planted trees, with only three analysing natural stands or remnant trees. The tree species assessed were mostly broadleaf deciduous trees, reflecting the geographical distribution of the study sites, with few studies assessing broadleaf evergreen species (Fig. 3). Only 12 out of 34 studies described the species composition, and the study by McPherson (2003) was the only one that reported species-specific costs, benefits and BCRs across time.

Most studies presented a "snapshot" of benefits and costs of established trees for a single year, and even those that considered a longer period were of short duration (i.e. 15–30 years) relative to the lifespan of most trees. Eight studies described the size or age distribution of trees in the urban forest (Table 2). Some studies attempted to assess how benefits changed over time, but few did the same for costs. Even those studies that did investigate these longer-term changes, rarely covered periods over 40 years. Species-specific allometric growth models were calculated based on samples of individual trees. As for estimates of tree mortality, the average annual mortality rates for individual studies ranged from 0.7 to 2.23%, though most studies did not assess the consequences of different patterns of mortality (e.g. high and low mortality). Indeed, only 11 studies performed sensitivity analyses in which benefits and costs, or growth and mortality rates were varied (Table 2).

Benefits of urban trees

<Insert Fig. 3 & Table 2>

<Insert Fig. 4>

Most of the studies investigated benefits relating to environmental regulation, especially improved air quality and carbon reduction, which were both reported in 20 studies, and to aesthetic or amenity value (Fig 4a). In contrast, other potentially important benefits such as biodiversity, resource provision, noise reduction, and recreation or tourism were considered in fewer than three studies. Most studies relied heavily upon the modelling methods developed by scientists in the U.S. Department of Agriculture (USDA) Forest Service, who also contributed to the development of the i-Tree software tools for the valuation of urban trees. These methods are described briefly in the following paragraphs, and more details can be found in the Supplementary Information.

1. “Aesthetic and amenity” benefits were largely quantified from the effects of trees on property sales prices revealed through hedonic pricing studies. More specifically, benefits per street tree, averaged across assessed urban tree populations, used algorithms within i-Tree Streets or it's predecessor STRATUM, which were based on a single study by Anderson and Cordell (1988). Annual economic benefits per tree ranged between $7 and $165.

2. Tree shading benefits were usually assessed by quantifying the energy savings due to reduced use of air conditioning. Energy simulations were based

on tree and building configuration data obtained from aerial photographs. Most studies used i-Tree and its predecessor algorithms that account for factors such as tree location, sky view factors, building orientation, local climate, and energy costs. Annual cooling savings per tree ranged from 23 kWh to 288 kWh while heating savings ranged from –3.06 kWh to 842 kWh. Studies that calculated net energy savings saw values ranging from 12 kWh to 919 kWh. Annual economic benefits ranged from $4 to $166 per tree.

3. The water regulating benefits of trees focused solely on rainfall interception by the canopies of individual trees, and were based on numeric models from Xiao et al. (1998, 2000). The annual volumetric benefit of rainfall interception per tree ranged from 0.28 m^3 to 11.3 m^3. Translated into economic benefit using stormwater mitigation costs, the annual benefit per tree ranged from $0.28 to $54.61.

4. Carbon reduction benefits considered carbon sequestration by biomass storage and growth, using species-specific tree growth models. Annual carbon storage per tree ranged from 11 kg to 852 kg, while annual carbon sequestration ranged from 3.5 kg to 96 kg per tree. Nine out of the 20 studies that assessed carbon reduction benefits also performed shading simulations to estimate avoided carbon emissions due to reduced building electricity usage. This ranged from 15.3 kg to 181 kg per tree. In order to obtain the net effect of carbon reduction, the costs of carbon emissions due to tree decomposition and maintenance activities were included in several studies. The value of net carbon reduction in these studies ranged from 0.1 kg to 734 kg. The average annual economic benefit per tree ranged from $0.34 to $13.38. The types of shadow prices used for economic conversion across the studies included non-traded

and traded carbon prices, as well as control costs incurred by municipal governments.

5. Benefits due to improved air quality took account of direct pollutant uptake and deposition, and were calculated using empirical multilayer- and big-leaf models (Baldocchi, 1988; Baldocchi et al., 1987). These models relied on variables such as pollutant concentrations, length of in-leaf season, precipitation levels, tree cover, as well as factors that affect transpiration and deposition velocities. Most examined the effect of urban trees on ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), as well as particulate matter less than 10 µm in size (PM_{10}). 14 of the 20 studies that assessed air quality benefits also included the indirect effect of avoided pollutant emissions owing to reduced building electricity usage caused by tree shade. Ten studies took into account disservices such as emissions of biogenic volatile organic compounds (BVOCs), to calculate net benefits to air quality (Table 3). Overall, net annual air quality benefits per tree ranged from –0.003 kg to 1.81 kg. Annual ozone reduction per tree ranged from 0.11 kg to 0.39 kg. Annual nitrogen dioxide reduction per tree ranged from 0.04 kg to 0.39 kg. Sulphur dioxide reduction ranged from 0 kg to 0.19 kg. PM_{10} reduction ranged from 0.05 kg to 0.93 kg. Following monetary conversion based on the abatement cost for each pollutant, the annual economic benefit per tree ranged from –$0.68 to $21.28.

6. Other benefits, including provision of biodiversity and resources, noise reduction, and recreation and tourism, used a range of different approaches. It is notable that the few studies to investigate these benefits were the only ones to use contingent valuation as a method (Table 2).

Overall, the mean annual benefit per tree was the highest for "aesthetic and amenity" ($51), followed by shading ($26), water regulation ($11), air quality ($7) and carbon reduction ($3) (Fig. 4b). However, the values for shading, "aesthetic and amenity", and water regulation varied very widely among studies.

Costs of urban trees

Table 3 shows the tree costs and disservices reported within the 34 studies. The majority of cost information was either obtained from official documents, or based on assumptions that costs were similar to those reported in secondary sources. Seven studies engaged in expert surveys, particularly for essential costs such as planting, removal, and maintenance. Relatively fewer studies included costs relating to hazards, liabilities, or carbon and pollutant emissions (Table 3).

<Insert Table 3>

While the majority of studies reported a generic value for tree costs, those that included a breakdown of individual costs were able to provide useful information about the care and condition of trees (refer to the Supplementary Information for details on economic costs reported in each study). For example, McPherson et al. (2005) reported that costs of tree removal in two cities with many over-mature trees ranged from 13–16% of annual expenditure, one of which also spends an additional 30% on storm clean-up and tree-litter removal. While pruning was generally the largest expenditure in most cities (27–43%), these two cities spent proportionally less on pruning.

Balance of benefits and costs

Of the 26 papers that analysed the BCR or net present value of urban trees, the benefits outweighed costs in 22 studies (Table 2). These included 14 studies that analysed a few specific benefits. One of these benefits, "aesthetic and amenity", actually outweighed mean annual costs even when considered alone.

In monetary terms, the mean annual benefit and cost per tree were $44.34 and $37.40, respectively (Fig. 4b). However, the median annual cost per tree ($25.07) was higher than the median annual benefit per tree ($21.19) across the studies reviewed. A paired Wilcoxon Rank Sum Test showed that there was no significant difference ($p = 0.60$, $n = 70$, $W = 550$) between total benefits and costs. Other joint analyses of benefits and costs included assessments of the cost-effectiveness of tree benefits (8 studies), some of which did not convert benefit values into monetary terms (Table 2). The mean BCR across all studies was 5.43, and the median 2.72 (Fig. 5).

<Insert Fig. 5>

Discussion

Joint analyses of benefits and costs

In most studies, the benefits of urban trees outweighed the associated costs, even when only one or few benefits were examined (Table 2). "Aesthetic and amenity", shading, and water regulation benefits had the highest economic valuations, and were the most likely to outweigh the costs (Fig. 4b). However, most studies focused on carbon reduction and air quality benefits (Fig. 4a), possibly owing to relative ease of calculation and current concerns about climate change and atmospheric pollution. These benefits turned out to have relatively low annual economic values, and a BCA based upon these alone would not usually justify planting trees in urban areas.

Despite the generally positive balances obtained in individual studies, the difference between mean benefits and costs over all studies was not significant.

This lack of a significant difference reflects the high variation in values, considerable differences in methods used, and the limited number of studies. Care should thus be taken when making comparisons between studies or in applying results in different contexts. For example, when we included the exceptionally high costs from McPherson (2007) in our calculations, the mean annual cost per tree increased from $37.40 to $173.00—considerably higher than the mean benefit. However, this particular study does not describe a typical situation, but illustrates the excessive costs that may arise through the inappropriate use of trees. Infrastructure damage of the kind reported by McPherson (2007) is not inevitable, and can largely be avoided through the careful choice of tree species and sites, and through appropriate management.

The studies reviewed were heavily biased towards North America, which is unsurprising given that researchers within the USDA Forest Service have been active in developing the methodology, and also in conducting surveys in North American cities. To gain a more general understanding of the benefits and costs of urban trees, research is required in other countries that represent other climates, ecosystems, and socio-economic systems, particularly in the tropics. The climates in most tropical regions are warmer and wetter, which may exacerbate problems due to the urban heat island and flash flooding (Feng et al., 2013). In addition to differences in climate and ecology, cities in the tropics also differ from those in temperate regions in human factors such as demography, economic development, and lifestyle. Such differences affect the demand for benefits and opportunities to provide them, as well as the challenges of urban forest management (Song et al., 2017).

The valuation and variability of economic benefits

The "aesthetic and amenity" values of trees were mostly assessed based on a study by Anderson and Cordell (1988), which showed that front-yard trees resulted in a 0.88% increase in the property value of low-rise residential homes in Athens, Georgia. While adjustments may be applied to account for differences in home prices, housing type, tree size and tree type (Peper et al., 2009a), this percentage is clearly not transferable to other regions, being highly dependent on local preferences and the state of the property market at the time of the study. The study by Chaudhry (2011) used a modified "Helliwell" valuation to determine visual amenity, while Dumenu (2013) used the contingent valuation method, by directly asking survey respondents their willingness-to-pay for conservation and maintenance of the urban forest. Such survey-based values are non-specific, larger in scale, and depend on the choice of sample population. Values are thus subject to greater variation, and may not capture benefits that survey respondents do not perceive as important (Price, 2014). Accordingly, such values cannot be easily combined with other amenity benefits for a more comprehensive assessment of the urban forest. There are opportunities to integrate local preference assessments within valuation studies (Plant et al., 2017), to account for the effect of large parks and forests (Crompton, 2005), as well as for differences across a broader range of property types such as high-rise housing and commercial properties (Laverne and Winson-Geideman, 2003).

Most studies used similar methods to quantify shading benefits, with particular emphasis upon savings in electricity due to reduced need for air conditioning. For example, Donovan and Butry (2009) found that the presence of trees in both the south- and west-facing quadrants of a house reduced summertime electricity use between 185 kWh and 457 kWh, depending on tree size. The highest reduction was due to trees planted along west-facing facades, because these shaded the house in the afternoon when temperatures were highest; on the other hand, trees in the southern quadrant usually provided more shade overall, owing to the southward direction of the sun's path at locations within the northern hemisphere. In wintertime however, though trees may serve as wind breaks to reduce heat loss, such relationships may be reversed as trees that block sunlight may increase heating loads, resulting in negative values for electricity savings. While i-Tree and its predecessor algorithms account for such variability, they have been developed for buildings constructed at different periods in the U.S. (i.e. pre-1950, 1950–1980, and post 1980; McPherson and Simpson, 1999), and make assumptions about energy efficiency that may not apply elsewhere.

Water regulation benefits in this review were quantified based on the ability of individual trees to intercept rainfall. Having calculated volumetric interception using statistical models that took account of meteorological and canopy architecture variables (Xiao et al., 1998, 2000), the data were subsequently converted into monetary values based on costs avoided in stormwater control. The models were very sensitive to the amount of rainfall per storm (Xiao et al., 2000), with the effectiveness of urban forests in reducing runoff declining drastically as this amount increased (Xiao et al., 1998). The benefits of rainfall interception are thus diminished at locations prone to intense precipitation, such as in the tropics, despite the importance of reducing flood risk in such areas. Future research could explore the interactions between trees and other hydrological processes such as evapotranspiration, drought tolerance, and water purification, which may contribute to other benefits such as improved forest resilience and water quality in urban areas (Sjöman et al., 2015).

Carbon reduction benefits are generally highest for large, long-lived and fast-growing species (McPherson, 2014), as these trees tend to contribute the most to carbon sequestration, reduced emissions, and especially carbon storage. Other than tree size, the variability in economic benefit, though minimal, might have been affected by type of economic conversion method, extent of infrastructure investment and local economic conditions. Importantly, net benefits are also highly affected by indirect emissions that have the potential to cause urban forests to become net emitters of carbon (Nowak et al., 2002), and cities should thus promote management practices that minimise wood decomposition and maintenance emissions, maximise shade and energy conservation, and improve tree health and longevity. Notably, recent studies of carbon emissions and storage have questioned the efficacy of urban vegetation in sequestering carbon: for example, Velasco et al. (2016) suggest that any such effect is very small, while Pouyat et al. (2006) show the potential for soil carbon storage is higher in urban areas with an arid climate than in those with a moist temperate climate. Further studies under different environments are needed to help us better understand the relationships between urban forests and soils.

There is much research interest in the air quality benefits of urban trees. Higher per-tree values were reported in cities with high pollutant concentrations, low precipitation and long in-leaf seasons (Nowak et al., 2006), and field tests have shown that factors contributing to the effectiveness of particulate matter removal include the effect of tree size, shape, deciduousness, as well as leaf morphology and anatomy (Saebø et al., 2012). To convert air quality benefits into monetary terms, most studies used shadow prices based on the cost of pollutant mitigation, while others estimated savings in healthcare (Chadourne et al., 2012). Yet another approach has been to record willingness-to-pay based upon damage values obtained from regression relationships between emissions values, pollutant concentration and population numbers (Soares et al., 2011). In accounting for net air quality benefits, the use of generic emissions factors in i-Tree models to estimate BVOC emissions in subtropical regions has shown high deviation from empirical studies (Dunn-Johnston et al., 2016). Care should thus be taken when employing these urban tree models to regions where emissions data are still lacking.

The importance of urban forest structure

Most of the studies provided estimates of the benefits and costs for inventoried trees over a limited period, usually one year. This kind of "snapshot" can help forest managers improve the efficiency of management (i.e. reduce future costs with maintenance, improve efficiency with better equipment). However, trees are long-lived organisms, and it would be better to have information of the changing balance of benefits and costs over longer periods.

One way to take track the changing costs and benefits of urban trees is to calculate BCRs separately for different size (or age) classes of trees. By considering tree size, it becomes easier to identify which species contribute most to the value of the urban forest (McPherson, 2003; Pothier and Millward, 2013). Also, linking this information to data on the age structure of urban tree populations makes it possible to estimate how benefits and costs will change over time. For example, to avoid an abrupt decline in ecosystem services, it may be necessary to forecast changes to the size/age structure of the tree population over time, and to develop a replacement strategy based upon size- or age-related BCRs. Such a strategy might also aim to increase species diversity as a means of guaranteeing the continued provision of ecosystem services.

Valuation studies are best compared when data about urban tree population composition and structure are collected and reported in a consistent manner. Improved researcher-practitioner coordination, standardised protocols and inventory sharing are needed, particularly at locations outside of the U.S. Notably, an international initiative by the Urban Tree Growth and Longevity (UGTL) Working Group (2016) aims to improve the communication between practitioners and researchers, and to align urban tree monitoring protocols between cities (see Vogt et al., 2014 for protocol). Such efforts can contribute significantly to improved comparability of results across different cities.

Limitations to urban tree economic valuation

The studies surveyed illustrate several limitations to economic valuation of urban ecosystem services, as currently practised. One limitation is the restricted scope of most studies. Very few, if any of them, considered all of the benefits and costs associated with urban trees, though this would be necessary to obtain an accurate estimate of the net benefits or BCR. Indeed, one of the important reasons for the wide variation in BCR has been the choice of benefits and costs included in different studies.

A second limitation is the inherent difficulty of assessing some benefits and costs (see Roy et al., 2012; Vogt et al., 2015). For example, trees planted in residential properties may provide benefits (i.e. aesthetic, thermal, air quality) to the surrounding neighbourhoods, while the costs of management may intertwine with those of other resources such as maintenance of roads and infrastructure, making it difficult to assess the incidence of benefits and costs (Fu et al., 2011). Many of the studies reviewed examined spatially discrete benefits at the scale of individual trees, and the cumulative values of multiple benefits can therefore be easily combined and compared alongside the costs of trees. On the other hand, effects that are experienced across larger spatio-temporal scales are challenging to assess, and may explain the lack of joint analyses between tree costs and other known benefits such as increased biodiversity, resource provision, tourism, and noise reduction. Indeed, many such benefits depend on larger patches of urban green space, and their effects can spread to surrounding neighbourhoods. Current research is filling important gaps in the benefits of urban trees to human health and well-being (De Vries et al., 2013; Thom et al., 2016), and newer methods that utilise “life-satisfaction” data have been used to place a dollar value on regional biodiversity and scenic amenity (Ambrey and Fleming, 2014). However, methodological differences and the lack of data at fine spatial scales tend to limit the wider application of such research (Wolf et al., 2015). Since some of these benefits are non-exclusive and complementary with others (Nowak and Dwyer, 2007), there is also a risk of double-counting, especially if spatio-temporal scales overlap, and if benefits are classified in a way that includes both intermediate processes and final goods or services (Fu et al., 2011).

Finally, there is a more philosophical difficulty with economic valuation; although the method may work well for planted city trees and be easily understandable by decision-makers, the approach attempts to interpret the entire value of trees in financial terms. Monetisation and commodification has helped integrate ecosystem services into markets and payment mechanisms, but there has been debate whether the outcomes have diverged toward profit-making rather than environmental conservation (Gómez-Baggethun et al., 2010). Furthermore, not all benefits necessarily make economic sense when assessed individually and at a small scale, as the results on carbon reduction and air quality improvement have shown.

Management implications and potential research priorities

While the economic valuation of ecosystem services is becoming increasingly common, we know rather little about the extent to which these valuations are actually used by decision makers (Laurans et al., 2013). Also, there have been few follow-up studies to investigate the actual outcomes of tree planting programmes for the urban environment (Pincetl et al., 2012). Indeed, existing economic valuations have been predominantly estimates from modelling tools, primarily providing an informative role for general influence and awareness-raising (Laurans et al., 2013), rather than to support spatially-explicit decisions for landscape design and management.

At the scale of single planting sites, a large variety of tools and databases allow planners to select tree species to plant based on numerous criteria (see Hotte et al., 2015). However, information provided are mostly qualitative in nature, and do not describe spatio-temporal heterogeneity in benefits and costs. Across larger spatial scales, tools within the i-Tree software suite allow users assess urban forest structure, function and value. For example, i-Tree Eco, Streets and Vue support the assessment of species diversity and canopy cover, and have been used to report tree benefits and costs within the studies reviewed. Advances in valuation methods could include alternative applications of existing valuation tools such as those in a study by Hilde and Paterson (2014), which integrated the i-Tree valuation models into a mainstream scenario planning software tool. In addition, there are opportunities to fine-tune inherent assumptions of existing models to better account for local context. At present, i-Tree has only been adapted to the U.S., U.K., Australia and Canada (USDA Forest Service, 2017). There are therefore opportunities to calibrate or adapt existing models to other locations, and to include other forms of green infrastructure.

Building appropriate evidence for investment in urban forests may also require us to look beyond specific valuation methods to broader economic decision-making frameworks. In order to balance between the complexity and specific informational needs of each decision-context, urban tree managers can consider the use of Benefit Relevant Indicators that are highly targeted and directly applicable to end users (Olander et al., 2017). For instance, Simpson and McPherson (2011) developed an index that calculates BVOC emissions based on tree species as well as planting and survival projections, while Cariñanos et al. (2017) developed an index for the planning of urban green spaces, based on the estimated allerginicity of tree species. While these do not provide a comprehensive assessment of tree contribution to air quality, such research on non-monetary costs can help ensure that the right species are planted at the right locations. Analysing the cost-effectiveness may also help decision makers explore trade-offs between a few important benefits, and help “optimize” benefits based on a wider range of possible goals other than the maximization of economic value. Economic assessment frameworks should thus offer various methods of assessment, including opportunities to measure "human demand" for benefits, through greater participatory-based planning and design (Liu and Opdam, 2014).

Finally, alongside the need for improved economic assessments of urban forests, the importance of good urban governance cannot be overlooked. Indeed, the practice of urban forestry and greening has in many cases been given significant support through policy and legislation (Feng and Tan, 2017; Tan et al., 2013). Ongoing support for relevant policy and governance continues to be informed by analyses of spatiotemporal changes in tree cover across both private and public land-use types (Daniel et al., 2016; Kirkpatrick et al., 2011) and through innovative assessments of resident preferences (Plant et al., 2017). In light of the anthropocentric nature of existing assessments, more can be done to quantify less-tangible tree benefits and costs (i.e. biodiversity and habitat provision), including the impacts of climate change and pest and disease vulnerability.

Conclusions

An analysis of 34 published studies concerning the costs and benefits of urban trees shows that in most cases the benefits of urban trees outweigh the costs. However, this analysis also reveals major gaps in our knowledge: while urban trees provide a range of benefits to people, research has focused on just a few—shading, air quality, and carbon regulation—which do not necessarily provide the greatest economic benefits. The aesthetic, amenity, and shading benefits of trees have been less studied, but our review suggests that they may be of greater value.

Intra-benefit variability is largely attributed to forest structure. However, few studies reported details such as the species, size, and age distribution of the urban forest, which would have improved the comparability of BCRs across different studies. Other gaps in research knowledge include limitations in biogeographical scope, with more studies being needed in tropical and boreal climates. Economic valuation will continue to be important evidence for justifying investment in urban tree planting and management, but its practical use for landscape planning and design will require us to explore its integration with decision-making frameworks. Ongoing improvements to allow for local context and greater consistency in benefit and cost assessment methods are needed, so that policy makers can be confident that the results provide a sound basis for decision-making.

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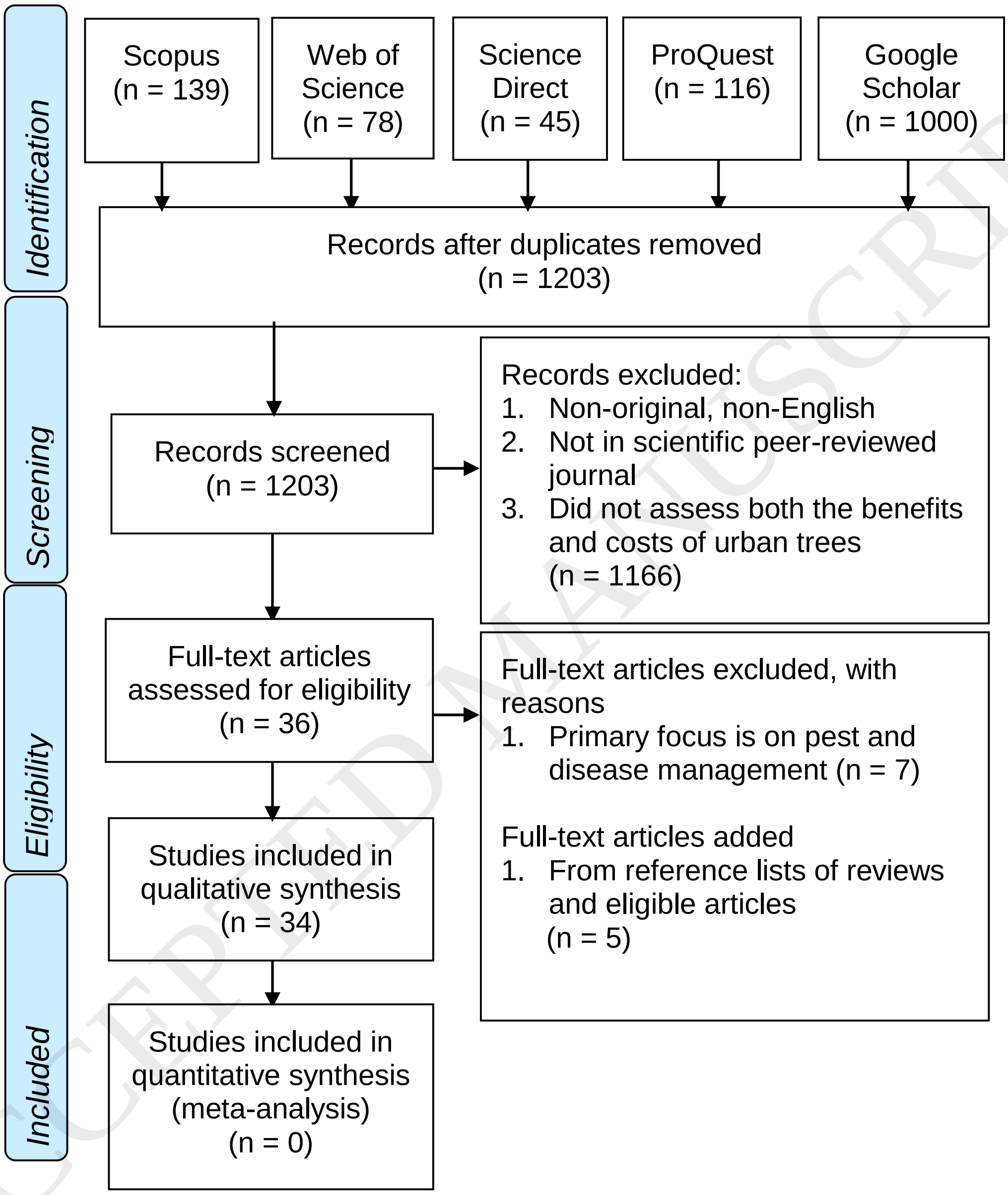

Figure 1. PRISMA flow diagram summarising the search results and screening workflow used in this systematic review. *(single column-fitting image)*

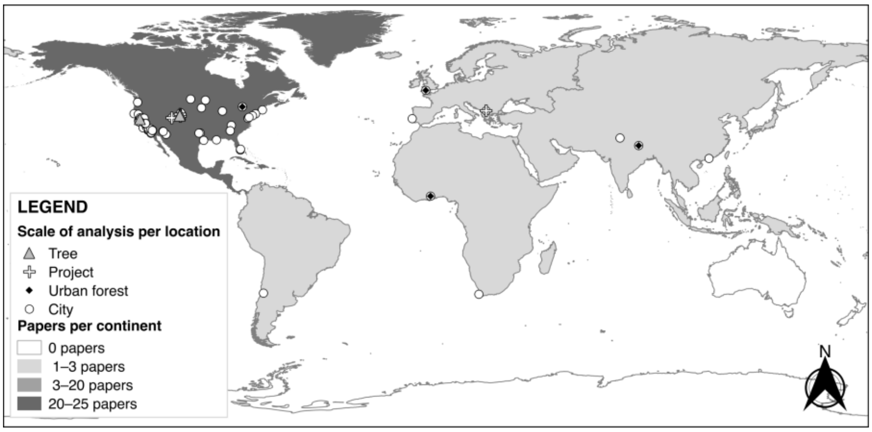

Figure 2. Geographical distribution of the locations of interest within the 34 research papers on urban tree benefits and costs. Symbols for each point represent the spatial scale of analysis used for each location. Shading of geographical areas represent the number research papers per continent *(1.5 column-fitting image).*

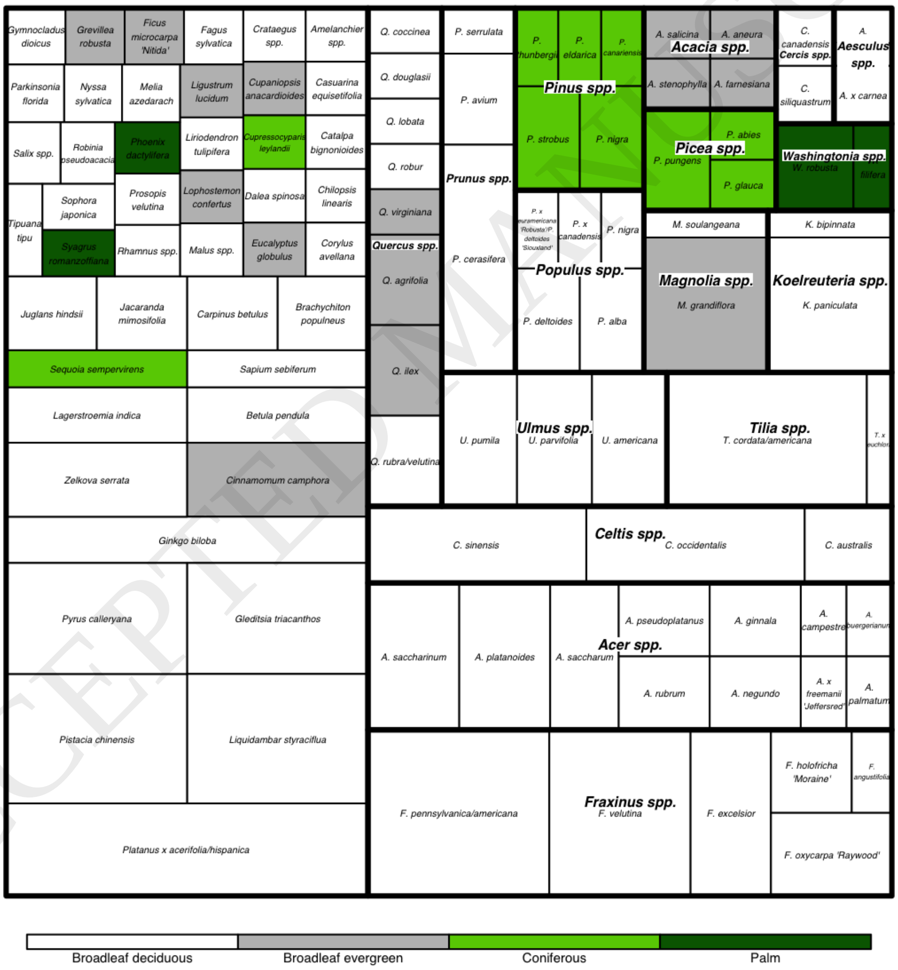

Figure 3. Hierarchical tree map showing the relative popularity of major tree species within the 34 research papers assessed in this study. The size of each box represents the number of papers that assess each species. *(1.5 column-fitting colour image on web version)*

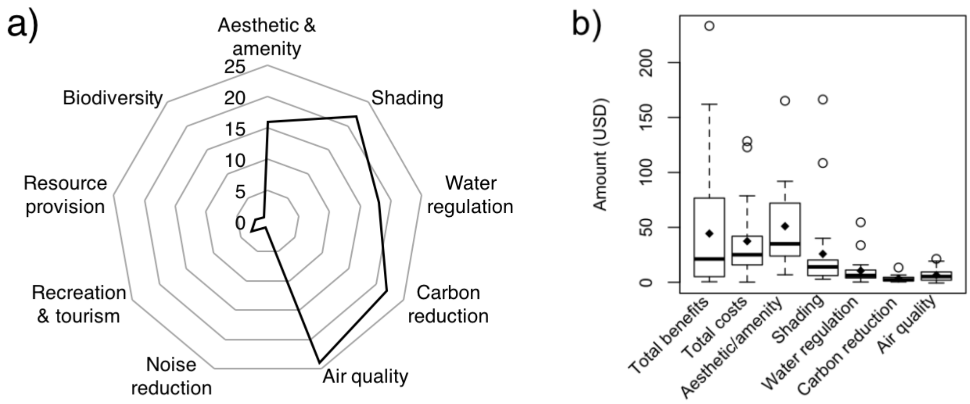

Figure 4 (a) Number of papers that analyse each benefit across the 34 studies on urban trees, and (b) box-and-whisker plot showing annual per-tree values for total benefits, costs, and each of the five commonly quantified benefits. Mean values are denoted by the diamond symbols. *(single column-fitting image)*

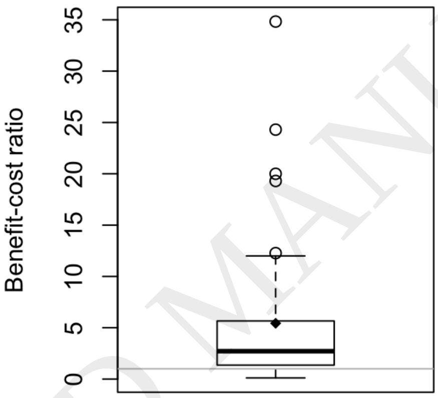

Figure 5. Box-and-whisker plot showing the urban tree benefit-cost ratios reported within the 34 research papers assessed in this study. The mean value is denoted by the diamond symbol. The break-even point (1:1 ratio) is denoted by the grey line. *(single column-fitting image)*

List of Tables

Table 1. Köppen–Geiger climate zone distribution for locations of interest within the 34 research papers on urban tree benefits and costs.

Köppen–Geiger climate zone	***No. of papers***
Tropical rainforest	1
Tropical monsoonal	-
Tropical savanna	3
Desert	4
Semi-arid	11
Mediterranean	18
Temperate hot summer	9
Maritime temperate (oceanic)	1
Temperate highland (dry winters)	-
Maritime subarctic	-
Hot summer continental	1
Warm summer continental	6
Continental subarctic	-
Tundra	-
Ice Cap	-

Table 2. Overview of scope and methods used in the 34 research papers on urban tree benefits and costs.

Urban tree assessments	*No. of papers*
Tree typologies	
Street trees	21
Green space trees	15
Private or residential lawn trees	12
Urban forest	9
Urban forest structure	
Species distribution	12
Size or age distribution	8
Benefit assessment or valuation method	
i-Tree software or its predecessor algorithms	19
Contingent valuation method	2
Joint analyses of benefits and costs	
Cost-effectiveness analysis	8
Benefit-cost analysis	26
Benefits outweigh costs	22
Assessment of a few specific benefits	14
Sensitivity analyses performed	11

Table 3. Costs included in the 34 research papers on urban trees assessed in this study.

Costs	No. of papers
Generic costs (no specific breakdown)	19
Essential costs	
Planting and establishment	29
Removal	25
Maintenance (pruning, mulching, etc.)	28
Irrigation/water use	11
Other (administration, staff, etc.)	19
Emissions	
Carbon (i.e. tree maintenance)	11
Biogenic compounds	10
Problems and hazards	
Pests	8
Damage	14
Liability	13