The Value of the Shading Function of Urban Trees: A Replacement Cost Approach

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Abstract

Cooling is one of the most important benefits of street trees, yet city planners lack estimates of the value of this benefit. Estimation of the value of the cooling effect could help to strengthen the case for investment in a tree cover as a part of the urban infrastructure for climate change adaptation. This article aims to address this research gap by presenting a novel application of a replacement cost method using the costs of parasols for estimating the value of shade provided by urban trees. Using the method, we calculated the net present value of the shade from a generic tree and used these estimates in a case study in Prague, Czech Republic. The results showed that the costs of tree planting and maintenance were higher than the estimated shading benefits in the short term (20–30 years), but the situation reversed when the tree life expectancy increased (> 40 years). Street trees are hence a long-term investment in terms of microclimate regulation. The proposed approach can assist city planners with an assessment of microclimate regulation by urban trees as it can be easily applied with local data, and can complement other methods to show the wider benefits of urban trees.

Keywords: city trees; ecosystem services; microclimate benefits; Prague; urban cooling

Introduction

Human modifications of land cover affect local and regional climate, especially in cities (Kalnay and Cai, 2003; Pielke et al., 2016). Built urban areas have higher ambient temperatures than the surrounding areas, resulting in the phenomenon known as the urban heat island - UHI (Arnfield, 2003; Gago et al., 2013; Oke, 1982). UHI is characterized by elevated temperatures compared to their rural surroundings during the daytime as well as night time (Santamouris, 2015; Zhou et al., 2014). The temperature difference is especially pronounced during winter clear and windless nights (Soltani and Sharifi, 2017). UHI has been documented in most medium and large cities in the world (Akbari and Kolokotsa, 2016; Santamouris, 2015). The higher temperatures in urban areas are caused by the emissions of anthropogenic heat, reduced vegetation, a large proportion of built-up areas absorbing solar radiation during the day, which are then slowly releasing the heat during the night, and changes in air circulation according to an urban geometry (Oke, 1982). UHI is expected to be exacerbated by climate change (IPCC, 2019) and to lead to an increasing frequency of heatwaves in cities (Christidis et al., 2015; Forzieri et al., 2016). It has been well documented that heat has adverse impacts on human well-being and productivity and presents a significant health risk (EEA, 2017; Fishman et al., 2019; Isen et al., 2017).

Green spaces provide cooler areas (Armson et al., 2012; Bowler et al., 2010; Gillner et al., 2015; Yu et al., 2020; Zölch et al., 2016); therefore, they offer a solution to reduce heat stress exposure. Vegetation regulates the climate through several processes (Bowler et al., 2010; Shashua-Bar and

Hoffman, 2000), and the relative importance of the cooling mechanisms vary with the characteristics of the plants, sites and local climatic conditions. Urban trees cool the environment mainly through shading and evapotranspiration. Leaves reflect and absorb solar radiation, preventing the radiation from being absorbed and stored in a surface (shading). The energy absorbed by a tree is then used for the plant´s processes, including evapotranspiration, thus increasing the latent heat flux that transfers the heat to the atmosphere, resulting in the air cooling (Rahman and Ennos, 2016). While shading mostly affects the local microclimate, evapotranspiration is considered important for regional cooling (Rahman et al., 2018; Rahman and Ennos, 2016). A meta-analysis (Bowler et al., 2010) shows that the average temperature is about 1°C lower in parks in comparison to a built-up urban area with similar temperature reduction during the day and night. Next, the review of Qiu et al. (2013) suggests a wider scale of the cooling effect of greenery in urban areas (0.5-4.0°C). It has been reported that temperature reduction due to tree shade is higher than the average temperature cooling by evapotranspiration (U.S. EPA, 2008). For example, Armson et al. (2012) show that shade reduces globe temperatures by up to 5–7◦C, other studies suggest that shade can reduce people's physiologically equivalent temperature by 7-15 °C (Rahman and Ennos, 2016).

Street trees provide many benefits (Elnabawi and Hamza, 2020; Niemelä et al., 2010; Roy et al., 2012), but microclimate regulation is among the most important (Takács et al., 2016). In a survey done by Camacho-Cervantes et al. (2014) shade provision was one of the most-mentioned tree-related benefits and one of the most preferred tree characteristics. Nevertheless, urban vegetation has been under the pressure from land competition with urbanization (Keeler et al., 2019; Veach et al., 2017). In a large part, this is because the societal value of the benefits of green infrastructure is rarely quantified or reflected in decisions, quite likely leading to suboptimal investment decisions (Gómez-Baggethun et al., 2010). Monetary valuation of the benefits of urban trees would enable policymakers to make informed decisions in planning urban landscapes and compare them with other investment options (Daily et al., 2009), such as grey infrastructure development.

Cost-based and benefit-based methods are generally used for assessing the value of trees (Cullen, 2002; McPherson, 2007). Cost-based methods approximate tree value from the cost for the cultivation of a comparable tree that would provide similar functions (Cullen, 2002; Ponce-Donoso et al., 2017). The most commonly applied cost-based methods use formulas (Watson, 2002) which derive the value of trees from various parameters e.g., size, location and trees' health (Ponce-Donoso et al., 2017; Watson, 2002). As the cost-based methods do not assess the benefits which trees provide to the society, benefit-based methods have been developed. They infer the value of trees from the benefits they provide, e.g., aesthetic benefits, water retention or microclimate regulation. As urban trees provide both monetary and non-monetary benefits, a variety of economic valuation methods have been applied to estimate the monetary value of all trees' benefits, e.g., discrete choice experiments

(Fruth et al., 2019; Vollmer et al., 2016), hedonic pricing (Czembrowski and Kronenberg, 2016; Melichar and Kaprová, 2013) and contingent valuation (Latinopoulos et al., 2016; Verbič et al., 2016). These methods are applied either separately to calculate the value of specific ecosystem service or in models to quantify the multiple ecosystem services provided by trees (Ponce-Donoso et al., 2017). I-tree is one of the most widely used tools based on the models quantifying diverse ecosystem services and values derived from trees' ecosystem services (Nowak, 2020).

The microclimate regulation has been mainly assessed by the changes in energy consumption of buildings resulting from tree shade and climate effects (Nowak, 2020; Pandit and Laband, 2010) and by productivity loss at different outdoor temperatures (Kjellstrom et al., 2009; Lundgren et al., 2014). The former approach does not evaluate the cooling of the outdoor environment, which is one of the most important benefits of street trees (Takács et al., 2016). The latter approach mainly applies to changes in outdoor work productivity, while many people in cities do not work outdoors and still benefit from heat mitigation by trees. Hence, a valuation of outdoor shading benefit can improve the estimation of the value of trees' benefits and contribute to a better understanding of the value of trees in an urban environment. In addition, the valuation of nature's benefits is essential for the implementation of nature-based solutions in land-use planning (Liquete et al., 2016) since it helps to better account for the diverse values associated with greenery. Furthermore, the valuation of ecosystem services is essential for improved planning policies (Diluiso et al., 2020).

In this article, we propose a variant of the replacement cost approach for the valuation of an outdoor shading benefit of urban trees. The significant advantages of the method are its transparency and low demand for the amount of data. Next, the method enables to estimate the value of cooling of an outdoor environment for pedestrians. This extends previous literature that either focused on the impact on energy consumptions of surrounding buildings or on outdoor work productivity. We developed the method for a generic urban tree in a major European city–Prague, Czech Republic–and then applied the method to calculate the value of shade from trees growing on embankments in the city centre. Nevertheless, the method can be easily adjusted and applied in another location. The method can be applied either separately to evaluate the outdoor cooling benefit only or in combination with other benefit-based methods to find the overall value of urban trees' benefits. The rest of the paper introduces the model and its assumptions and presents the results of the generic application and of the case study. Then, we discuss the results and the approach in general and conclude.

Methodology and data

Replacement cost method

The replacement cost method was applied to assess the shade benefit of urban trees. The replacement cost method estimates the economic value of an ecosystem service by the cost of replacing the service with a human-made substitute (Barbier, 2007). The replacement cost includes the investment cost as well as maintenance costs (De Groot et al., 2002; Sundberg, 2004). The method has been widely applied for the valuation of ecosystem services, e.g., water filtration and provision (Cruz et al., 2011; Heal et al., 2005), pollination (Allsopp et al., 2008), seed dispersal (Hougner et al., 2006) and wetland ecosystem services (Byström, 2000). A particular advantage of applying the replacement method, in this case, is that it evaluates the microclimate benefit only and hence, can be combined with value estimates of other ecosystem services. The method has to be applied with caution since costs are used as a proxy for benefits (Barbier, 2007). Shabman & Batie (1978) defined the following necessary conditions for the validity of the method:

1. The human-made system provides functions that are equivalent in quality and extent to the ecosystem service (the perfect substitute condition).
2. The human-made system is the least-cost alternative way of replacing the ecosystem service (the cost-effectiveness condition).
3. Individuals in aggregate would be willing to incur these costs if the ecosystem service was no longer available (the willingness-to-pay condition).

The proposed method works with the assumption that parasols, similar to trees, provide shade, which cools the local temperature by reflecting solar radiation. Shade can also be provided by other objects, but parasols can be easily placed and adjusted and are relatively inexpensive. Parasols have been used for shading for centuries since they can substitute natural sources of shade (Encyclopaedia Britannica, 2020), and they are still widely used for shading in private as well as public places. While they were exclusively used by nobility in some previous centuries, parasols are now in high demand all over the world (Mertes, 2020). We lack information on whether people are willing to pay for parasols when tree shade is not available (the willingness-to-pay condition) in general; the condition was fulfilled with a high probability in the case study (embankments in the city centre). However, public support for shading public spaces can be expected due to increasing temperatures in cities. For example, municipalities in Prague have registered an increasing demand for shading public playgrounds during recent years (Brendlová, 2019; Jaroševský, 2019). The increasing public support for shading public spaces is also probable in other cities as temperatures rise since it was observed that people prefer shaded places to direct sunlight when temperatures exceed 20°C (Zacharias, 2001). Parasols hence provide a nearly perfect substitute for tree shade; they are likely the cheapest option available, and both the private and public sectors actually pay for them. Taken together, this allowed the cost of the parasol to be used to estimate the value of the shade function.

Model assumptions

We assumed that the shade of a tree can be replaced by the shade of a parasol. The calculation of the shading benefit of a tree was based on the parasol price, assumptions about the frequency of parasol replacement, the life expectancy of a tree, and discount rates. The simple spreadsheet model (provided in Supplementary materials) was applied to evaluate the shading benefits.

Since there is a large variety of types of parasols, we assumed that trees were substituted by the type of parasols that has been installed on many playgrounds in Prague (**Error! Reference source not found.**1). The parasols on playgrounds are closer substitutes to trees than garden, hospitality or patio parasols because parasols on playgrounds have closer characteristics and usage to trees. First, parasols (or their canopies) on playgrounds are installed in spring and stand throughout the spring-summer season. Hence, they provide shade during the whole vegetated season, similar to the tree canopy. Next, the parasols on playgrounds have to be wind-resistant since they are not removed ahead of storms and other extreme weather events (similar to trees).

The model is suitable for busy areas with a lack of natural shade, e.g., along the street in front of the stores and restaurants, on playgrounds or along city streets. Parasols are usually placed in these areas as a second-best option when tree planting is not possible or when trees do not cast enough shade. For example, parasols are placed on playgrounds that lack trees but are not installed on forest playgrounds or other well-shadowed places in Prague (Brendlová, 2019; Jaroševský, 2019). Urban areas with frequent visitation ensure that demand from the urban population for the substituted service is in place.

The least-cost solution was obtained from a supplier who reported the prices of the types of parasols installed on Prague's playgrounds (**Error! Reference source not found.**1), which had a parasol canopy area of 16 m^2 (Bonita Group Service s.r.o., 2020). Based on the information provided by the parasol supplier, the canopy usually needs to be replaced every 2 years, and the canopy costs are half the price of the whole parasol. The canopies are installed and uninstalled each spring and autumn, which brings annual maintenance costs. The whole parasol is replaced every 20 years.

Figure 1 Parasols on the playgrounds in Prague. Source: (Jaroševský, 2019; Prokůpková, 2018)

The model can be adjusted to changes in the canopy area as well. However, the adjustment requires additional information on the price of a parasol canopy per $1m^2$ and installation costs since a parasol price consists of the installation costs and a canopy price which is determined by its area.

To achieve a shading effect similar to that of a tree, the benefit value was calculated as the present value of a parasol that is bought and appropriately replaced throughout the valuation period. The model was estimated for 20, 30, 40 and 50 years with the same assumptions over the whole period. Tree life expectancy is usually more than 20 years, although trees are more vulnerable and stressed in urban environments and under changing climate; hence, life expectancy is lower in city areas than in the countryside (Roman and Scatena, 2011; Smith et al., 2019). In accordance with the literature (Moser et al., 2015), we found that 20- and 30-year periods of tree life expectancy in the urban environment were a conservative estimate, while 40- and 50-year scenarios were considered rather optimistic.

Another assumption applied in the model was a 2% annual inflation. The exchange rate was assumed to be 26 CZK/EUR over the whole period, and 2%, 3% and 4% real discount rates were applied (see section *Net present value of tree shadeNet present value of tree*). The assumptions of the model are summarized in

Table 1. The same assumptions are applied in the adjusted canopy model where we assume that the area of the canopy changes every 20 years together with the replacement of the whole parasol. The installation costs and price of a parasol canopy per $1m^2$ is based on the research of parasol prices offered in the Czech Republic in December 2020. The assumptions of the adjusted model are summarized in

Table 1.

Table 1 Assumptions of the model.

	Original (unadjusted) model	Model adjusted for canopy increase
price of a parasol	769 EUR	Not applied*
frequency of a purchase of a new canopy	every 2 years	every 2 years
a new canopy price (% of a parasol price)	50%	50%
frequency of a purchase of a new parasol/ canopy increase	20 years	20 years
yearly maintenance costs	63 EUR	63 EUR
valuation period (years)	20/30/40/50	20/30/40/50
real discount rates	2%, 3%, 4%	2%, 3%, 4%
annual inflation	2%	2%
exchange rate CZK/EUR	26	26
parasol installation cost	Not applied	242 EUR
price of canopy per m^2	Not applied	40 EUR

* The price of the parasol in the adjusted model consists of the installation cost and price of the canopy which is given by the area of the canopy and price of canopy per m^2.

Tree planting and maintenance costs

Typical costs of planting and maintenance of a street tree in Prague, which were stated in the "Action plan of tree planting" (Prague City Hall, 2019), were used to compare the estimated value of a tree's shade with its costs. The typical planting costs for a street tree in 2019 were 42,350 CZK (1,629 EUR, incl. VAT), and the 5-year maintenance costs were 48,400 CZK (1,862 EUR, incl. VAT), according to this publication. The relatively high maintenance costs reflect the increased demand for watering and other related costs due to climate change.

The "Action plan of tree planting" contains planting and 5-year maintenance costs only. The report shows that the intensity of maintenance will decrease and costs will be orders of magnitude lower after 5 years. Nevertheless, the maintenance costs for the period after 5 years from planting are not stated. Based on communication with urban tree managers from the Environmental Protection Department, Prague City Hall and Technical Road Administration Prague, we assumed that the maintenance costs would decrease by 50% from the 6th year after planting (compared to an average 1-year maintenance cost in the first 5-year period after planting). A similar pattern in tree maintenance cost was also recorded in other cities (Vogt et al., 2015). We assumed an annual increase in maintenance costs in compliance with the projected inflation over the whole assessment period.

Net present value of tree shade

The net present value (NPV) was calculated to compare the cost of a tree and the value of shading benefits that the tree would deliver during its expected lifetime. Calculation of the NPV is a standard benefit-based method of expression of greenery value (Cullen, 2002; McPherson, 2007). The estimated future streams of costs were deducted from the estimated future streams of benefits and discounted finding the NPV of tree shade as follows:

$$NPV = \sum_{t=1}^{T} \frac{Benefit_t - Cost_t}{(1+d)^t}$$

where NPV is the net present value of tree shade, $Benefit_t$ is the value of the shading benefit obtained in time t, $Cost_t$ is the value of cost incurred in time t, d is the discount rate, t is the time in years, and T is the expected lifetime of a tree.

Discounting was applied to compare the costs and benefits, which will arise at different points in time. The choice of a discount rate has a critical implication since a discount rate that is too low results in overvaluation, while a discount rate that is too high results in undervaluation. The European Commission (2014) recommends a 5% real social discount rate for cohesion countries and a 3% for other states for the 2014-2020 period. However, different values can be justified, and member states are encouraged to adopt their own guidelines (European Commission, 2014); thus, each country in the European Union has adopted a different method for the calculation of social discount rates. In the Czech Republic, a government's borrowing rate was used in recent years (Hepburn, 2007) and to the best of our knowledge, there are currently no guidelines for the application of a social discount rate in the Czech Republic. Because long-term yields of government bonds were well below 3% in recent years (Trading Economics, 2020), and arguments have been made for a 3.5% social discount rate (Freeman et al., 2018), we applied a 4% real discount rate to obtain conservative estimates. A 2% and a 3% real discount rate was applied for sensitivity analysis of the results.

Methodology - case study

We demonstrated our approach on a case study of trees on the main embankments in Prague. The three embankments (Smetanovo, Masarykovo and a stretch of Rašínovo, see Figure 2) are located in the city centre and are frequently visited by locals as well as tourists. The embankments are hot in the summer months due to frequent traffic, which is a source of anthropogenic heat (Sailor, 2011) and because they are too high above the river for the water cooling effect to occur. Hence, there is a high demand for shade in this location. The roads are wide, which allows better wind flow (Wang and Akbari, 2016); therefore, heat is unlikely to be trapped under tree crowns, as some authors have suggested might happen otherwise (Shashua-Bar and Hoffman, 2003). The trees on the embankments, thus, are expected to cool the local climate.

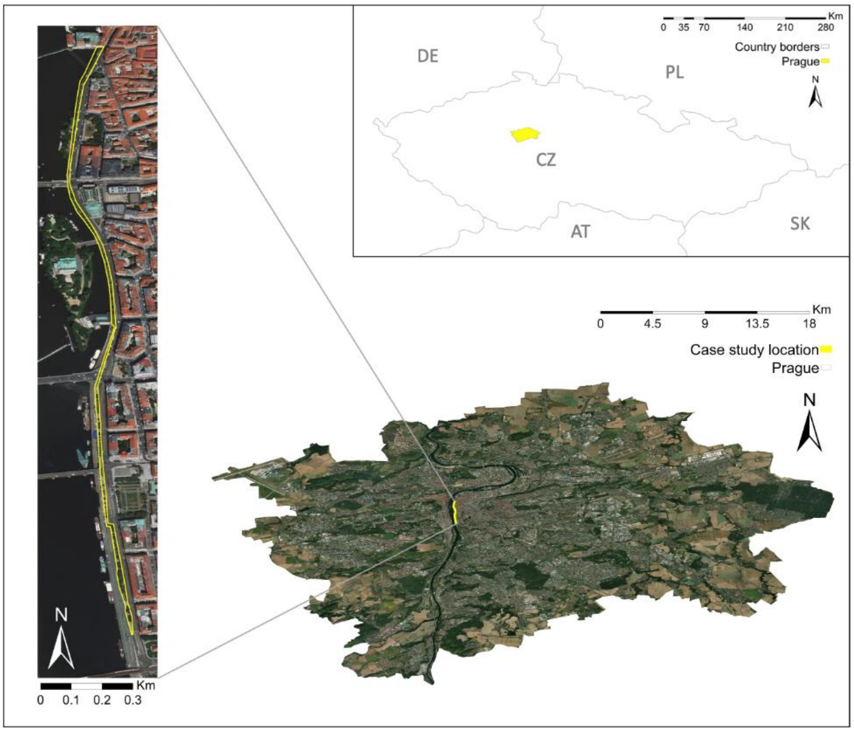

Figure 2 Location of the studied embankments in Prague, Czech Republic.

There were 174 trees on the case study embankments. All trees belonged to the linden (*Tilia*) genus. The tree height and crown diameter ranged between 4 m and 17 m and 1 m and 9 m, respectively. According to the approximate year of planting (provided by Technical Road Administration Prague), the trees were divided into 4 age categories (less than 10 years, 10–20, 20–50 and 50–80 years). Most trees are 10 - 20 years old (88 trees) or 20 - 50 years old (83 trees). The characteristics of the evaluated trees were provided by Technical Road Administration Prague and are summarized in

Table 2 and Appendix 1.

Table 2 Average crown diameter, tree height and stem diameter according to age categories.

Age category (years)	Avg. Crown diameter (m)	Avg. Tree height (m)	Avg. stem diameter (cm)	No. of trees
< 10				1
10 - 20	3.5	7.4	17.1	88
20 - 50	5.2	8.1	28.4	83
50 - 80	7.5	14.5	59.5	2
Total	4.4	7.8	23	174

The assessed trees were assumed to live from 40 to 50 years since the 20–50 age category was abundant, while there were only 2 trees older than 50 years. This life span is in line with the expected tree lifetimes in other cities (Moser et al., 2015) and with the model assumptions. Equally, the model assumption about the length of a conservative scenario (20 and 30 years) corresponded to the case study. If we assume that crowns are circles and that trees provide shade by the area of crown diameter, then each tree provides 15.2 m^2 of shade on average (an area under a tree with a 4.4 m crown diameter). The area under the youngest trees (age category 10–20 years) was 10.2 m^2 on average and 21.2 m^2 for the trees aged from 20–50 years. Trees older than 50 years had an average area of 44.2 m^2 under a tree. Hence, even relatively young trees provide plentiful shade, and the assumption about the area of a parasol canopy (16 m^2) does not overestimate the area of shade that a tree provides. In reality, the trees provide more shade because the sun is not directly over the tree most of the time, so the size of the shade area is also determined by the tree (crown) height.

Since the location-specific cost data were not available, we approximated the past planting and maintenance costs with the current planting and maintenance costs discussed above (Prague City Hall, 2019). The past planting and maintenance costs are likely to be lower than current costs due to increased watering and other related costs induced by climate change.

Results

The present values of tree shade are summarized in Table *3*. The value of shading ranges between 4,362 EUR and 9,163 EUR depending on the discount rate and the length of the valuation period. The value of the shading is 47-77% higher after 50 years in comparison to the 20-year valuation period. When the 2% and 3% discount rates were applied, the value of the shade increased by 19-43% and 9-18%, respectively, compared to the 4% discount rate.

Table 3 *Present value of a tree shade based on the replacement cost method (in 2019 EUR).*

	20 years	**30 years**	**40 years**	**50 years**
PV (2% d.r.)	5,170	6,702	8,132	9,163
PV (3% d.r.)	4,737	5,929	6,934	7,594
PV (4% d.r.)	4,362	5,293	6,002	6,427

Table 4 presents the net present values of the shade from a tree planted in Prague over 20, 30, 40 and 50 years. The present value of costs exceeded the present value of shading for all discount rates in the 20-year valuation period. The NPV was positive for the 2% discount rate in 30 years and longer periods. When the 3% discount rate was applied, the NPV was positive for 40 and more years. The 4% discount rate resulted in the negative NPV in all valuation scenarios even though the costs nearly equalized the shading benefits in 50 years.

Table 4 Net present value of a street tree shade in Prague (in 2019 EUR).

	Net Present Value			
discount rate	**20 years**	**30 years**	**40 years**	**50 years**
2%	-377	30	538	812
3%	-511	-197	154	328
4%	-623	-380	-136	-26

The results indicated that the estimated value of a tree shade over a conservative scenario (20 - 30 years) was lower than the planting and maintenance costs of the tree, while the value of the tree shade was higher than the costs over a longer period (40–50 years).

The NPV of the shade provided by the trees growing on the described embankments is depicted in

Table 5, and it corresponded more to the NPV of the trees, which would replace the trees currently growing there since we used the planting and maintenance costs paid for new planting in 2019. The results indicated that the value shading of the trees growing on the embankments exceeded the tree costs in valuation periods of 40 years and longer.

Table 5 Net present value (NPV) of a shade of trees growing on the embankment in Prague (Smetanovo, Masarykovo and a stretch of Rašínovo) in 2019 EUR.

	NPV			
discount rate	**20 years**	**30 years**	**40 years**	**50 years**
2%	- 65,552	5,286	93,697	141,368
3%	-88,904	-34,329	26,789	57,006
4%	-108,343	-66,167	- 23,739	-4,491

The results of the model adjusted for the canopy increase are stated in Appendix 2. The results are indicated for 3 different changes in the canopy extent. The first table includes the results for the area of the canopy 10m^2 in the first 19 years, 18 m^2 in the 20th – 39th year and 20 m^2 from the 40th year onwards. The second and the third tables include the results for the area of the canopy 12m^2, 18 m^2, 20 m^2 and 12m^2, 16 m^2, 20 m^2, respectively, for the respective periods. The results indicated that in the first 20 years the value of the shade in the adjusted model was lower than in the original model. Yet, the shade value in the adjusted model exceeded the original model shade value in a longer period. The assumptions about the canopy changes and discount rate affect the differences in the results of the adjusted and original model.

Discussion

The results indicated that in terms of cooling cities, planting trees was valuable when the trees had a long-life expectancy. If the trees were replanted every 20-30 years, then the trees would generate fewer shading benefits than the costs invested in their establishment and maintenance, with all things holding equal. Which corresponds to Moser et al. (2015) who found that shading from urban trees increases with the age of the trees. Our findings were caused by high planting costs in comparison to the cost of purchasing a parasol, and by high tree maintenance costs in the first 5 years after planting. Next, parasols have lower installation costs but need regular reinstallation and yearly upkeep during the entire assessment period. The choice of a discount rate was also important for the results. The higher the discount rate was, the lower the NPV since the high values of a discount rate implies that a society values present benefits more than future ones. The results of the model adjusted for the canopy increase indicate that the shade value is lower than the value obtained from the original model in the first part of the valuation period. However, the values from the adjusted model get over the values calculated in the original model in the long run. In the adjusted model, the total value of the shade depends on the assumptions about the canopy changes and the length of the valuation period and can be both, lower and higher than the shade value calculated in the original model. The adjusted model is more complicated and data demanding compared to the original model. Hence, for a quick brief assessment and/or for assessment by non-specialists, the un-adjusted (original) model is more suitable.

Next, it is also important to note that the provision of all ecosystem services, including shading and tree life expectancy, is affected by tree health and vitality (Brune, 2016). Hence, tree growth monitoring, care and species selection considering climate sensitivity are central for trees' functioning and delivery of ecosystem services.

While the results presented estimated benefits and costs for generic trees in Prague, we acknowledge that costs and benefits might be context-dependent and spatially heterogeneous. The planting costs for trees likely vary according to the location in the city. Higher tree costs can be generally expected in the city's central areas due to less available space and higher opportunity costs, e.g., because of demand for parking or street shops. At the same time, shading benefits are likely to be higher in densely populated areas, which are often more likely to suffer from the UHI effect. Low sensitivity to the demand side of ecosystem services could be one of the critiques of the replacement cost approach; hence, caution should be applied to whether shading is in demand when applying this method. A possible solution to this problem is to use biophysical modelling of heat stress in cities and apply this method in areas that are projected to be under severe heat stress (see, e.g., Geletič et al. (2019)).

To keep the model simple, some simplifying assumptions (e.g., the constant area of a parasol canopy and the same shading benefits from all tree species) were applied. The calculation of the shading benefit would be more accurate if an increase in the canopy of a parasol was considered, similar to tree crown growth. However, as the results of the model adjusted for canopy changes showed (Appendix 2) this assumption did not affect the overall results much. Next, we assumed that the same shading benefits were obtained from all trees despite trees differing in their shading depth and potential to reduce the temperature by shading (Gillner et al., 2015; Rötzer et al., 2019). The model can be applied to account for different species if needed (e.g., if we assess trees with big differences in a canopy size) by using parasols of a different canopy size. As a larger parasol is more expensive than a smaller parasol, the shading value of a bigger canopy tree will be higher than the shading value of a smaller canopy tree. Accounting for growth conditions and tree species would improve the model, but it would significantly increase the data requirements (e.g., data on the species composition and tree characteristics; especially data on the leaf area index are not usually available), and at the same time, it would not considerably improve the estimates.

Street trees alter and cool the local climate not only by shading but also by evapotranspiration (McPherson and Rowntree, 1993; Shashua-Bar et al., 2009), which was not evaluated in this study. The valuation of tree evapotranspiration cooling using the replacement cost method was proposed in Moss et al. (2019). This approach infers the value of evapotranspiration from the electricity consumption of evaporative coolers with the same cooling power as evaluated trees. The method requires data on the energy removed by evapotranspiration from the atmosphere. Data on the amount of removed energy are less accessible since this variable has to be quantified in a biophysical study. Next, the shading effect has the biggest effect on a local scale (Rahman et al., 2018), and tree shade alone decreases wall surface temperatures by up to 9°C and external air temperatures by up to 1°C (Berry et al., 2013). Thus, the valuation of the shading benefit probably represents a conservative estimate of the tree cooling benefit.

The results were affected by the assumptions of the model, uncertainties in future costs and tree health and stressors, especially in the context of a changing climate. Therefore, it is important to put the results in the context of the broader benefits that street trees provide, which are very likely to strengthen the case for the investment in urban trees. In addition to microclimate regulation, street trees provide further value to the urban population. Especially street trees support stormwater management, remove air pollution, sequester carbon, increase the infiltration capacity of urban watersheds and have a positive impact on mental health (Berghöfer et al., 2011; Keeler et al., 2019). Other ecosystem services can be quantified according to other methodologies, e.g., tree's carbon sequestration and storage value can be calculated using the i -Tree methodology (Nowak, 2020) or IPCC methodology (Penman et al., 2003). The values of other ecosystem services can be added up to the values calculated by the proposed method due to the complementarity of the proposed method with other ecosystem services assessment methods. If we account for the value of more ecosystem services, the value of benefits which trees provide would be much higher than the results in the presented study. McPherson et al. (2016) found the annual value of five ecosystem services provided by California's street tree population amount to 110.63 USD per tree, which is 5.82x more than an average annual cost per tree management. This finding is close to the benefit-cost ratio (5.60) for New York (Peper et al., 2007). In another study, McPherson et al. (2005) found that street and park tree benefits and benefit-cost ratios ranged from $31 to $89 per tree and from 1.37 to 3.09 respectively in five US cities. The largest benefit was the effect on property values (McPherson et al., 2016) and aesthetic & other benefits (Mcpherson et al., 2005). However, it is important to note that street trees also cause disservices, e.g., the production of pollen and organic waste, destruction of pavements by tree roots, and increase in energy consumption for lighting and winter heating costs or blocking of wind flows (Escobedo et al., 2011; Lyytimäki and Sipilä, 2009).

The notable advantages of the proposed method are its simplicity and applicability for the assessment of cooling an open-air environment, from which more people benefit than from cooling buildings. An accurate assessment of microclimate benefits through the impacts on energy consumption of adjacent buildings, which is applied, e.g., in i-tree (Nowak, 2020), requires a large amount of locally specific data, e.g., about a period of construction and energy use in the buildings. Hence, the international application of the i-tree is limited (Moss et al., 2019). Since the assessment of all relevant costs and benefits is essential for efficient decision making, the method can assist city planners in estimating the value of urban tree benefits.

Conclusions

An increase in urban tree cover is an adaptation measure to climate change in built-up areas. Trees provide protection from the sun and help to mitigate heat stress. However, the value of this 'street shade' benefit is rarely, if at all, reflected in planning, which is likely to decrease the case for investment in urban green infrastructure, including trees, over alternative investments. This paper provided an approach to partly remedy this imbalance. It presented a novel application of a replacement cost method that used the costs of parasols to approximate the value of the shading that urban trees provide (the spreadsheet model is provided in Supplementary materials). We applied the method to a case study location in Prague, Czech Republic. The case study results indicated that the value of shade was lower than the cost when a tree´s life expectancy is low (below 30 years), but it exceeded the cost as life expectancy increased. Nevertheless, other benefits trees provide could make up for the higher costs in the short term. The approach can be combined with valuation methods of other services trees provide, enabling more informed investment decisions in urban planning. The proposed application of the replacement cost method for a tree's shade estimate is suitable for the valuation of trees growing in areas that are frequently visited (in summer) and those with high demand for refuge from the sun, e.g., in city centres and commercial areas. The proposed method represents a quick, easily applicable and easily understandable approach for the assessment of tree microclimate benefits. Given the data availability related to costs of parasols, tree planting and maintenance, the proposed approach could be implemented in other cities that are expected to be under heat stress and that are considering investments in the extension of urban tree cover. The method could be also used to provide estimates of the value of existing trees. Indeed, the relative simplicity of the proposed approach might be an open door for a wider appreciation of the use of urban tree benefits in city planning. The method is based on an exchange value concept and therefore could be potentially used within urban ecosystem accounting (United Nations, 2014). Yet, care needs to be taken in the application of our approach to ensure that the method satisfies the validity conditions in the concerned locations (the lowest costs of parasols, in areas that are frequented in summer and need shade from the sun). The method may be extended in the future, including more closely specifying these conditions. Furthermore, the method could be extended to account for the assessment of the evapotranspiration cooling process and the extension of the model with other variables.

Appendix 1 – Case study - characteristics of the evaluated trees growing on the main embankments in Prague (Smetanovo, Masarykovo and a stretch of Rašínovo).

Smetanovo embankment				**Rašínovo embankment (the stretch between Jirásek and railway bridge)**		
	Stem diameter (cm)	Tree height (m)	Crown diameter (m)	Stem diameter (cm)	Tree height (m)	Crown diameter (m)
min.	11	4	1	11	4,5	3
max.	53	12	9	48	13	9
average	25.4	6.9	4.8	21.2	8.0	4.3
No of trees	57			89		
Masarykovo embankment				**Total (all embankments)**		
min.	13	5	3	11	4	1
max.	66	17	6	53	17	9
average	23.9	8.8	3.9	23.0	7.8	4.4
No of trees	27			173*		

Species	**No of trees**
Tilia tomentosa	63
Tilia cordata	33
Tilia platyphyllos	21
Tilia x europaea ´Pallida´	57
Total	174*

Age category	**No of trees**
< 10	1*
10 - 20	88
20 - 50	83
50 - 80	2
	174*

* We only lack measurement of the tree younger than 10 years; hence, this tree could not be included in the top table, and the total number of trees was 173 and 174 in the top table and in total, respectively.

Species	**No trees in the age category**			
	< 10	**10 - 20**	**20 - 50**	**50 - 80**
Tilia tomentosa	0	15	47	1
Tilia cordata	0	5	28	0
Tilia platyphyllos	1	11	8	1
Tilia x europaea ´Pallida´	0	57	0	0

Appendix 2 – Results of the model adjusted to the canopy changes - Present value of a tree shade based on the replacement cost method (in 2019 EUR).

The tables include the present value of a tree shade based on the model adjusted to canopy changes after 20 years and the difference of the present value of a tree shade calculated in the original model (without canopy optimization) and in the adjusted model. The results are stated for 3 different canopy increases.

a) Area of the canopy: 0 – 19 year: 10m^2, 20 – 39 year: 18 m^2, ≥ 40 year: 20 m^2

	Model adjusted for canopy changes				Model without canopy optimization minus model with canopy adjustment			
	Valuation period (years)				Valuation period (years)			
	20	30	40	50	20	30	40	50
PV (2% d.r.)	4,726	6,557	8,316	9,629	-444	-144	183	466
PV (3% d.r.)	4,309	5,734	6,968	7,809	-428	-195	34	215
PV (4% d.r.)	3,950	5,062	5,932	6,473	-413	-231	-71	46

b) Area of the canopy: 0 – 19 year: 12m^2, 20 – 39 year: 18 m^2, ≥ 40 year: 20 m^2

	Model adjusted for canopy changes				Model without canopy optimization - model with canopy adjustment			
	Valuation period (years)				Valuation period (years)			
	20	30	40	50	20	30	40	50
PV (2% d.r.)	5,107	6,938	8,696	10,010	-63	236	564	847
PV (3% d.r.)	4,663	6,088	7,322	8,163	-74	159	388	569
PV (4% d.r.)	4,281	5,394	6,263	6,804	-81	100	261	377

c) Area of the canopy: 0 – 19 year: 12m^2, 20 – 39 year: 16 m^2, ≥ 40 year: 20 m^2

	Model adjusted for canopy changes				Model without canopy optimization - model with canopy adjustment			
	Valuation period (years)				Valuation period (years)			
	20	30	40	50	20	30	40	50
PV (2% d.r.)	5,053	6,763	8,440	9,754	-118	61	308	591
PV (3% d.r.)	4,619	5,950	7,126	7,967	-118	20	192	373
PV (4% d.r.)	4,244	5,283	6,112	6,653	-118	- 10	110	226

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