VISUALISATION AS A TOOL TO GUIDE OPTIMAL BENEFIT FROM STREET TREE PLANTING

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Abstract

Urban heat islands have been shown to adversely affect people´s health and wellbeing. Urban trees have the potential to modulate the urban climate by intercepting precipitation, reducing wind speed and cooling local temperatures through evapotranspiration, thus helping to mitigate the urban heat island. By providing shade and reflecting solar energy they also protect people from ultra-violet radiation. However, it is important to choose the right tree for a given location to meet this, climate regulation, as well as other local urban forestry management objectives, such as positively influencing human health.

This research sought to create a model to assist urban planners and managers in the selection of preferential planting locations for street trees according to their shading potential. This required trees to be considered as part of the street-scape. Shade projected by adjacent buildings was taken into account, as was orientation, in the modelling process. A three-dimensional landscape visualisation technique is employed. Trees of different sizes, planting design, location, and streets of varying width, with differing building heights and orientation were considered across a one-year time window to illustrate and measure shading provision.

Using Buckingham Palace Road, London as a case study the visualisation tool demonstrates that street orientation and height of surroundings buildings had a reducing effect on the number of hours the trees received direct solar radiation and cast shade. The number of hours varied from eight hours daily in summer to three hours daily in winter. The visualisations were presented to London Tree Officers to assess their potential as planning and communication tools.

Introduction

Urban populations, globally, are forecast to nearly double by 2030, increasing from 2.84 billion (in 2000) to 4.9 billion (Secretariat of the CBD, 2012). This poses numerous challenges to the quality of life of urban dwellers. Cities, for example, are particularly vulnerable to the direct impact of increasing average temperatures from climate change as they are already warmer than the surrounding countryside due to a phenomenon known as the urban heat-island effect (Oke, 1989). Heat-related stress already accounts for around 1,100 premature deaths per year in the UK (Doick and Hutchings, 2013).

Trees help regulate the urban climate. Indeed, increasing the extent of tree cover is suggested as one of the most cost-effective ways of mitigating urban heat-island formation (Akbari et al., 1988). Furthermore, it has been reported that an approximately 10% increase in green cover in dense urban areas of Greater Manchester could negate all projected increases in maximum surface temperatures due to climate change in the 2050s (Gill et al., 2006).

The cooling mechanisms of trees are linked directly with specific morphologic attributes. Firstly, trees provide shade preventing solar radiation from reaching and warming street and building surfaces. Canopies that are larger cast more shade and denser canopies prevent more of the solar radiation reaching built surfaces. Secondly, part of the solar energy is reflected back into the atmosphere as indicated by the vegetation's albedo, which is relatively high when compared with other typical urban materials.

It is important to consider which of these properties of urban trees are desirable given local climatic conditions. Some locations require shade during the summer, but not necessarily during the colder winter months. Others need vegetation to help control the flow of excess precipitation to drainage. Shading may be desirable in parking lots or to reduce cooling energy demands of buildings. However, pedestrians might like sunny walkways in places were summer temperatures are milder. Therefore, it is important to choose the right tree and the appropriate location when considering urban forestry planning and management.

An increasingly useful tool for allowing consideration of variables in planning and decision making is ‘visualisations’: defined as computer-generated images based on geodata that allow the generation of 3D perspective views from a potentially limitless number of different viewpoints and which can range in terms of realism from abstract to photo-realistic (Ervin, 2001; Sheppard and Salter, 2004).

Visualizations are commonly used by architects and urban planners for built infrastructure and also in the planning and design of green spaces. They are also widely used in landscape visualisations for (rural) forestry management, spurred on by the research demonstrating its effectiveness and advantages (e.g. Orland, 1992, Meitner *et al.*, 2001; Sheppard and Salter, 2004). Their use among urban forestry managers and planners is less common (Macias, 2016). However, urban forest attributes such as land cover, forest structure, species composition and condition, as well as heat island effects and carbon storage can be derived from the timely and extensive data provided by GIS geospatial tools (Ward and Johnson, 2007). Geospatial tools adapted for urban forest applications can include data fusion, virtual reality, and 3D visualisation. 3D visualisations, for example, have been used to assist in urban forestry planning and management by displaying modelled air pollution and air flow (Maktav *et al.*, 2005).

The main aim of this research was to develop a model to assist urban planners and decision makers in the selection of priority planting locations for street trees according to shading potential. To this end, the research:

- employed three-dimensional landscape visualisations to calculate shade provision by two different trees species in different case study locations and quantify changes in shading over the course of a one-year time frame;
- presented examples of the case study visualisations to tree officers in London to assess the fitness-for-purpose of the created model; and,
- provided indications on how to continue developing the model to adapt it to other locations and case study sites.

Methods

Case study

The chosen case study was Buckingham Palace Road in London, UK. It is 1.1 km in length and varies in width from ca. 18 to 35 m. The orientation of the street is approximately north-northeast-south-southwest, with a 22.4 degree inclination. Its canyon ratio (building height-to- street width ratio) ranges from 0.6 to 1.0 (Macias, 2016). Specifically, along the three main sections of Buckingham Palace Road it ranged 0.6-0.7: Eccleston Street to Elizabeth Street; 0.7: Eccleston Street to Grosvenor Gardens; and 0.6-1.0: Elizabeth Street and Ebury Bridge. To calculate the street canyon ratio, building height was estimated based on number of storeys multiplied by 3.5 m, and street width was measured in Google Earth™, including pavements and front gardens where appropriate.

Study unit

In order to standardise the methodology for use in other locations and street typologies, a ’street unit’ was defined as one section of street 50 m long with a determined width and buildings on both sides. One street unit was considered in the study, being alternatively populated by trees varying in species, location within the street scape and spatial distribution. The width of the street and the height of the buildings along the street unit were, for the purposes of this study, those corresponding to Buckingham Palace Road between Eccleston Street and Grosvenor Gardens, with its centre at 51º29'41.31''N and 0º08'46.48''S.

Considered variables

When considered in isolation, the shade cast by a tree depends on its dimensions and the angle at which light projects onto its surface. When trees are planted along a street, the buildings around them intercept solar light, casting their shadows on them, the surrounding terrain and adjacent buildings.

When considering the interaction between tree characteristics and the context in which those trees are found, the shade cast by a street tree depends upon geographic latitude, time and time of year, street dimensions, and the characteristics of the tree. Latitude and time of the day determine the angle at which light from the sun contacts the Earth surface at a specific location. The further from the perpendicular that angle is the more elongated the shade cast and the less intense the solar radiation. For this study, latitude, street canyon ratio and street orientation of the street unit were fixed, corresponding to Buckingham Palace Road. Sun trajectory moves east to west, so street orientation constitutes an important factor to determine the number of hours that solar radiation reaches a street's surface.

Street characteristics establish the period of the day during which sunlight reaches the trees and, therefore, cast shade. High buildings block more sunlight than low ones but wider streets have more surface in which to locate trees outside the building's area of influence. Both variables are included in the street canyon ratio.

The physical characteristics of a tree: size, shape and opacity, determine the size and quality of its shadow. By changing these, shade provision can be altered. Different tree species have different crown shapes and sizes, but crown shape can be altered by human intervention too; for example, pollarding. Deciduous trees lose their leaves during the autumn and winter, intercepting less light during those months (transmissivity can be reduced by 80% or more in the summer compared to 10-15% in the winter). For simplicity, a fully-leafed tree was been modelled in each calendar month; in future work, autumn/winter shade can be calculated by applying a crown transmissivity correction factor.

For the purposes of this study, two tree species commonly used as street trees in London were modelled:

1. Big tree: London plane (*Platanus x hibrida*)

Height at maturity: 20-30 m
Spread typically matches the height in unpollarded or crown managed specimens
Pyramidal crown shape in youth, more wide spreading with age
Shading capacity: Rated as dense in leaf and moderately low out of leaf (SelectTree, 2013)

2. Small tree: Callery pear (*Pyrus calleriana*)

Height at maturity: 12-20 m
Spread typically 1/3-1/2 its height
Tear-drop shaped in youth, spreading out with age
Fast growth
Shading capacity: rated as moderately dense in leaf and moderately dense out of leaf (SelectTree, 2013)

The final tree dimensions used in the modelling are presented in figure 1. They are adjusted from the literature values to comply with street tree crown height recommendations and because urban trees crowns cannot spread as much as the ones from trees growing in open spaces due to the adverse growing conditions and space constrictions.

Figure 1. Dimensions of *Platanus x hibrida* and *Pyrus calleriana* models. Source: Own elaboration

Two planting densities were envisaged as representative for street trees (figure 2). High density was defined as trees planted with a distance between them that is equal to their maximum diameter crown. In high density, mature trees will form a continuous canopy cover along the street. Low density was defined as trees planted two maximum crown diameters apart. Mature trees planted at low density do not form a continuous canopy cover. Though two densities were defined, only low density is considered herein as it is more typical of UK streets.

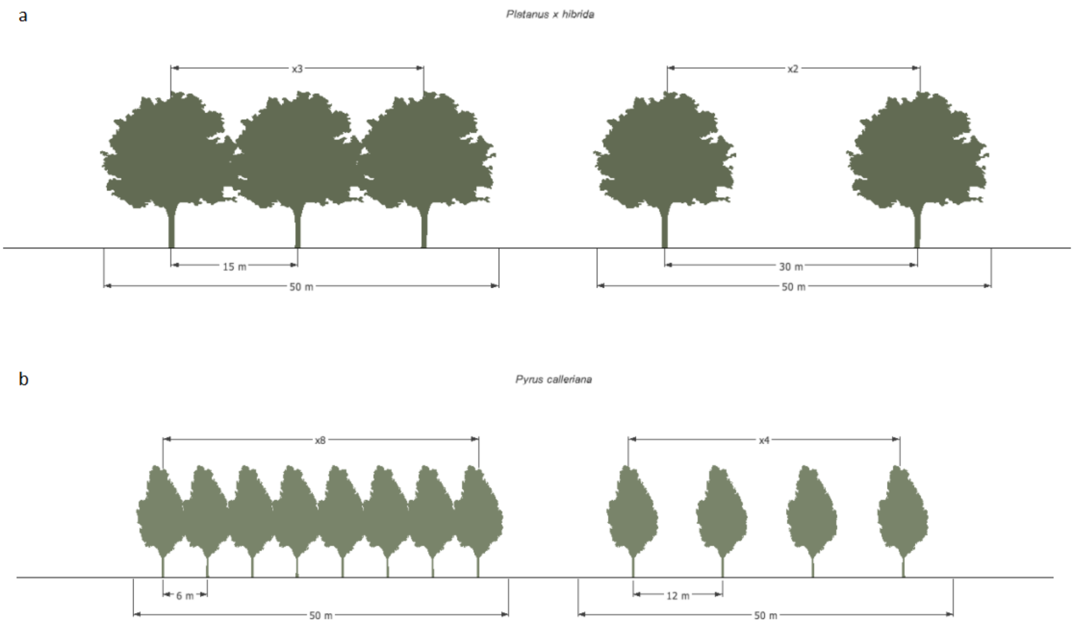

Figure 2. High and low density planting design for London plane (2a) and callery pear (2b).
Source: Own elaboration

The variables considered in the different simulation scenarios are summarised thus:

1. Tree:
    a. Size:
        i. Big trees, represented by *Platanus x hibrida* (London plane)
        ii. Small trees, represented by *Pyrus calleriana* (Callery pear)
    b. Location: trees planted on the western side of the street only
    c. Density: trees planted at low density only, leaving the equivalent of one mature tree diameter crown in between them.
2. Time:
    a. Seasons: each scenario has been modelled for one day of each season:
        i. Spring, 1st March
        ii. Summer, 1st June
        iii. Autumn, 1st September
        iv. Winter, 1st December
    b. Hours: each scenario was been modelled every hour from 4 am to 8 pm, taking the longest day of the year as reference, for 17 hours in total.

Figure 3. London planes (3a) and callery pear (3b) planted at low density on the western side of the street.
Source: Own elaboration

Visualization modelling

The landscape visualisation and 3D modelling software chosen for this study was SketchUp (version Pro 8 from Trimble). It allows easy importation of CAD files and geolocation of the models based on actual coordinates and Google Earth integration. Once the scene is correctly located and oriented, and by specifying a specific time, day and month in the Shadows Menu, the software is able to model the shadows based on the geographic position.

Each of the described scenarios was modelled into a three-dimensional scene in which the terrain was populated by objects common to the urban landscape: buildings, sidewalks, pavement, and trees. Accessory elements such as street lights, traffic lights, bollards, bus stops, fences or phone boxes can be added to make the scene more realistic and add a sense of place. However, for this study sense of place and realism were not needed; the aim was to create abstract representations.

Detailed models of adjacent buildings were not required. Instead, texture-less simple parallelograms were used because we were only interested in their volume, the space they occupy and the shade they cast. These simpler contoured buildings were created by extruding building contour shapes to their corresponding heights, with heights measured either from reviewed detailed models from Google Warehouse or estimated based on number of storeys.

To minimise interferences when rendering the shade cast, trees were modelled based upon a billboard-type object. In a three-dimensional scene, we have a three-dimensional terrain that can be populated by different types of objects. Some of those objects will be three-dimensional, while others will be planar or lines. In computer modelling, three-dimensional objects are occasionally represented by a textured two-dimensional billboard consisting ofa plane silhouette of the actual object.

Billboards face the camera rotating on its z axis, giving the appearance of an object with volume. But when seen from above, billboards appear planar and almost completely disappear. This characteristic represents a crucial advantage in our case, as the trees themselves will not mask or interfere with shade renders with the camera in an overhead position. This is possible because, even though tree billboard objects “disappear” in top view renders, they still cast shadows, rotating on their z axis to face the sun at the different times of the day.

Image Processing

A total of 136 images were rendered and exported as 1920x964 pixel tiff files to retain maximum image quality. The image files were imported into Gimp 2.8 (GNU Image Manipulation Program) image processing software to calculate the shaded area via pixel counting. The automatic selection tool was used to isolate shaded areas and count the number of pixels, by selecting contiguous pixels with similar colour.

In addition to the 136 images with street trees, auxiliary renders were created for each day and hour to separate the shade cast by buildings. By importing both as layers into a single file, changing the colour of the mask and fusing layers it was possible to isolate the shade cast by the trees using the automatic selection tool.

The shades cast by the trees extended along the surface of the street unit and also beyond it. Only the shaded pixels included inside the street unit were taken into account in this study. Finally, the number of pixels was converted into an area (m^2) of shading based upon the total number of pixels in a street unit of known area.

Interviews

The visualisations and shading results were tested to evaluate their potential usefulness and applicability by presenting them to urban forestry managers (some of whom worked within planning). The visualisations were presented during sixteen one-to-one semi-structured interviews (lasting 30 to 60 minutes) with London tree officers from 13 of the 33 boroughs.

The use of visual stimuli during semi-structured qualitative interviews, known as photo-elicitation, helped participants elucidate perceptions or concepts that may otherwise be difficult to articulate (Lewis, 2008); helped to engage participants in conversation and to respond to them without vacillation because of the familiarity of talking about images (Meo, 2010); and they also increase the participant's comfort with the interview process by transferring focus away from the participant and towards a common reference point for both researcher and participant (Lewis, 2008).

The visualisations were compiled into a visualisation presentation package to be introduced in person during the interviews. The presentation was made via a laptop with a high-resolution display and a size of 17" to be view at a distance of 50 cm, approximately. The correct viewing distance was calculated as 1.373 times simulation width (Sheppard, 1989) to ensure the visualisations were viewed at an angle that matched the actual field of view of the scene. Additionally, hard copies of the images were provided to the participants enabling them to examine the images in a more informal way (Lewis and Sheppard, 2005; 2006).

The three images selected from those used to calculate shaded provision at selected time frames and that were included in the presentation were:

- Abstract renders of a ground view of the study area with trees similar to existing in the study area, planted on the west side, simulating shade along the day for the 14th of June.
- One of the renderings used in the project to calculate shaded areas by the trees, showing a top view of the study area under the following set of variables: *Platanus x acerifolia* planted on the west side, simulation for the 14th of June at 14 h.
- Graphic with preliminary results of the project showing shaded area provided exclusively by the trees (*Platanus x acerifolia* planted on west side), calculated subtracting the area shaded by the surrounding buildings.

The concepts used to question interviewees about the evaluation of the visualization used the criteria proposed by Sheppard (1989), which are: accuracy, representativeness, visual clarity, interest, and legitimacy.

Responses from the interviews were recorded, transcribed and analysed using a thematic top-down analysis (known as thematic theoretical analysis). Thematic analysis is a method for identifying, analysing, and reporting patterns or themes within data. It organises and describes the data set in detail and interprets various aspects of the research topic (Boyatzis, 1998). The interview transcripts were coded using the software NVivo by repetitive readings, developing a list of initial themes and sorting similar comments into groups.

Results

Image processing

The results of measured shade cast by the street trees for the different scenarios are recorded in the graphs of figures 4 and 5.

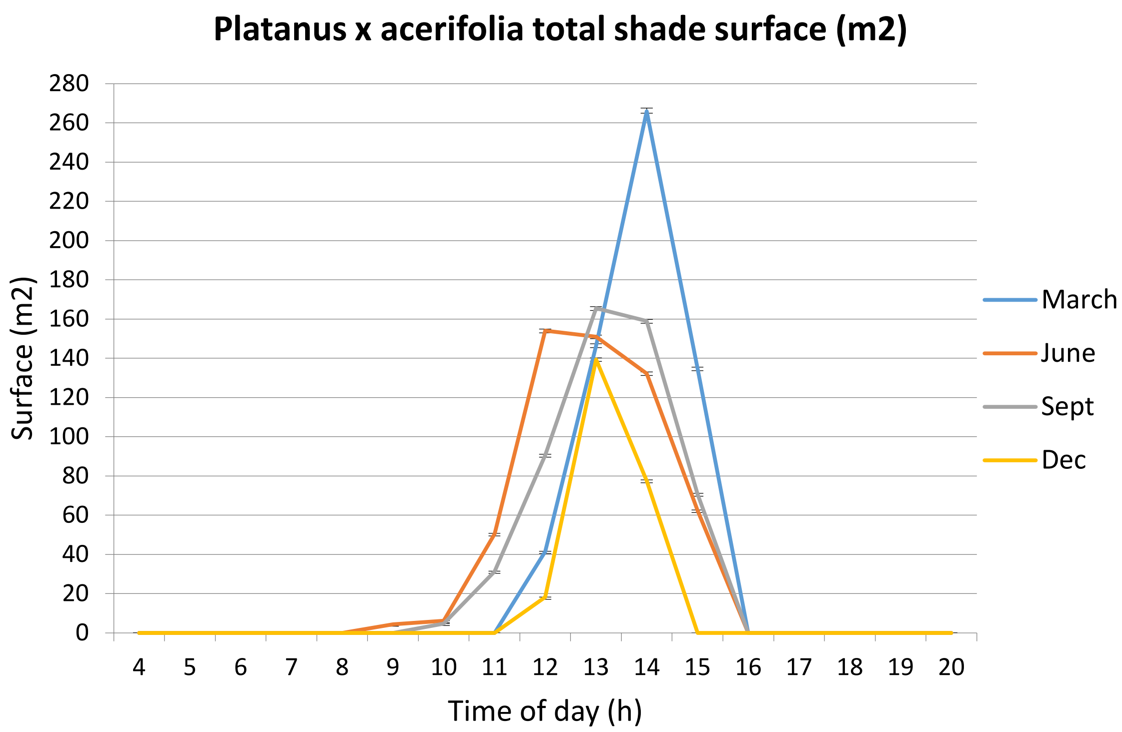

Figure 4. Shaded surface for *Platanus x hibrida.*
Source: Own elaboration

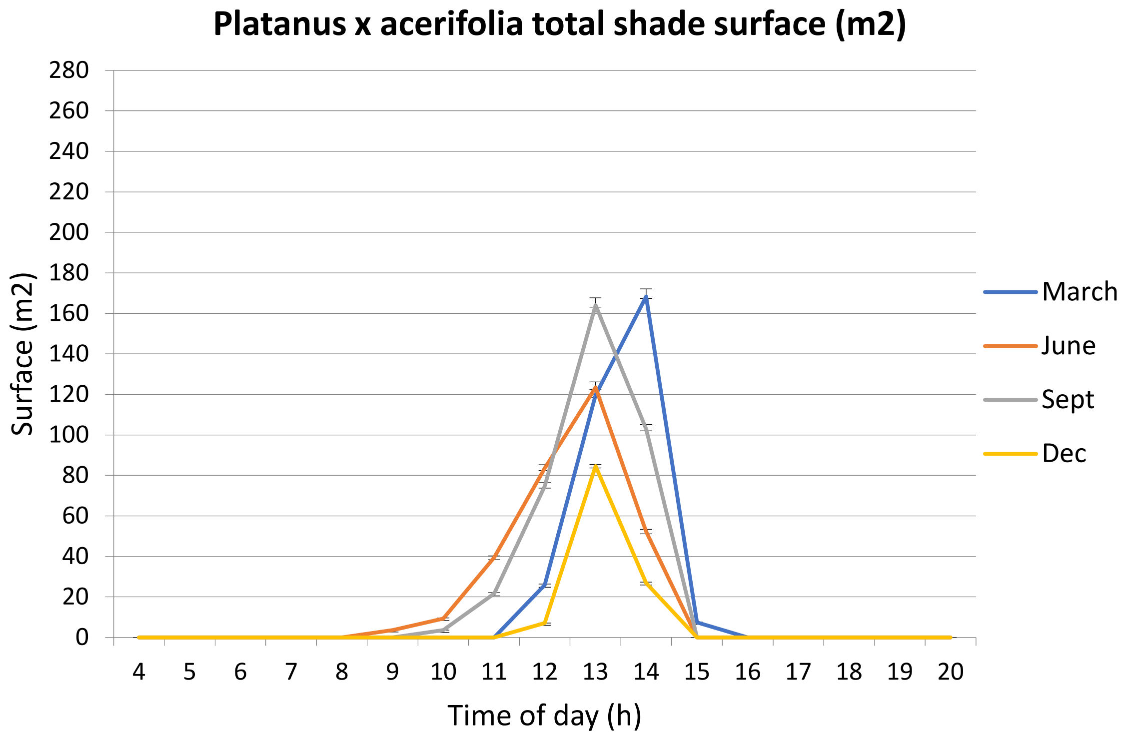

Figure 5. Shaded surface for *Pyrus calleriana.*
Source: Own elaboration

The number of hours that the street trees cast shadow varied with the season, changing from eight hours in the summer to only three hours in December. The number of hours a day that the street trees receive direct solar light was determined to be:

- 1st March: 4 hours
- 1st June: 8 hours
- 1st September : 6 hours
- 1st December: 3 hours

The results showed how shade surface in winter was much smaller because only the shade cast over the street unit had been considered and in winter, when the shade is elongated due to sun light inclination, most of the shade extended outside the 50 meters of unit considered – this error could be considered in future work. For example, by considering several contiguous units, the shade of the contiguous units could be augmented by the trees from the adjacent units. Shade surface would be bigger, but it is important to consider that it would not be calculated by a simple addition, due to the overlapping effect between neighbouring trees. Besides, during the colder months, solar radiation intensity is much lower, so, even though the shaded surface is much bigger the quality of that shade would be reduced. Also, in case of planting deciduous species, the density of the shade cast would also be reduced.

The error associated with the measuring method chosen was calculated by comparing the automatic pixel selection tool with a manual pixel selection method. It was observed that the error was bigger for *Pyrus calleriana* than for

Platanus x hibrida because of the smaller size of the tree and the higher number of trees per street unit. The error increased with the number of trees per unit, but at < 2% the error was, in both cases, considered acceptable when weighted against the additional time required for a manual selection.

Interviews

Overall evaluation was positive for the model developed using visualizations to calculate shaded area for different tree sizes, planting design and street orientations, receiving positive comments from 37% of the interviewees, neutral comments from 63% and no negative comments. Table 1 summarizes the responses of tree officers.

Table 1. Responses from the tree officers evaluating the visualisations from the presentation

Comments from interviewees	Positive	Neutral	Negative
Total	6	10	0
Total%	37	63	0

Source: Own elaboration

Across the board, participants also thought of different ways this model would be of use and these were overall more positive than purely as a shading-technical tool. Some tree officers saw visualisation as useful to deal with complaints related with trees shading residents' properties, while others saw it as positive for backing up applications to the Mayor Re:Leaf Program. Some considered it useful for selecting new planting sites with climate change and urban heat island regulation in mind. But they also mentioned the difficulty for finding space for new planting sites due to the density of underground infrastructure.

> *(9) From my point of view that is very important and if we can estimate the number of hours a property is getting shade we would be able to answer complaints. We would say you are complaining but you only get shade from 2 pm to 4 pm.*
> *(9) Tree shade modelling is fantastic, for the shade of the building and also for plant health.*
> *(7) I can see how that would be very useful. For the mayor's Re:Leaf program one of the criteria is canopy cover, shading, water management, pollutant capture. This would be a good tool to identify the places in London where shade is most needed.*
> *(16) The model would be useful for planning for heat island [mitigation], reflectivity on hard surfaces.*
> *(3) It would be interesting to have this data before planting. Even if the model showed up a potential site I would have to look and try to dig on-site. Water mains and electricity, etc. complicate things.*

One tree officer also considered shade visualisation modelling as useful for internal use to help on species selection for new planting, to evaluate the intensity and spread of the shaded area for different species:

> *It would be fantastic to have those tools. I tend to use my head to think about the aspect, what would work as far as species selection as well as ultimate canopy shading. Because those sort of things have a big impact; if you are going to plant big canopy trees that are going to make the area completely dark, it is not going to be very inviting and I would be better choosing something with an interesting smaller leaf.*

Participants also suggested the convenience of using shade modelling data to evaluate shade tolerance on species selection for new planting sites or to evaluate the impact of new buildings in the number of sun hours existing trees would receive.

The importance of having scientific studies and data to support their decisions and increase their credibility in front of the politicians, insurance companies and the public was also mentioned by London tree officers.

> *(6) We don't do anything as formal as this, having the science to back up our plans to plant more trees. Sometimes we are accused of being hippies and the data would be useful [for arguing our point]. Insurance companies just see us as tree huggers. Data is important.*

The main barrier that almost all tree officers mentioned was time. Producing visualisations can be a very time consuming process. Time is a very limited resource among tree officers, especially recently as most of the boroughs have suffered economic cuts resulting in loss of personnel. The time limitation was decisive in several cases, denying the possibility of attempting to introduce visualisations altogether, as it is not only the time required to create the scenarios and the 3D modelling itself, but also the time required for training and learning new software.

One possible solution mentioned by four of the participants was that visualisations should be a feature integrated into their existing management software that would use a generic library of visualisations to facilitate the generation of the scenes.

Implications and future research

The model will be able to provide a general set of rules to identify within a city those streets and those sides of the streets where tree planting could be prioritised in order to maximize their shading potential or deprioritised due to the unsuitability of a location for tree planting. Trees are planted for many reasons including aesthetic beauty, reducing wind speeds, and intercepting precipitation; however, shading potential is an increasingly more important criteria to adapt urban environments to climate change and to moderate extreme temperatures.

The model provides a general set of rules to orientate city planning and design by identifying those streets and street-sides that should be prioritised for planting. This information can be especially useful for new developments because in densely populated urban areas the availability of planting sites is heavily reduced. Additionally, the model can help address a problem with the planning and design of highways, where tree officers are often only involved in the latter stages to provide their input on adequate species selection. In this setting, the model could be a useful aid to guide the initial design, by identifying where trees should be planted to maximize their shading benefits. It should be acknowledged also, however, that the model will not be able to substitute knowledge of an experienced tree officer in the selection of appropriate tree species for a specific site. It is vital to start by identifying a short list of tree species suited to the specific conditions of the target location and then model to determine which could optimise shading provision, as a tree that fails to thrive will not provide as much shading as a healthy tree due to losses in canopy quality and quantity.

London tree officers referred to many of the visualisations in the presentation as "*what they already do in* [their] *heads*". The ability to simulate several alternative present and future scenarios constitutes a powerful tool to assist with planning and management decisions. Even if expert knowledge is invaluable and an experienced arborist may be able to identify the optimal location of trees in some situations, for others choosing the optimal tree size, planting frame and tree line location for different street orientations and canyon ratios is not trivial.

Visualisations can help decision making when different alternatives are being considered by providing a visual impression of the impact of different management proposals on aesthetics and trees (Macias, 2016). Additionally, as an internal modelling tool, visualisations can let tree officers experiment with different species, planting designs and planting locations. Moreover, by incorporating tree growth simulation into future scenarios it will be possible to study shade footprint evolution, helping management, species selection, planting site selection and studying the effect of future buildings on existing trees.

Planting criteria for species selection is based on London tree officer's expertise but sometimes they felt that they did not have much room for experimentation, as a young tree dying is considered a "failure" by the public and colleagues alike. Virtual experimentation using visualiation tools with different species would let urban forestry practitioners incorporate and evaluate new tree species, reducing the risks. Visualisations have the ability to present alternative futures side-by-side and pose 'what-if' questions (Ervin 1998).

Results from the application of the methodology to the Buckingham Palace Road case study showed a range of three hours in the winter to eight hours during the summer. The north-northeast-south-southwest orientation of the street and the high buildings at both sides limit considerably the number of hours street trees received solar radiation, and therefore, the number of hours in which shadow provision was coming from the trees. The visualisations clearly showed the combined effect of orientation and building height in reducing solar exposure and where this could not be compensated for by street width (i.e. where it was less apparent in a wide street than in a narrow street). Other combinations of street canyon ratio and street orientation should be modelled in the future to quantify the impact of different planting scenarios in streets of different orientation and design. Such work should include those variables considered in this study, plus the following factors.

Street canyon ratio

The study area chosen for the first phase was Buckingham Place Road, a wide street with high buildings on both sides. It would be necessary to include in following research different street canyon ratio typologies that include:

- Wide street with low buildings
- Narrow street with high buildings
- Narrow street with low buildings

Planting locations for trees

Urban trees are typically planted along one or both sides of a street. In wide avenues, trees could also be planted in centre. Depending on street orientation and planting locations, different results are projected:

- north-south orientation: both sides need to be considered as similar as the shadow they cast will be symmetrical, only changing the moment they receive light (morning vs. afternoon sun)
- west-east orientation: only one location, the north side of the street, need be considered in terms of shading potential, as it will be the only one receiving solar radiation throughout the day, unless no constructions exist on the south side or buildings are less than four stories high
- Centre only: when street are wide enough so it is also feasible and does not interfere with vehicle traffic.

Tree planting density

Only low density was included in this study. High density should also be studied.

Shade reduction for deciduous trees in spring, winter and autumn

Quality of shade (transmissivity) depends on species (leaf colour), albedo, LAI and season; in addition to quantity of shade. In this study, trees were modelled ‘in leaf’ in each of the four seasons, in future research it would be important to consider:

- Adjustment for those months when trees are not in leaf
- Modelling of shading effect of tree limbs, branches, twigs – where suitable imagery exists or can be constructed.

Overlapping effect when other contiguous street units

The difference in shading provision between streets, corner units and street junctions/intersections should be considered by future research.

This research has highlighted the potentially useful role of visualisations in urban forestry planning and management. In the opinion of the tree officers interviewed, the images were considered to have a range of potential roles including in communicating the benefits of trees and providing quantitative evidence on the shading provision of [street] trees, which itself can be useful in countering complaints about trees. The tree officers did however acknowledge their lack of time and, often, intellectual and software capacity to generate site/street specific visualisations limiting likely further use of this particular tool. One option would be to create a generic library of visualisation for them to draw upon in their planning and management discussions and deliberations. This library would need to consider the range of future-work considerations highlighted herein.

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