Research Paper

Using unmanned aerial vehicle data to assess the three-dimension green quantity of urban green space: A case study in Shanghai, China

Huilin Liang, Weizheng Li, Qingping Zhang, Wen Zhu, Di Chen, Jie Liu, Ting Shu

ABSTRACT

Urban green space (UGS), which plays an important role in reducing the problems associated with urbanization, needs to be evaluated by metrics. Three-dimension green quantity (3DGQ), a quantitative index that measures the crown space occupied by a growing plant, is often used to evaluate the extent, and the environmental and climatic benefits of UGS. The objective of this study was to measure the 3DGQ of Paotaiwan Wetland Park (PWP) in Shanghai, China. Implementation of the 3DGQ index was supported by remote sensing (RS) images taken by an unmanned aerial vehicle (UAV). The 3DGQ calculations for 100 species of trees were used to calculate the 3DGQ of the UGS in PWP. The environmental and climatic benefits of UGS in PWP were also evaluated. The 3DGQ for the whole PWP was 668,624.13 m³. The mixed woods in the PWP annually absorbed 1,635.57 t CO₂, 2.03 kg SO₂, 735.48 t dust, and 2,254.49 t of O₂. There was 367.74 t of diurnal transpiration. The lowered temperature of the PWP in the transpiration scope at 100 m altitude was 1.8 °C. The use of a UAV to assess UGS could help planners and policy makers to improve the environmental and climatic benefits of UGS.

1. Introduction

Cities around the world are becoming increasingly hot, congested, crowded, and polluted (Wolch, Byrne, & Newell, 2014). Fortunately, the impacts can be mitigated by green space, which can moderate some of the urban heat island effects (Feyisa, Dons, & Meiby, 2014; Kong, Yin, James, Hutrya, & He, 2014), and improve microclimate regulation (Neunschwander, Hayek, & Grêt-Regamey, 2014), air filtering (Kabisch, 2015), water cleaning, noise reduction, and rainwater drainage (Derkenen, Teefelen, & Verburg, 2015; Schäffler & Swilling, 2013; Yang, Zhang, Li, & Wu, 2015). The importance of urban green space (UGS) to urban environments (Munton, 1983; Szulczewska et al., 2014) means that the planning and design of UGS are becoming increasingly important, especially with regards to sustainable development practices in growing metropolitan areas (Erickson, 2006; Li, Wang, Paulussen, & Liu, 2005). Furthermore, in order to improve the planning and design of UGS, landscape metrics that can qualify and assess the climatic functions of UGS are needed.

The Green Index (GI), i.e., percentage area of green space, is an objective measurement of greenness, is regarded as having the greatest influence on ecological performance when developing indicators for the ecological performance of urban areas in the United Kingdom (Whitford, Ennos, & Handley, 2001). Other traditional indices that are internationally used to evaluate the extent of UGS are also two-dimensional, such as the number and area of parks in a city, area of parks per capita, and percentage of park area compared to city urban area (Chiesura, 2004; Xiaojun, 2009). Furthermore, there are some other indices related to the instrumental functions of urban forests, such as total leaf surface areas (Duursma & Falster, 2016), the canopy cover (Parmehr, Amati, Taylor, & Livesley, 2016), total leaf biomass (Nowak & Crane, 2002), leaf area density (Béland, Widlowski, & Fournier, 2014), leaf area index (Xiaojun, McPherson, Ustin, & Grismer, 2000), and green plot ratio (Ong, 2003). The green view index, which was developed to evaluate the visibility of urban forests, can be used to evaluate the visual impact of various planning and management practices on urban forests (Li et al., 2015). However, none of the above indexes can function as a three-dimension green quantity (3DGQ), which accurately reflects the regression models of plant species (Yamada et al., 2007) and provides a basis for evaluating the environmental and climate benefits of UGS (Cheng, Matteo, Zhongke, & Siyu, 2013).

3DGQ is defined as the three-dimension volume of the leaves and stems of plants in an area (Fig. 1), and can be estimated by ground surveys and remote sensing (RS) technology (Yamada et al., 2007).

Keywords:
Three-dimension green quantity
Unmanned aerial vehicle
Urban green space
Environmental and climatic benefits
However, it is difficult to calculate a 3DGQ for large areas using ground surveys, so it has gradually been replaced by RS technology, which can classify vegetation (van Beijma, Comber, & Lamb, 2014; Yu et al., 2014). The 3DGQ regression models of some species of trees (Jianhua & Tianzong, 1995; Král et al., 2010), as well as the methods used to estimate the ecological environmental benefits of UGS by 3DGQ (Keith, Mackey, & Lindenmayer, 2009), have been studied in previous investigations. The aim of this study was to estimate the 3DGQ of trees in Paotaiwan Wetland Park (PWP), Shanghai, China, and to measure the park’s environmental and climate benefits. An unmanned aerial vehicle (UAV) was used to collect data to make our calculations more accurate and precise. Overall, we present a straightforward methodological approach that can estimate the 3DGQ of trees. We believe that the 3DGQ of plants in many different areas needs to be estimated in order to measure the environmental and climatic benefits of green space. Our approach and findings are applicable to other UGSs around the world.

2. Materials and methods

2.1. Study area

This study was conducted in PWP, a park in the eastern Chinese city of Shanghai (121°50′E, 31°40′N) (Fig. 2a). Shanghai is the most important city in terms of China’s economic development. It has a registered population of 18.6 million, covers an area of 634,050 ha, and is located at the mouth of the Yangtze River (Chang Jiang). Its climate belongs to the subtropical moist marine climate zone, and has four distinct seasons, large amounts of sunshine, and sufficient rainfall. PWP, a riverside urban wetland forest park located to the east of Baoshan district, Shanghai (Fig. 2b) on the southern bank of the Yangtze River, is the largest wetland park in Shanghai. It was established in 2007, with a surface area of 60.84 ha, including 50.00 ha mud flat wetland (Fig. 2c). With an average elevation of 6.74 m, it has a coastline length of 1974.13 m and is about 230 m wide. PWP is one of the city’s main green spaces and is its most visited park. It has a green coverage of 81.60%. The PWP contains 11,494 trees that cover 100 species, which is why PWP was selected for this study.

Paotaiwan was built as a naval fort by the Qing government and was an important military base between the Yangtze River and Huangpu River (Dan & Xiaoxiao, 2006). After 1949 and the founding of the People’s Republic of China, Paotaiwan was converted to an important coastal defense fort. In the 1960s, after Paotai Mountain had been filled and piled by steel slag, this place became a parking lot, a stope, a steel bay, and a homeless person’s residence, which caused serious damage to the ecological environment. Its geographical features, caused by the confluence of the Huangpu River and the Yangtze River (Fig. 2b), led the Shanghai government to plan and build the PWP to improve the local environment and celebrate local history and culture.

2.2. Data collection

The authority who issued the permission for the study area was the PWP Service. Data for the research included RS images, records from the PWP greening reformation project in 2009, and field surveys. The RS images consisted of 426 UAV high resolution images, which were acquired on July 20, 2013. The UAV had a 3.0 m fixed-wing platform, an 18.5 kg take-off weight, and a 62 cc gasoline engine. The flying platform was controlled by a YS-09 autopilot system (Zero UAV (Beijing) Intelligence Technology Co., Ltd.). The UAV could fly autonomously based on coordinates programmed in during mission planning. UAV aerial images, with approximately 5616 by 3744 pixels, were taken at an altitude of 300 m along 12 film flight lines. The PWP greening reformation project records from 2009 were used to obtain the tree species information. Field surveys conducted in August and October 2013 marked species and counted the number of different tree
types in the PWP.

2.3. Mosaicking of UAV imagery

The detailed methodology is illustrated in Fig. 3. Our UAV Canon camera collected 24 MP images of the test site can record 24 MP images, and the average jpg file size was approximately 10 Mb. After joining the images into a single mosaic of the whole study area, the commercial software package – Pix4D UAV (Pix4D LLC, Swiss) – was selected to automatically georectify and mosaic the visible UAV imagery (Yang and Jinxing, 2007). Prior to processing, the images were geotagged with their approximate location as recorded by the UAV’s on-board navigation-grade GPS. The internal time of the camera was set to GPS time prior to flight to ensure that the images were easily synchronized with the position data in the UAV GPS log file.

The 426 images were imported into Pix4D desktop (pro), which detected and matched thousands of features on the images. For better mosaicking of the UAV images, 24 ground control points (GCPs) were manually distributed to complete cover the study area with less number and well distribution in the imagery and measured (Fig. 4). To improve the absolute spatial accuracy of the mosaics, the 24 GCPs were analyzed using Differential RTK GPS (DGPS), with a typical accuracy of 2 cm in the horizontal and 4 cm in the vertical direction. Of the 24 GCPs, 14 were chosen for processing, and the other 10 were used as check points. The mosaicking process was time-consuming and it took about 2–3 h to mark about 14 GCPs in the data set of photographic images. Using Gauss-Kruger Projection and the Beijing Coordinate System from 1954, the Root Mean Square Error was computed between check point coordinates measured in the field by DGPS, and the coordinates retrieved from georeferenced image mosaics. The spatial accuracy of the orthomosaic (Table 1) had the following error values: error X (mean 0.034 m, Sigma 0.027 m), error Y (mean 0.023 m, Sigma 0.020 m), and error Z (mean 0.031 m, Sigma 0.030 m). The degree of image overlap was calculated and is shown in Fig. 5. The red and yellow areas indicate low overlap where poor results may be generated. Green areas indicate an overlap of over five images for every pixel and covered all of the PWP area. The UAV orthophotomaps of PWP were completed with a high spatial resolution of 5.44 cm (Fig. 6).

2.4. Analysis of tree species information

The records for the PWP greening reformation project in 2009, the
field surveys in 2013, and the UAV aerial image plan were inputted into the ArcGIS (10.0 Esri) software package for RS interpretation and mapping. The tree information obtained from the analyses (i.e., tree species, number, crown diameter, center point geographic coordinate, etc.) was used to support the 3DGQ calculation. RS interpretation was based on the direct and indirect interpretation marks of the RS images. Direct interpretative marks include an object’s shape, color or hue, size, shadow, mode or graph, texture, etc. Indirect interpretative marks include an object’s location and the relationships between ground marks. RS mapped patterns using the “new polygon” and “split polygon” tools in ArcGIS. This information was then used to obtain a green land use map and analyze species information from the trees identified in the study, including the crown diameter of every tree and the number of trees for each species.

2.5. Calculation of “3DGQ”

The overall 3DGQ for PWP was the sum of 3DGQ for each tree in PWP. The calculation of 3DGQ for each tree were based on its crown diameter, crown height, and the “3DGQ” equation. The crown diameter of each tree was measured by high-precision aerial photographs and ArcGIS. The crown height of each tree in PWP was calculated from its crown diameter and the corresponding “crown diameter – crown height” equation for its species (Jianhua & Tianzong, 1995). The results of the tree species information analysis showed that there were 100 species of trees in PWP. 49% of the “crown diameter – crown height” equations of the 100 species of trees were obtained from previous studies: the “crown diameter – crown height” equations of 32 species were obtained from previous case studies (Jianhua & Tianzong, 1995; Xueyan et al., 2013) (see Table S1 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006); the “crown diameter – crown height” equations of 7 species of trees were also described by three previous studies (Amati & Yokohari, 2004; Biaojun et al., 2005; Howard, 1965) (see Table S2 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006); the average crown height of a further 10 species were calculated by Hu et al. (Hu, Wu, & Wu, 2010) and are shown in Table S3 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006. The “crown diameter – crown height” equations of the other 51 species were substituted by the “crown diameter – crown height” equations of trees from the same family or category with the most similar shape in previous studies (Amati & Yokohari, 2004; Biaojun et al., 2005; Chen et al., 2006; Howard, 1965; Hu et al., 2010; Jianhua & Tianzong, 1995; Xueyan et al., 2013). The substituted species for each of the 51 species were shown in Table S4 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006. The “crown diameter – crown height” equation for *Catalpa bungei* was substituted by *Catalpa ovata G. Don.*, which was reported by Chen et al. (Chen et al., 2006) as being $Y = 1/(a + be − cx)$ ($a = −0.05153$, $b = 0.15269$, $c = 0.01$), where “x” was crown diameter and “Y” was crown height. And the “crown diameter – crown height” equations for the other substituted species were included in Tables S1, S2 and S3 in the online version at DOI:
The "3DGQ" equations for species of tree were obtained from the volume equations of corresponding regular solid geometry similar to their canopy shape. Each tree species in PWP was matched to the regular geometries, such as ellipsoid, cone, spherosome, hemisphere, cylinder, fan-sphere, and nullisomic-sphere, to find the corresponding geometry whose shape was the most approximate to its canopy shape and the "crown diameter – crown height" relationship. And the corresponding geometric volume was calculated to obtain the canopy volume.

Table 1
Aerial triangulation precision.

<table>
<thead>
<tr>
<th>Classes</th>
<th>3D GCP (m)</th>
<th></th>
<th>3D Check Point (m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
<td>X</td>
</tr>
<tr>
<td>Median</td>
<td>0.026</td>
<td>0.015</td>
<td>0.022</td>
<td>0.137</td>
</tr>
<tr>
<td>Mean</td>
<td>0.034</td>
<td>0.023</td>
<td>0.031</td>
<td>0.179</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.087</td>
<td>0.038</td>
<td>0.122</td>
<td>0.364</td>
</tr>
</tbody>
</table>

2.6. Calculation of PWP environmental and climatic benefits

Environmental and climatic effects are criteria that define the overall benefits of UGS (Heidt & Neef, 2008; Lafortezza, Carrus, Sanesi, & Davies, 2009). The standard conversion values and 3DGQs of PWP (Yifan & Jianhua, 2001) allowed the oxygen ($O_2$) production, carbon dioxide ($CO_2$) absorption, sulfur dioxide ($SO_2$) absorption, dust absorption, and transpiration of the aboveground parts of the trees to be calculated. These values were then used to evaluate the environmental and climatic benefits of PWP. The lowered temperature at PWP of the transpiration scope at 100 m altitude was calculated as described by Zhou et al. (Zhou & Zhou, 2001).

3. Results

3.1. Tree species information

According to the ArcGIS results, there were 11,494 trees covering 100 species in PWP (see Table S6 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006). There were 10,816 trees in total, of which 45 species were common and dominant, but had different canopy shapes. They accounted for 93.20% of the trees.

There were 2586 Cinnamomum camphora trees, which accounted for 22.49% of the total number of trees. This was far more than the other species. In contrast, Sabina chinensis cv. kaisuca, Cyclobalanopsis glauca, Lagerstroemia indica, and Eucalyptus robusta were the four species that accounted for the least number of trees. The 100 species were classified as being either "evergreen" or "deciduous" when constructing the PWP tree distribution map (Fig. 7).

3.2. 3DGQs of the trees in the PWP

The corresponding “3DGQ” equations were used to obtain the 3DGQ for each species (see Table S7 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006). To quantify the overall areas taken up by deciduous and evergreen trees, the total 3DGQs of deciduous and evergreen trees was calculated, and the results showed that deciduous trees covered 443,196.78 m$^3$ and evergreen trees covered 225,427.34 m$^3$. In other words, the 3DGQs of deciduous trees in PWP in 2013 was larger than that of evergreen trees. The woodland is mixed throughout the PWP, so the 3DGQ of mixed wood in PWP in 2013 was the same as the 3DGQ for the whole PWP, i.e. 668,624.13 m$^3$. The 3DGQ per tree for a species was derived from the 3DGQ for the species divided by its number (see Table S7 in the online version at DOI: http://dx.doi.org/10.1016/j.landurbplan.2017.04.006). Distylium racemosum Sieb.et Zucc (69.14 m$^3$) had the largest evergreen 3DGQ and Bischofia polycarpa (676.35 m$^3$) had the largest deciduous 3DGQ. In contrast, the 3DGQs of the evergreen Photinia serrulata Lindl and the deciduous Koelreuteria integrifoliola were the lowest. The data above and the species distribution map meant that the 3DGQ distribution for the whole of the PWP could be mapped using ArcGIS (Fig. 8). The trees with 3DGQs of less than 100 m$^3$ accounted for 88.23% of the total number, 75.52% of the canopy cover, and 40.07% of the total 3DGQ for the PWP. Furthermore, the sum of the individual 3DGQs in PWP was 668,624.13 m$^3$. The total area of the PWP was 6,086.00 ha, and the 3DGQ per green area was 10,989.87 m$^3$/ha.

3.3. PWP environmental and climatic benefits

Oxygen ($O_2$) production, carbon dioxide ($CO_2$) absorption, sulfur dioxide ($SO_2$) absorption, dust absorption, and transpiration by the trees were calculated to evaluate the environmental and climatic benefits of the PWP (Table 2). All the woods in the PWP are mixed woods. Therefore, the 3DGQ of mixed wood in PWP was the same as the 3DGQ for the whole PWP. A 3DGQ value of 668,624.13 m$^3$ meant that the mixed woods in the PWP annually absorbed 1,635.57 t CO$_2$, 2.03 kg SO$_2$, 735.48 t dust, and 2,254.49 t of O$_2$. There was also 367.74 t of diurnal transpiration. The lowered temperature of the PWP in the transpiration scope at 100 m altitude was 1.8 °C.

4. Discussion

Urban areas are globally growing at an alarming pace, especially in developing countries. It is therefore necessary to obtain quantifiable information regarding the amount, type, and structure of urban green space (Lang et al., 2007). The 3DGQ, a three-dimensional index, accurately reflects vegetation configuration, ecological situation, and the extent of urban greening. This case study describes an approach for calculating 3DGQ using RS data and “crown diameter – crown height” equations”. The “crown diameter – crown height” equations were selected and based on previous studies, and have been shown to be reliable. These equations (Tables S1, S2, and S3) were confirmed through repetition at different growth stages and under different environments (Jianhua & Tianzong, 1995; Xueyan, 2009). The Tree 3DGQ results for each species in the PWP showed that the 3DGQs of
different tree species are not the same, even when excluding other factors (e.g. the growth rate and age of the trees). Hence, we may conclude that environmental benefits of trees, which affect their 3DGQ, vary depending on species.

Compared with previous studies, our study is different and has some advantages. In some previous studies, RS images were taken by other methods, such as by satellite (Cheng et al., 2013; Millward & Sabir, 2011; Mohammadi, Shataee, & Babanezhad, 2011). The resolution of the images obtained were lower and were usually too coarse for the estimation of 3DGQ. Compared to the satellite images with a resolution of 1000.00 cm, the images used in this study had a resolution of 5.44 cm. The higher resolution of the RS data obtained by the UAV in this study made the calculation of 3DGQs more accurate. In some previous studies, several software packages were usually used for RS images mosaicking (Lang et al., 2007; Mohammadi et al., 2011). Using just one software (Pix4UAV) package for RS images mosaicking in this study was more convenient and produced less error. In some previous studies, 3DGQs of trees were calculated by measuring the crown width and diameter at the breast height of each tree (Buckley, Isebrands, & Sharik, 1999; Hopkinson, Chasmer, Young-Pow, & Treitz, 2004; Jim & Chen, 2009; Kira, 1991). Our study used ArcGIS to analyze the UAV orthophotomap and obtained the trees’ canopy diameter, the "crown diameter – crown height" equations, and the crown height of trees. It meant that the 3DGQ calculation procedure in our study was
more efficient and less time and labor consuming than the ground survey method, especially on the scale required to map the PWP. In some previous studies, 3DGQ of trees were obtained on the base of LiDAR data (Cheng et al., 2013). Although with more precision, the acquisition and processing of LiDAR data for such a large number of trees were far more time and labor consuming than UAV images taking. The larger area or more objects the sites with, the obvious and greater the efficiency differences were. Weighting the factors of precision and
efficiency, the methods in this study were more appropriate for the measure of such a large number of trees. For the study area, the urban park used in our study is different to the whole city or forests used in previous studies (Baraloto et al., 2011; Cheng et al., 2013).

However, this paper has some limitations. Although the growth rate and age of the trees were considered in the “crown diameter – crown height” equation, the 3DGQ for the whole PWP was focused on one time point. The objective of our study was to introduce a method for 3DGQ measurement, so one time point was sufficient for our objectives. The 3D green biomass of the Beijing urban forest also had one time point (Cheng et al., 2013). If the statistical changes in 3DGQ over a number of years are needed, then more time points are required. Thus, future studies should include more time points, which will improve the accuracy of the results.

The 3DGQ for UGS in PWP was calculated and evaluated with the support of RS data taken by the UAV. This study offers a straightforward method to quantify the environmental and climatic value of UGS. In general, 3DGQ could be used to improve initial plant selection during the UGS design and planning stages, and could facilitate quantitative research into UGS qualitative development.
Table 2
The environmental and climatic benefits of the PWP (2013).

<table>
<thead>
<tr>
<th>Category</th>
<th>3DGG (m²)</th>
<th>CO₂ Abs. (t/year)</th>
<th>O₂ Pro. (t/year)</th>
<th>SO₂ Abs. (kg/year)</th>
<th>Dust Abs. (t/year)</th>
<th>Tra. (t/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deciduous Trees</td>
<td>443,196.78</td>
<td>842.07</td>
<td>1,161.17</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Evergreen Trees</td>
<td>225,427.34</td>
<td>793.50</td>
<td>1,093.32</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mixed Wood</td>
<td>668,624.13</td>
<td>1,635.57</td>
<td>2,254.49</td>
<td>2.03</td>
<td>735.48</td>
<td>367.74</td>
</tr>
<tr>
<td>PWP total</td>
<td>668,624.13</td>
<td>1,635.57</td>
<td>2,254.49</td>
<td>2.03</td>
<td>735.48</td>
<td>367.74</td>
</tr>
</tbody>
</table>

Abbreviations: Absorption (Abs.); Production (Pro.); Transpiration (Tra.).

References