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Measured and modelled leaf area of urban woodlands, parks and trees in Gothenburg, Sweden

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14 June 2015

1. Introduction

Today more than half of the world's population lives in urban areas (in Europe 73%) and by 2050 the urban population is projected to be 66% (UN, 2014). Urban settlements transform the natural environment and accompanying the rapid urbanization are problems such as the urban heat island effect, decreased air quality, and increased surface runoff. The presence of urban trees has been recognized to provide a large number of ecosystem services, benefitting the human population (Escobedo et al., 2011; Gomez-Baggethun and Barton, 2013; Roy et al., 2012). Urban trees reduce the urban heat island effect in the summer through shading and evapotranspiration (Bowler et al., 2010; Konarska et al., 2014; Mayer et al., 2009; Shashua-Bar et al., 2011) and improve air quality through absorption of gaseous pollutants through the leaf stomata and interception of particles on plant surfaces (Grundström and Pleijel, 2014; Nowak et al., 2006; Nowak et al., 2014). Storm water runoff is attenuated by rainwater interception and storage in urban tree canopies (Roy et al., 2012; Xiao and McPherson, 2002) which reduces flooding damage and water quality problems.

The amount of foliage in a canopy is a basic ecological characteristic and canopy leaf area serves as an important control over e.g. transpiration (Asner et al., 2003), air pollution deposition (Escobedo et al., 2011; Hirabayashi et al., 2012) and water storage during rainfall (Keim et al., 2006). Leaf area has been used as an indicator of several ecosystem services (Dobbs et al., 2011; Gomez-Baggethun and Barton, 2013). It is commonly reported as leaf area index (LAI), a dimensionless quantity defined as the total one-sided leaf area (m^2) per unit ground surface area (m^2).

Two commonly used indirect methods to estimate LAI are the commercial plant canopy analyzer LAI-2200 (LI-COR Inc., Lincoln, USA) and hemispherical photography. Both methods are based on gap fraction analysis. The gap fraction based methods include all canopy elements intercepting radiation and cannot distinguish photosynthetically active leaves from other plant elements e.g. stems and branches. Therefore the term effective LAI (L_e) is used to describe LAI estimates derived with these methods (Jonckheere et al., 2004). Thorough reviews of different methods to estimate LAI can be found in e.g. Breda, (2003) and Jonckheere et al. (2004).

Considering the importance of leaf area as a fundamental measure of urban forest function and a key input parameter in process-based ecosystem models, relatively few studies have presented leaf area measurements in the urban environment. Measurements of LAI is time consuming and therefore impractical or even impossible to perform over larger areas, making indirect remote sensing techniques attractive. Aerial light detection and ranging (LiDAR) is one such technique that recent studies indicate successful (e.g. Richardson et al., 2009), but which still needs more tests in the urban environment.

The aim of this study was to i) describe different types of urban green areas in terms of effective leaf area index (L_e) of trees and tree cover, ii) compare two different methods to measure L_e of urban trees and iii) estimate urban L_e based on aerial discrete-return LiDAR.

2. Study area

The present work was conducted in Gothenburg (57°42´N, 11°58´E), located on the west coast of Sweden. It is the second largest city in Sweden with approximately 510 000 inhabitants. It has a maritime temperate climate with moderately cool summers and mild winters. The average air temperature is 17.0 °C in July and -1.1 °C in February and the average annual precipitation is 758 mm of which 202 mm falls in June-August (SMHI, 2015, statistics from 1961-1990). Deciduous trees normally become foliated in late April or May and defoliate around October.

Seven green areas, representing different types of urban greenery, were selected: a central urban deciduous woodland, a suburban mixed forest, a central old park, a central new park by a river, a grove adjacent to a traffic route, a residential area with green courtyards and allotment gardens. In addition, single street trees of six common urban tree species in Gothenburg were measured (*Acer platanoides, Aesculus hippocastanum, Betula pendula, Prunus serrulata, Quercus robur and Tilia europaea*).

3. Methods

3.1 Ground measurements of L_e

Ground estimates of L_e were made using two methods: 1) the commercial plant canopy analyzer LAI-2200 (LI-COR Biosciences, Lincoln, USA) and 2) hemispherical photography. The measurements were conducted in the summer of 2014 which was very sunny and dry in July. In the late summer early leaf senescence was observed due to drought stress at most sites. The measurements were taken at breast height, which means that no understorey vegetation was included. At the urban parks and woodlands the measurements were performed in a grid or cross with 8-32 points with fixed intervals. For single urban trees, 3-6 specimen of each species were measured.

The LAI-2200 Plant Canopy Analyzer estimates L_e by measurements of solar radiation below and above the canopy with a fish-eye optical sensor in five angular bands with central angles of 7, 23, 38, 53 and 68° from the zenith (LI-COR, 2009). In the urban parks and woodlands simultaneous above canopy readings were taken in a nearby open area or at a roof-top site. For single trees, only one instrument was used, with pairs of above and below canopy readings taken in as many directions as possible around the tree. To avoid disturbance of buildings and also allowing above canopy readings to be taken in smaller canopy clearings, measurements were conducted with a 45° or 90° view cap covering the sensors. In case of single trees, often only one or two directions could be used to avoid interference of buildings, thus the trees were assumed to be vertically symmetric. L_e was recomputed in the FV2200 v.1.2 software, following guidelines for continuous (urban parks and woodlands) or isolated (single trees) canopy measurements provided in the instrument manual (LI-COR, 2009). The fifth ring (zenith angle 68°) was excluded from the analysis to avoid influence of topography and adjacent buildings.

L_e was also estimated using a Nikon D5100 digital single-lens reflex camera with a Sigma 4.5 mm circular fish-eye lens (180° angle of view). Photographs were taken simultaneously with LAI-2200 measurements, at the same measurement points. At least two to three hemispherical photographs with different exposures were captured at each measurement point. The digital images were analyzed with Hemisfer software (Schleppi, WSL). The blue channel of the hemispherical photographs was used in the analysis since it has been shown to give the best contrast between sky and canopy as well as lower variance values, indicating a higher degree of precision in the measurements (Brusa and Bunker, 2014). The literature remains unclear of what the optimum exposure should be. Brusa and Bunker (2014) illustrate that automatic and under-exposed images performed much better than the over-exposed images for canopy closure estimates. The optimal threshold between sky (white) and canopy (black) was determined automatically in Hemisfer according to an algorithm which recognizes edges on the image developed by Nobis and Hunziker (2005). The images were manually controlled to find the lowest exposure that still was not too dark for the automatic threshold method to work. Analogous with the LAI-2200, the ring closest to the horizon was excluded in the analysis. L_e was estimated both from the sector in the direction of the LAI-2200 measurements and for the full hemispherical photograph.

Diffuse light is the recommended conditions for both methods, either from a uniformly overcast sky or measurements at the time just before sunrise or after sunset. Uniformly overcast skies are rare during summers in the Gothenburg area and the time before/after sunrise/sunset is too short to measure L_e with both methods in a grid. Therefore some measurements were performed during clear blue sky and sunny weather for comparison.

3.2 Discrete-return LiDAR

Gothenburg municipality LiDAR data, obtained in 2010 using a Leica ALS 50-II sensor at a flying altitude of 550 m, were used in this study. The maximum scan angle was ±20° and the mean pulse density 13.65 m^{-2}. LiDAR returns were divided into categories e.g. ground, medium and high vegetation, buildings etc. FUSION software was used to process raw LiDAR data files. The vegetation part of the point cloud was filtered according Lindberg and Grimmond (2011) in order to remove objects such as cars, light posts and balconies.

Richardson et al. (2009) tested four different methods to model L_e from LiDAR data in a mixed forest in Seattle, USA. They found that the following Beer-Lambert law based approach gave the best result:

$$L_e = -\beta \ln\left(\frac{R_{ground}}{R_{total}}\right) \qquad \text{Eq. 1}$$

where R_{ground} is ground returns, R_{total} is ground and canopy returns and β is a constant (2.097).

Cylindrical point clouds of 10 m radius were extracted for the measurement points. 10 m radius was chosen in agreement with findings of Richardson et al (2009). These were compared with L_e measurements based on both LAI-2200 and hemispherical photography. Hemispherical photography gave the highest correlation, probably due to the use of full hemisphere and not only one sector as with LAI-2200, and was therefore used for further comparisons.

Esri ArcGIS 10.1 was used to create a raster map of L_e for all seven study areas. The above described model was problematic in grid cells with very dense vegetation, which could have zero ground returns. A resolution of 5 m was chosen as the highest possible resolution with ground returns in all grid cells.

4. Results and discussion

4.1 Measurements of L_e

The comparison between LAI-2200 and hemispherical photography showed good correlation under uniformly overcast weather conditions (Fig. 1a). During sunny conditions (Fig. 1b) the correlation was poorer. The LAI-2200 tended to underestimate L_e in sunny conditions due to reflection of light on sunlit leaves (LI-COR, 2009). To avoid the LAI-2200 sensor being directly sunlit the measurements were performed towards the north with shaded sensor. However, in the northern part of the image the sky was much darker than in the southern part which made it difficult to set a threshold between white (sky) and black (vegetation) pixels. As a result L_e based on hemispherical photography tended to be overestimated in the northern part of the image.

A major advantage of hemispherical photography was the possibility of checking and re-analyzing the images if necessary. Also important in the urban environment was the possibility to exclude part of the image (e.g. buildings) from the analysis. However, the Hemisfer software used in this study does not yet include the possibility to estimate L_e from single trees, a drawback in the urban environment.

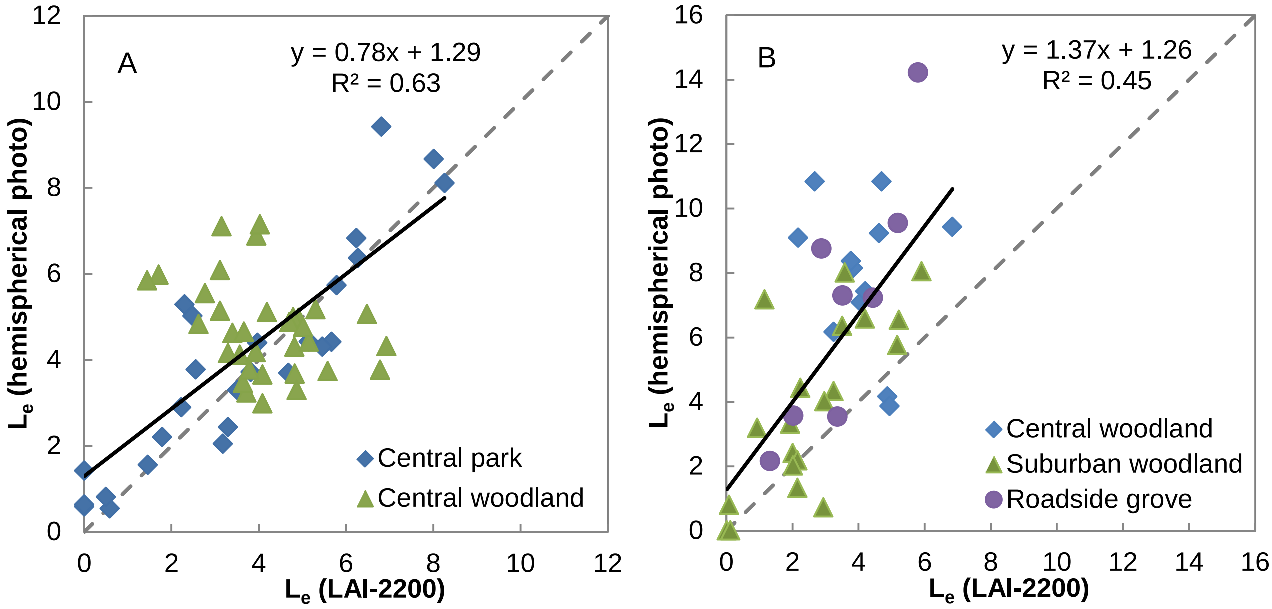

Fig. 1 Comparison of effective leaf area index (L_e) measured with LAI-2200 and hemispherical photo. In A) the measurements were performed during the recommended uniformly overcast weather conditions and B) in sunny weather conditions.

Leaf area of individual trees is usually measured as leaf area density (LAD) with the units of m^2 foliage area per m^3 canopy volume (Li-cor, 2009). LAD measured with LAI-2200 differed substantially among the six common urban tree species analyzed (Fig. 2). *Acer platanoides* had the highest LAD (1.8) and *Aesculus hippocastanum* the lowest (0.7). Re-calculated to average L_e the range was from *Betula pendula* with the highest L_e (6.5) to *Prunus serrulata* with the lowest (3.6).Single trees can be assumed to have higher LAI since they grow denser when not having to compete for light with other trees. In addition, gaps between the trees are included in the continuous canopy LAI measurements. On the other hand, the trees in this study were street trees which were also influenced by drought stress worsened by impervious surface close to the trees, air pollution, shading by houses, etc (Rhoades and Stipes, 1999).

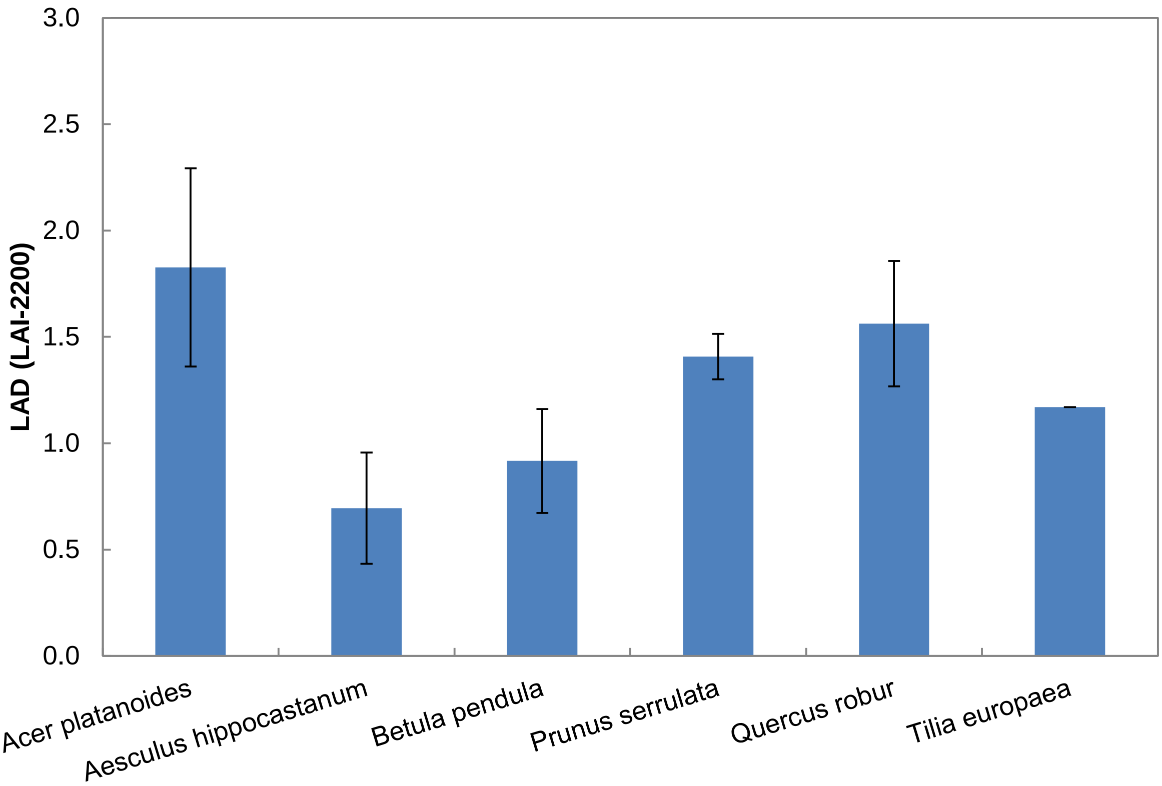

Fig. 2 Measured leaf area density (LAD) of six different urban tree species common in Gothenburg. Error bars are ±1 standard deviation.

4.2 LiDAR

L_e based on both LAI-2200 and hemispherical photographs (all sectors/full images) were compared to L_e estimated from LiDAR. Hemispherical photographs exhibited higher correlation and are shown in Fig. 3. The good agreement indicates that LiDAR can be used successfully to model L_e also in an urban environment.

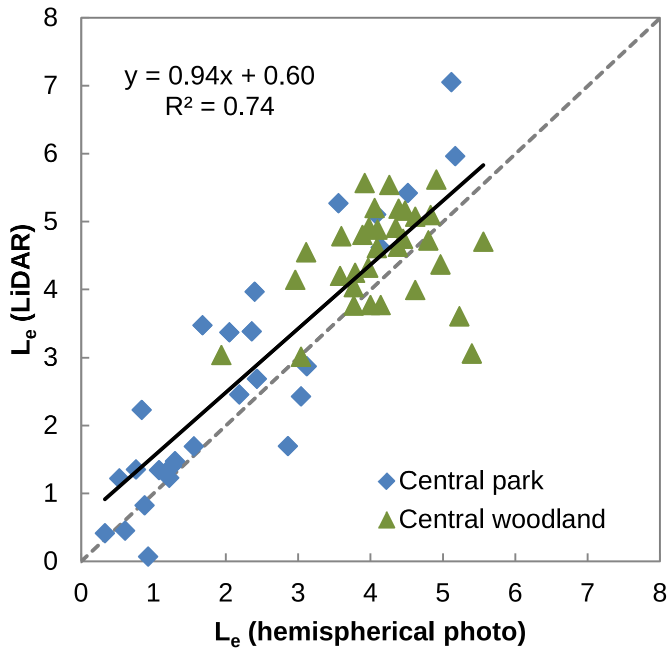

Fig. 3 Modelled effective leaf area index (L_e) based on LiDAR data compared to measured L_e.

Table 1 summarizes characteristics of the seven study sites with different types of urban greenery based on LiDAR data. Vegetation (>1 m) cover ranges from 11.4% in the residential area with green courtyards to above 80% in the central woodland and the suburban forest. Average L_e of the vegetation ranges from 1.5 in the residential area to 4.4 in the central woodland. The variation within the areas was large as shown by the large standard deviation (Table 1). As a comparison, Asner et al. (2003) reported an average LAI of 5.1 for temperate deciduous broadleaf forests in a global synthesis of plant canopy LAI. The results clearly show the heterogeneity of the urban environment and the importance of detailed estimates of L_e for urban applications is emphasized.

Table 1. Modelled effective leaf area index (L_e) based on LiDAR data of vegetation (>1 m) at the seven study sites in Gothenburg. Canopy cover and vegetation height is estimated with 1 m resolution; L_e is modelled with 5 m resolution.

Site	Total area (ha)	Canopy cover (%)	Average vegetation height (m)	Max vegetation height (m)	Average L_e of vegetation	STD of L_e	Max L_e
Residential green yards	8.9	11.4	6.3	18.7	1.5	1.6	9.3
New park by river	6.4	31.9	7.0	19.2	2.0	1.9	11.1
Old central park	9.8	60.7	12.3	28.1	3.3	2.4	12.2
Suburban forest	38.4	87.7	10.4	31.8	4.0	1.5	11.8
Allotment gardens	1.9	49.2	3.6	18.3	1.9	1.5	10.2
Central woodland	12.0	88.5	10.9	26.7	4.4	1.9	12.8
Traffic area	2.3	34.0	6.2	21.4	2.3	2.0	9.4

5. Conclusions

1) In overcast weather conditions both LAI-2200 and hemispherical photography gave comparable estimates of effective leaf area index (L_e). Hemispherical photography has the advantage that the images are saved and possible to re-analyze. However, the Hemisfer software used in this study does not yet include the possibility to estimate L_e from single trees, a drawback in the urban environment. A problem with both methods was the dependency on weather conditions.
2) L_e was successfully modelled based on LiDAR data in the urban environment and showed good agreement with measurements.
3) Average leaf area density (LAD) varied between 0.7 and 1.8 for the single tree species. Average L_e of vegetation (>1 m) varied between 1.5 and 4.4 for the different types of urban greenery included in this study. The large variance between species and types of greenery in the urban environment emphasizes the importance of detailed estimates of L_e for urban applications.

Acknowledgment

This study was performed within the project *Valuation of ecosystem services provided by urban greenery*. We thank the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), the Swedish Transport administration and Mistra Urban Futures for financial Support. We also thank Professor Leif Klemedtsson for letting us borrow the LAI-2200 instrument.

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