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Mapping leaf area of urban greenery using aerial LiDAR and ground-based measurements in Gothenburg, Sweden

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A B S T R A C T

Leaf area of urban vegetation is an important ecological characteristic, influencing urban climate through shading and transpiration cooling and air quality through air pollutant deposition. Accurate estimates of leaf area over large areas are fundamental to model such processes. The aim of this study was to explore if an aerial LiDAR dataset acquired to create a high resolution digital terrain model could be used to map effective leaf area index (L_e) and to assess the L_e variation in a high latitude urban area, here represented by the city of Gothenburg, Sweden. L_e was estimated from LiDAR data using a Beer-Lambert law based approach and compared to ground-based measurements with hemispherical photography and the Plant Canopy Analyser LAI-2200. Even though the LiDAR dataset was not optimized for L_e mapping, the comparison with hemispherical photography showed good agreement (r^2 = 0.72, RMSE = 0.97) for urban parks and woodlands. Leaf area density of single trees, estimated from LiDAR and LAI-2200, did not show as good agreement (r^2 = 0.53, RMSE = 0.49). L_e in 10 m resolution covering most of Gothenburg municipality ranged from 0 to 14 (0.3% of the values > 7) with an average L_e of 3.5 in deciduous forests and 1.2 in urban built-up areas. When L_e was averaged over larger scales there was a high correlation with canopy cover (r^2 = 0.97 in 1 × 1 km^2 scale) implying that at this scale L_e is rather homogenous. However, when L_e was averaged only over the vegetated parts, differences in L_e became clear. Detailed study of L_e in seven urban green areas with different amount and type of greenery showed a large variation in L_e, ranging from average L_e of 0.9 in a residential area to 4.1 in an urban woodland. The use of LiDAR data has the potential to considerably increase information of forest structure in the urban environment.

1. Introduction

The presence of urban trees has been recognized to provide a large number of ecosystem services benefitting the urban population (Escobedo et al., 2011; Gomez-Baggethun and Barton, 2013; Roy et al., 2012). For example, urban trees reduce the temperature through shading and evapotranspiration (Bowler et al., 2010; Gillner et al., 2015; Konarska et al., 2014, 2015; 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, 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. A critical structural attribute that is of importance for these services is the amount of foliage in the tree canopy, i.e. the leaf area, which is an important variable for models used to quantify ecosystem services such as temperature regulation, air quality regulation and noise reduction (Burkhard et al., 2012; Gillner et al., 2015; Gomez-Baggethun and Barton, 2013; Hardin and Jensen, 2007; Robinson and Lundholm, 2012).

The leaf area index (LAI) is a dimensionless quantity commonly defined as total one-sided green leaf area (m^2) per unit ground surface area (m^2) (Chen and Black, 1992). LAI can be assessed directly by harvesting and litter collection. LAI can also be estimated through allometric techniques, which rely on relationships between leaf area and e.g. stem diameter, tree height or crown base height (Breda, 2003). Indirect ground-based estimates of LAI include optical methods based on measurements of light transmission through the canopy (Breda, 2003; Jonckheere et al., 2004). Two commonly used methods are the commercial Plant Canopy Analyser LAI-2200 (LI-COR Inc., Lincoln, USA) and hemispherical photography. Unless corrections are applied, these 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

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(Jonckheere et al., 2004).

In contrast to homogeneous forest canopies, for measurements of single trees the amount of foliage over a given area depends on the ground position; it is larger close to the trunk compared to close to the tree edge. Therefore leaf area of individual trees is measured as leaf area density (LAD), defined as the total one-sided leaf area per unit volume ($m^2 m^{-3}$).

Ground-based measurements of leaf area are time consuming and therefore impractical and costly to perform over larger areas, making remote sensing techniques attractive. Aerial LiDAR (light detection and ranging) utilizes a scanning laser mounted on an airplane with an integrated GPS unit to collect three-dimensional data points. Based on laser penetration metrics, maps of L_e can be produced and have been shown successful on a limited range of L_e values and/or for vegetation with limited species diversity (Korhonen et al., 2011; Morsdorf et al., 2006; Solberg et al., 2009).

The urban environment is complex and heterogeneous with high species diversity and a wide range of LAI values. Little is known about LAI variation within an urban context and between urban areas in different climates. To our knowledge LAI has not been assessed on city scale in a high latitude city before. Such estimates of LAI over large geographical areas are highly valuable as input for models and for assessments of ecosystem services from the urban greenery. For example, LAI is an important input parameter in various surface energy balance or microclimate models, e.g. ENVI-met (Bruse and Fleer, 1998), WRF/urban model (Chen et al., 2011) and SUEWS (Järvi et al., 2011) used in the urban environment. Another example is the i-Tree model (http://www.itreetools.org), based on the USDA Forest Service's Urban Forest Effects (UFORE) model (Nowak et al., 2008)) which estimates urban LAI based on allometric relationships to produce estimates of environmental services provided by trees.

The availability of LiDAR data has increased substantially in recent years. Recent studies have indicated the possibility to use aerial LiDAR to map L_e in a heterogeneous urban park (Richardson et al., 2009) and in an urban environment (Alonzo et al., 2015). However, in an urban environment the LiDAR data is often not obtained with the explicit purpose to map L_e. As a result, features such as the scanning angle and pulse density are not optimized for estimating L_e in a spatial resolution high enough to resolve the complexity of urban vegetation.

The overall objective of this study was to explore if a LiDAR dataset produced with the purpose to create a high resolution digital elevation model (DEM) of the ground surface could be used to map L_e in a high latitude urban area, here represented by Gothenburg, Sweden. More specifically the aims were to:

- Estimate L_e based on LiDAR data using a Beer-Lambert law based approach and compare with ground-based measurements.
- Produce a map of L_e based on LiDAR, assess the variation in estimated L_e within different land use categories and compare L_e with other vegetation characteristics.
- Describe seven different green areas with varying amount and type of greenery in terms of L_e and other vegetation characteristics as well as LAD of six common urban tree species in Gothenburg based on measurements and LiDAR data.

2. Study area and field sites

The high latitude city of Gothenburg (57°42′N, 11°58′E) is located on the west coast of Sweden. It is the second largest city in Sweden with approximately 540 000 inhabitants. It has a maritime temperate climate with moderately cool summers and mild winters for the latitude. Gothenburg is situated in the nemoral vegetation zone, characterised by temperate deciduous forests (Gundersen et al., 2005). Deciduous trees normally become foliated in late April or May and defoliate around October.

Gothenburg is a relatively green city with a green area (defined as un-built land with a size of ≥1 ha) of 55%. More than half of the population (58%) has a green area ≥10 ha within 300 m from their home (SCB, 2010). In the central area of the city, park and street trees are dominated (46%) of the genus *Tilia* (lime or linden). Other common genera in the city of Gothenburg are *Acer* (5.8%), *Prunus* (3.5%) and *Aesculus* (3.3%) (Sjöman et al., 2012). Scots pine (*Pinus sylvestris*) followed by Norway spruce (*Picea abies*) are the most common tree species of the urban woodlands in and around Gothenburg. However, the portion of deciduous trees is relatively high, nearly 50% (Gundersen et al., 2005).

Table 1
Description of the six urban and one suburban green areas selected for detailed study.

ID	Site	Description	Total area (ha)
1	Suburban woodland	Suburban mixed forest with pond in south	38.4
2	Urban woodland	Deciduous woodland with walk/bike paths	12.0
3	Urban park	Old park close to the city centre	9.8
4	Allotment area	Area with allotment gardens	1.9
5	Infrastructural green space	A forecastle surrounded by greenery in between traffic infrastructure	2.3
6	Urban park and woodland	Newly established park surrounding a forested hill close to the Göta river	6.4
7	Residential area	Residential area with 3-storey buildings and green yards	8.9

Seven green areas within Gothenburg municipality, representing different structures, amount and type of urban greenery, were selected for detailed study of vegetation characteristics with focus on L_e: a suburban mixed forest (Titteridamm), a deciduous urban woodland (Gudlheden), an old park close to the city centre (Kungsparken), an area with allotment gardens (Änggårdskolonin), a forecastle surrounded by greenery in between traffic infrastructure (Skansen Lejonet), a newly established park (Sörhallsparken) and a residential area (Wieselgrensplatsen). The study sites are further described in Table 1 and the site locations are shown in Fig. 1.

In addition, leaf area of single street trees of six common urban tree species in Gothenburg was measured: common lime (*Tilia europaea*), Norway maple (*Acer platanoides*), horse chestnut (*Aesculus hippocastanum*), Silver birch (*Betula pendula*), Japanese cherry (*Prunus serrulata*) and English oak (*Quercus robur*). The sites were chosen to represent a variety of growing conditions, from trees planted in small pits and in narrow lanes along heavy traffic roads, to those surrounded by grass. For each site, the average fraction of permeable surfaces within vertically projected tree crown was calculated. The single street tree sites are further described in Table 2.

3. Methodology

Ground estimates of L_e were conducted in June 2015, using two common methods: 1) a commercial Plant Canopy Analyser LAI-2200 (LI-COR Biosciences, Lincoln, USA) and 2) hemispherical photography. Both methods are further described below. The measurements and photographs were taken at breast height, i.e. no understory vegetation was included. Measurements were performed in the suburban park, urban woodland and in the urban park (ID 1–3 in Table 1 and Fig. 1) in a 50 × 50 m grid with fixed intervals of 10 m. The midpoints of these grids were chosen to coincide with biodiversity inventories by Gunnarsson et al. (2016). In this study a stratified sampling design was used. For single trees, 4–6 specimen of each species (Table 2) were measured to capture the variation within a plot and between trees. Since diffuse light conditions are recommended for both methods, the measurements were taken on overcast days.