APPLICATION OF NEAR-INFRARED HEMISPHERICAL PHOTOGRAPHY TO ESTIMATE LEAF AREA INDEX OF URBAN VEGETATION

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Abstract

Visible wavelength hemispherical photography is unsuitable for estimating the leaf area index of urban vegetation, which is typically difficult to differentiate from surrounding built form. But since foliage is highly reflective in the near-infrared (NIR), non-leaf elements may be segmented from a hemispherical NIR image by applying appropriate thresholds. A comparative analysis of visible and NIR images was undertaken for a moderately vegetated urban site in Sydney, Australia and compared with LAI estimates derived from allometry. NIR fisheye photography is suggested as a "fast and frugal" way to estimate relative LAI of urban vegetation, which also connects the domains of urban climatology and ecology with spatial analysis frameworks used in urban planning and design.

Key words: leaf area index, hemispherical photography, near-infrared

1. INTRODUCTION

Leaf area index (LAI), defined as the leaf area of a vegetation canopy per unit ground area, is a key indicator of vegetation primary production and energy exchange (Scurlock *et al*., 2001). As such, it offers a useful insight into *ecosystem services* such as carbon sequestration, microclimate amelioration and horticultural amenity. Hemispherical (fisheye) photography is an established and rapid indirect method for estimating LAI in forest ecology and meteorology, through determination of the gap fraction, or distribution of light penetration through the canopy (Bréda, 2003; Jonckheere *et al*., 2004). However, standard digital fisheye photography is unsuitable for estimating the LAI of urban vegetation, which is typically sparse and difficult to differentiate from surrounding built form in the visible spectrum. But since foliage is highly reflective in the near-infrared (NIR), leaf and non-leaf elements may be segmented in a hemispherical NIR image using readily available image processing software.

Chapman (2007) describes a simple method of adapting a conventional digital camera for NIR photography in forest environments, for example to distinguish between branch/bole-view and foliage-view factors. NIR photography can also discriminate between foliage and built form pixels, which may help to overcome the obstructive underestimation problem with visible light hemispherical photography in measuring the LAI of urban vegetation. This case study reports a comparative analysis of visible and NIR fisheye images for a set of positions across a moderately vegetated urban site in Sydney, Australia. $LAI_{visible}$ and LAI_{NIR} were calculated for each location and compared with estimates derived from allometry.

The study site is the main campus of the University of New South Wales (UNSW), located in Sydney, Australia. The campus covers 38 hectares and accommodates some 40,000 enrolled students and 5000 staff. Buildings are predominantly of four to eight storeys, the proportion of impervious surface is 71.2% and tree canopy cover is 18.9%

2. METHODS

2.2. Indicative allometric estimation – the "green plot ratio"

Sampling strategies for indirect LAI measurement typically involve transect-based or random distributions of measurements within discrete vegetation stands (Bréda, 2003), neither of which is easily adaptable to the urban situation of extreme landscape heterogeneity and diversity of land ownership. Direct LAI measurement through destructive harvesting of vegetation is clearly problematic in cities. Hence percentage tree cover, or more generally, vegetation cover is frequently used as a surrogate for the sustainability benefits of urban vegetation in planning and design. Ong (2003) introduces a promising new metric, the "green plot ratio" (GPR), expressed as a ratio of average LAI to site area, similar to the building plot ratio (usable floor area : site area) employed in urban planning. Ong uses the data of Scurlock *et al*. (2001), obtained from extensive field measurements, as indicative values for the LAI assessment of urban vegetation structural types.

The LAI values used here are also based on the work of Scurlock *et al*. (2001), but whereas Ong sets his measures at 1:1 for grass, 3:1 for shrubs and 6:1 for trees, the metrics used in this research are expressed as decimal numbers, include paved surfaces (LAI = 0) and introduce a distinction between shrubs (LAI = 2) and small trees (LAI = 4). Figure 1 depicts the coverage of paved surfaces, grass, shrubs and small and large trees for the UNSW campus in terms of indicative LAI at 5 metre resolution. This method gives an average LAI for campus open space of about 1.9.

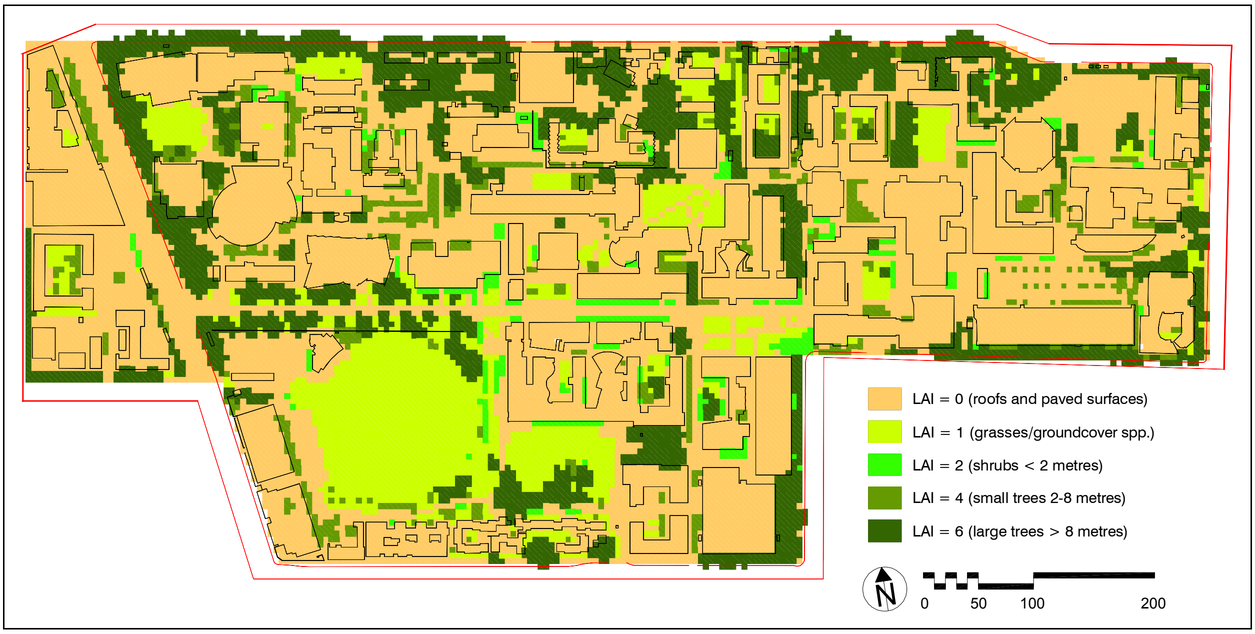

Figure 1: GPR plan of the UNSW campus at September 2007. Building footprints are outlined in black.

Space syntax techniques were applied to define a suitable spatial denominator to compare LAI results obtained through GPR with results obtained from fisheye photography. Space syntax is a method of spatial analysis based on the idea that the architectural structuring of space creates the material preconditions for human patterns of movement, encounter and avoidance (Hillier and Hanson, 1984). Syntactic analysis begins with the decomposition of the continuous but articulated structure of an urban space into the least set of two-dimensional convex spaces – street segments, squares, parks etc. A convex space is defined such that any line between any two internal points remains internal to the given space, and no internal angle is greater than 180^o, i.e. all points within the space are intervisible.

417 convex spaces > $5m^2$ were defined on a CAD plan of the campus, (Figure 2). The centroid of each space was identified, and the *isovist* at that point determined using the space syntax software UCL Depthmap (Turner, 2007). An isovist is the set of all points visible from a given point in space with respect to an *environment*, defined as a set of visible real surfaces in space (Benedikt, 1979). It thus represents a location-specific "sample" of an environment, and any environment can be described spatially in terms of its complete set of isovists. The 3D fisheye view from any location covers the same spatial extent as the 2D isovist from that location, hence includes the same vegetation elements, providing a basis for comparison between LAI derived from GPR and LAI derived from fisheye photography.

A sample of 79 isovists was selected to achieve maximum site coverage while reducing overlap, and excluding inaccessible areas, e.g. campus construction sites and spaces belonging to private residential colleges. Figure 2 shows the convex decomposition of the campus, the centroids of the selected convex spaces and an example of an isovist taken from one of the centroids. The average LAI_i value for each isovist i was calculated from the formula:

$$\mathrm{LAI}_i = \sum A(\mathrm{LAI}_n)\times(\mathrm{LAI}_n) \Big/ \mathrm{A}_i \;, \; n = \{0, 1, 2, 4, 6\} \qquad \mathbf{1}$$

where $A(LAI_n)$ = area covered by elements of leaf area index n and A_i = total area of the isovist.

2.2. Hemispherical photography

Indirect LAI estimation methods based on light transmittance such as hemispherical photography invoke the Beer-Lambert law, which assumes that light is attenuated exponentially as it passes through the canopy. Hemispherical photography relies on determination of the "gap fraction" $P(\theta)$, the amount of sky visible through the canopy:

$$P(\theta) = e^{-G(\theta,\alpha)\mathrm{LAI}/\cos(\theta)} \qquad \mathbf{2}$$

Thus $\mathrm{LAI} = \ln(P(\theta))\cos(\theta)/G(\theta)$ **3**

where θ = zenith angle of view, α = leaf angle, $G(\theta,\alpha)$ = the "G-function", which corresponds to the fraction of foliage projected on the plane normal to the zenith direction (Bréda, 2003).

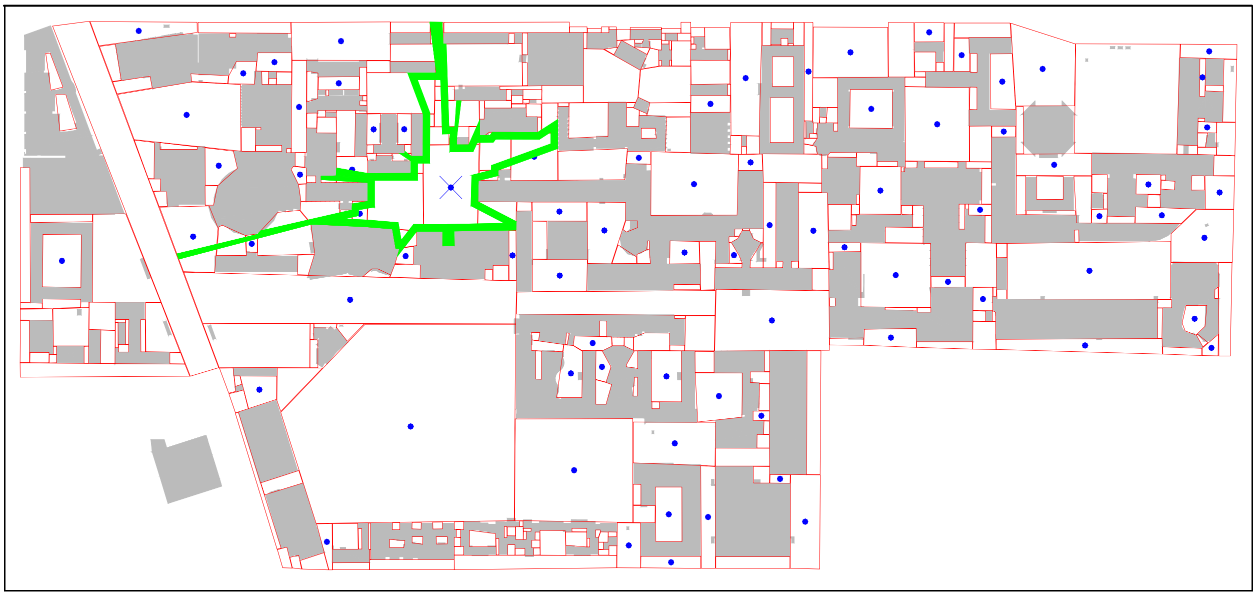

Figure 2: Decomposition of the campus into its constituent convex spaces (red); centroids of the sample set are shown in blue and the boundary of the isovist generated from centroid x is shown in green. Buildings are shaded grey.

Two Nikon Coolpix 990 digital cameras (one standard, one NIR-adapted by removal of its IR filter and attachment of a "cold mirror" filter to block visible wavelengths (Chapman, 2007)) were used to record two 2048 x 1536 pixel images from each centroid at 1.5 metre height. The same FC-E8 fisheye lens was used on both cameras. The photographs were taken during overcast conditions to ensure relative uniformity of sky luminance with respect to the zenith angle, and were overexposed approximately one stop to maximise the contrast between sky and foliage. The image processing software ImageJ v1.33 (Rasband, 2007) and canopy analysis program Gap Light Analyzer v2 (Frazer *et al.*, 1999) were used to segment foliage from non-foliage pixels through adjustment of histogram values prior to calculation of $LAI_{visible}$ and LAI_{NIR} for all locations. Figure 3 illustrates a typical NIR image pre- and post-processing.

Figure 3, left to right: hemispherical NIR image of a typical isovist; binary segmented image; binary segmented image following application of suitable thresholds to separate foliage from built form pixels.

3. Results and discussion

Table 1 sets out the statistical relationships between $LAI_{visible}$ and LAI_{NIR}, derived from analysis of the fisheye canopy images taken from the campus convex space centroids, and LAI_{GPR}, obtained from green plot ratio analysis of the isovists generated from the same convex space centroids. Since hemispherical images are taken from beneath the vegetation canopy, grasses and groundcover species are not included in the $LAI_{visible}$ and LAI_{NIR} calculations. These elements account for about 9% of total LAI according to the green plot ratio analysis.

	N	Mean	SD	LAI_{GPR}	$LAI_{visible}$	LAI_{NIR}	$LAI_{visible}$ contr. for A_i	LAI_{NIR} contr. for A_i
LAI_{GPR}	79	1.89	1.17	1	-	-	0.53	0.61
$LAI_{visible}$	79	0.43	0.41	0.49	1	-	-	-
LAI_{NIR}	79	0.62	0.53	0.58	0.87	1	-	-

Table 1: Descriptive statistics (columns 2-4), Pearson correlations (columns 5-7) and partial correlations controlling for isovist area for the sample dataset (columns 8 and 9). The sampling intensity, i.e. degree of overlap of the isovists and hemispherical images with respect to the overall site area, is 1.4.

The correlation between LAI estimated by the GPR method and LAI derived from hemispherical photography of the UNSW study site is significantly stronger for the NIR dataset. Controlling for the effect of isovist area A_i strengthens the association between LAI_{GPR} and both LAI_{visble} and LAI_{NIR}. This acknowledges that for a given vegetation structure type, LAI_{GPR} is invariant with respect to distance from the convex space centroid, whereas LAI_{visble} and LAI_{NIR} are dependent on the distance between the origin point of the fisheye image and the visible vegetation canopy.

Visible wavelength fisheye photography includes only vegetation which is exposed to the sky, i.e. unobscured by background buildings. Segmentation of the NIR image separates foreground foliage from background built form, which explains the significant difference in mean LAI values for the two methods. In addition, segmentation supports a closer approximation to *leaf* area rather than *plant* area index, as non-foliage canopy elements such as branches and stems which are less NIR-reflective are also excluded from the LAI calculation (Figure 3).

Regression analysis indicates a linear relationship between LAI_{GPR} and LAI_{NIR}, but data from sites of varying morphology and vegetation structure are clearly necessary to establish any predictive value for LAI_{NIR} with respect to LAI_{GPR}. Since GPR is itself an indirect method, a comparative analysis of LAI_{GPR}, LAI_{NIR} and one or more of the *direct* methods for assessing LAI (Bréda, 2003) across a variety of sites is required for calibration. Moreover, Jonckheere *et al.* (2004) note that fisheye photography in general tends to underestimate LAI, due largely to the effect of clumping. However, if *inter-site comparison* is the desired outcome rather than a high degree of accuracy of individual results, NIR hemispherical photography may provide the required information within acceptable limits.

This essentially exploratory research suggests that NIR hemispherical photography offers a rapid and convenient way to estimate comparative LAI between urban sites, as an indicator of vegetation primary production and hence the *ecosystem services* provided by urban vegetation, with potential application in urban landscape evaluation, planning and design. Additional benefits of fisheye photography include measurement of the sky view factor, and also the *fractal dimension of urban skylines*, which is associated with urban character (Cooper, 2003). Finally, the two spatial units utilised in this research – the *convex space* (derived from space syntax) and the *isovist* – establish a useful link between urban climatology/ecology and frameworks for spatial analysis employed in urban planning and design.

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