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UNDERSTANDING THE RADIATIVE PERFORMANCE OF URBAN TREES Does leaf reflectance up to 2.5 µm vary significantly with cardinal direction and sample locus?

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ABSTRACT

Three adolescent open grown urban trees have been analysed for variation in percent canopy reflectance. The experimental design segregated each canopy into eight blocks aimed at distinguishing between cardinal directions, upper and lower as well as inner or outer location of leaf samples in a canopy. Spectral reflectance data from 0.4 to 2.5 µm was taken and analysed for significant differences between the blocks. Variation in percentage reflectance was measurable and found to be significant in statistical analysis depending on locus.

KEYWORDS: Urban trees, Species variation, Leaf reflectance, Hemispherical influence, Tree canopy

INTRODUCTION

One of the key ecosystem services administered by trees is the provision of shade and cooling. Considerable efforts have been made to quantify these services to understand the energy-saving benefits of trees and other vegetation[1,2]. Urban areas provide potentially hostile conditions for trees, due to high impervious cover, poor soil conditions and changed radiation regime. In the built environment, trees may also be exposed to low vapour pressure deficits, anthropogenic heat sources, high wind speeds due to canyon effects, and higher ambient temperatures that contribute to a dynamic plant response[3]. These urban specific conditions result in variation between tree parameters (like above ground biomass and leaf area) of open grown trees and forest trees of the same species[4,5]. Since the capacity to dissipate thermal energy depends on morphological and physiological features as well as water availability and wind intensity[6], the cooling potential and capacity for heat and drought tolerance varies on an inter- and intra-species level[7]. Empirical evidence, however, on structure, morphology, and ecophysiology of urban trees (especially species specific) is relatively scarce. This short study was carried out to identify potential differences in reflectance of leaf samples due to hemispherical influence and sample location on the tree. The results will inform methodological choices for spectral sampling of trees to further the understanding of the radiative properties of urban trees.

MATERIALS AND METHODS

Adolescent trees (~6m height) were sampled on the Whiteknights Campus, University of Reading, and corresponding dendrological information (Diameter at breast height (DBH), Height, Crown Spread, GPS data) recorded. Three trees, one Yellow Buckeye (Aesuclus flava) labelled A and two Paper Birch (*Betula cordifolia*) labelled B and C, were sampled on three consecutive afternoons (29.09.2015 – 01.10.2015). Each canopy was divided into four upper and lower sectors corresponding to cardinal direction (Figure 1). Out of each sector an inner and outer branch were sampled with three visually healthy leaves, washed (distilled water), dried and weighed before spectral analysis being carried out within 30 minutes of collection. Five measurements of reflectance spectra were taken on the abaxial and adaxial side of each leaf using Spectral Evolutions SM-2500 spectrometer with leaf clip (0.4 – 2.5 µm), automatic integration time of 20 ms, and 10 scans to average. A digital camera (Samsung ST30) mounted on a laboratory stand was used to take equal distance and angle pictures of each sample. Two 80 Watts light sources were used to minimize shading effects.

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The mean of the five spectral readings for each upper leaf side was used for further analysis. Gausman and Allen (1973) proposed seven representative wavelengths, 550 nm (green reflectance peak), 650 nm (chlorophyll absorbance peak), 850 nm (infrared reflectance plateau), 1450 nm (water absorption band I), 1650 nm (peak after water absorption band I), 1950 nm (water absorption band II) and 2200 nm (peak after band II). These were adopted for this study. Noise in spectral measurement below 400 nm set the lower threshold for data analysis; carried out using Statgraphics XVII by Statpoint Technologies, Inc.

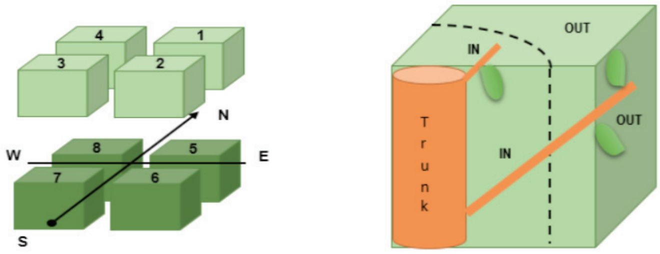

Figure 1: Eight sampling blocks per tree, cardinal direction for upper (light green) and lower (dark green) canopy. Samples considered inner (near trunk) canopy and outer canopy in magnified block.

RESULTS AND DISCUSSION

To determine whether a significant difference at 5% significance level (p=0.05) exists in the reflectance values of A, B, and C, the data were normalised using the mean for all species and across the whole spectrum. A variance check showed non-significance between same species standard deviations of Betula cordifolia (B, C), but p << 0.05 between Aesculus flava (A) and each Betula cordifolia, highlighting an interspecies variation (Table 1). Two sample comparison (t-test) returned a significant difference in means for A vs B (p=0.000) and no significance for B vs C (p=0.243). Given the non-significant difference between B and C an analyses based on species i.e. A against B and C combined would be possible but rejected to allow for identification of borderline significant reflectance values. As a result data were analysed separated by individual trees.

Table 1. Standard deviation, F-Ratio and P-Value for species comparison.

Comparison	σ 1	σ 2	F-Ratio	P-Value
Sample A / Sample B	0.10729	0.0887952	1.45994	0.0006
Sample A / Sample C	0.10729	0.0833022	1.65883	0
Sample B / Sample C	0.0887952	0.0833022	1.13623	0.243

ANOVA for reflectance by waveband was carried out for the datasets indicating a statistically significant difference (p=0.00) between the means of the seven wavebands. A total of seven outliers were identified at 650 nm, 1450 nm and 1950 nm. Out of these, five were associated with A and one with B and C each. As these wavebands correspond to chlorophyll and water absorption bands these outliers suggest a species and/or plant health related influence[9]. Visual inspection of the outlying sample pictures show slight leaf colouration changes compared to the rest of the sample set indicating a physiological cause that cannot be further investigated visually. The outliers were subsequently removed in the analysis of the three influenced wavebands. Given the wider focus on radiative properties of trees, special interest was paid to the near infrared (NIR) reflectance plateau at 850 nm. At this waveband, A shows the highest average reflection at 53.26 %, on average 0.73 % more than B and C. This means A absorbs less in the NIR, which could be an expression of species difference in leaf strategy. Average leaf area for A is 41.98 cm^2, B = 24.91 cm^2 and C = 28.68 cm^2. Whilst bigger leaves provide a better photosynthesis capacity it is beneficial to such leaves to absorb less light in the non-photosynthetically active spectrum to ease the heat burden[10].

Comparison between top and bottom sections of each tree canopy showed a statistically significant difference between the means of upper canopy and lower canopy samples at 1650 nm (p = 0.0130) as well as 2200 nm (p = 0.0038) for A. These reflection peaks are outside the corresponding water absorption bands at 1450 nm and 1950 nm, indicating variance based on species specific cellulose/lignin content. When disaggregated for each individual tree, no significant difference between top and bottom canopy reflectance at 1650 nm could be identi-

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fied for B and C, supporting this explanation. At 2200 nm only samples from specimen B displayed significance with p = 0.0381. This could indicate stress effects due to heavy metal pollution[10] for B, but has not been tested in this study. Incidence of higher reflection was more frequent in samples from the lower canopy across all wavebands with an exception at the chlorophyll absorption band 650 nm. Here, samples from the top half of each tree showed a higher reflectance and subsequently less absorption. This is to be expected, as shade acclimatised leaves contain relatively more chlorophyll to counter balance a photosynthetically unfavourable chlorophyll-a to chlorophyll-b ratio[11]. Full spectrum canopy reflectance for A showed on average +0.24 % for the upper canopy samples and –0.220 % for the lower canopy. Values for B were +0.13 % and –0.13 % as well as +/- 0.33 % for C, all values in relation to whole canopy average reflection. Distribution testing returned average kurtosis values of -9.7 for each block, outside the expected range of +/- 2 for normal distribution; performing a non-parametric Kruskal-Wallis test on sample medians demonstrated samples in different blocks cannot be considered equivalent (p=0.00). Since significance was implied, a post hoc multi-comparison with Bonferroni correction was applied to identify blocks significantly different from each other. Each block combination was tested pairwise. Out of 28 block pairings per tree, eight were significantly different at the 95.0% confidence level for A, seven for B, and six for C. All six or 21.43% of significant sample pairings for C were between upper and lower blocks, as opposed to A and B with four (14.29%) such pairings in the upper block and four respectively three in the upper to lower comparison (Table 2). Sample pictures from C gave no indication why this effect is visible. Klich (2000)[11] studied leaf variation in *Elaeagnus angustifolia* (Russian olive), suggesting effects due to environmental gradients but given the difference in climatic zones an application to this study's findings would be speculative. Lower canopy blocks proved to be statistically equivalent to each other emphasizing light intensity effects on upper canopy leaves[13].

Table 2. Number and percentage of significantly different upper and lower block pairings out of 28 possibilities.

Tree / Combination	UP / UP		UP / LOW		LOW / LOW		Total	
A	4	14.29%	4	14.29%	0	0.00%	8	28.57%
B	4	14.29%	3	10.71%	0	0.00%	7	25.00%
C	0	0.00%	6	21.43%	0	0.00%	6	21.43%

Comparison of inner to outer leaves within and against each other returned highest incidence of significant difference for A, B and C at the interlocus comparison. For C, 32 out of a total of 38 significance incidents belonged to this category. A and B displayed highest values in the inner leaves versus outer leaves category with 20 out of 37 for A and 26 out of 43 for B (Table 3). Intra comparison for inner and outer leaves shows smaller incidence values indicating a locus dependence. This effect is likely related to light intensity and biochemical effects i.e. 'sun' versus 'shade' leaves (Jones, 2013; Barton, 2001).

Table 3. Number and percentage of significantly different inner and outer block pairings out of 120 combinations.

Tree / Combination	IN / IN		IN / OUT		OUT / OUT		Total	
A	10	8.33%	20	16.67%	7	5.83%	37	30.83%
B	6	5.00%	26	21.67%	11	9.17%	43	35.83%
C	6	5.00%	32	26.67%	0	0.00%	38	31.67%

To assess the impact of cardinal direction, all significant block pairings were ranked by number of occurrence for each block and between inner and outer leaf location due to the higher rates of difference between those leaves (Table 4). For all trees, block 1 IN, facing N.E returned the highest number of incidence of significant pairings. For tree A, Block A1 IN was highlighted 11 times out of 37 occurrences of significant differences, B1 IN 7 times, and C1 IN 10 times. For outer samples, block A2 OUT (facing S.E) and B3 OUT (facing S.W) had highest frequency with 4 significant pairings each. As indicated by the previous findings, C did not have significantly different pairings and no similar relationship to cardinal direction can be identified.

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Table 4. Locus of highest per tree frequency of difference with absolute value, percentage and cardinal direction.

A				B				C			
Locus	∑	%	Direction	Locus	∑	%	Direction	Locus	∑	%	Direction
A1 IN	11	29.73	NE UP	B1 IN	7	16.28	NE UP	C1 IN	10	26.32	NE UP
A2	4	10.81	SE UP	B3	4	9.30	SW UP	n.a.	0	0	n.a.

Reflectance differences in relation to whole canopy reflectance between the blocks are generally small ranging from +2.47 % to –2.24 % (range = 4.71 %). Table 5 shows percent reflectance difference from average canopy reflectance by tree, block and cardinal direction, upper or lower as well as inner and outer canopy.

Table 5: Reflectance difference in % per block for each tree with locus and cardinal direction. Light green highlights upper canopy, dark green indicates lower canopy.

Tree/Block		1 NE	2 SE	3 SW	4 NW	5 NE	6 SE	7 SW	8 NW
A	IN	2.4730527	0.9620475	-0.5973735	1.1128279	0.1829755	-0.8027637	-0.4449069	-1.5011647
	OUT	-0.0483188	-1.5393014	-0.7776057	0.1998305	-0.7164677	0.5603878	1.0235857	-0.0868053
B	IN	1.8060609	-0.9074178	0.0509663	1.0659125	0.830945	0.3369672	0.2058526	0.3706334
	OUT	-0.2858501	0.3920301	1.1427541	-2.2447316	-0.9229859	-1.2980055	-0.6948414	0.1517102
C	IN	1.440871	0.8113571	1.4178957	0.6138028	0.3435203	-0.1904697	0.082318	1.028815
	OUT	-0.5521308	-0.210307	-0.7003126	-0.184688	-0.7383716	-1.3538716	-1.1825661	-0.6258625

Even though absolute values of percent reflectance are small, the differences are found to be statistically significant. It is important to note that other factors will play a potentially bigger role on result variation. Leaf physiological characteristics change not only with a diurnal cycle but also over the course of the seasons (Jones, 2013). This temporal variation needs to be explored to truly inform methodological choices. A potential outcome would be a reflectance variation parameter to adjust data depending on time and locus of sampling. Increasing sample size combined with extending the spectral sampling into the mid-infrared region will help to improve the robustness of the findings in this short study. Given the findings, leaf location and tree orientation should be recorded as valuable parameters for post sample harvest analysis.

CONCLUSION

A variation in percent leaf reflectance is measurable and comparisons between the blocks show statistically significant deviations within a 95% confidence interval. For this dataset, N.E facing inner canopy leaves show highest incidence of difference. These can be attributed to factors like chlorophyll, cellulose or lignin content due to their shade adaptation. Outer leaf samples show higher difference facing S.E and S.W respectively likely due to light intensity impacts. The spectral information supplemented by the wavelengths suggested by Gausman and Allen (1973) have proven useful to explain outliers and should be retained in further experimental setups as a fast method to support data analysis. Results suggest leaf reflectance up to 2.5 µm varies significantly with cardinal direction and sample locus. It is, therefore, necessary to adopt a sampling design that observes these findings for wavelengths up to 2,500 nm. Use of octants for such profiling will be useful to produce canopy spectral maps. A similar study should be repeated for wavelengths in the near- to mid-infrared region to check for similar influence on those wavebands.

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