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Evaluating the ultraviolet protection factors of urban broadleaf and conifer trees in public spaces

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ABSTRACT

Urban trees provide natural shade and moderate human exposure to solar ultraviolet radiation. To date, most studies quantifying UV attenuation by urban tree canopies have taken place in Australia, with no studies in North America. Few studies have utilized sensors sensitive to UV-B radiation, although the shorter wavelengths are more important in determining erythemal (skin burning) UV. We collected solar UV radiation exposure data beneath 64 individuals of 16 tree species commonly planted in the City of Toronto's schoolyards and public parks, using UV electronic logging dosimeters that have a spectral response closely matching the erythemal action spectrum. Additional data were collected on canopy structure (crown radii, crown transparency, crown depth, diameter at breast height, height to live crown, and leaf-level data). UV protection factor (PF: the ratio of open-site UV to below-canopy UV) varied 2.6-fold among species, ranging from ~1.3 – 3.4. Statistical models for variation among trees indicated that crown transparency (%), the ratio of crown breadth to height to live crown, and species shade tolerance were important predictors of PF. *Acer platanoides* 'Crimson King', *Celtis occidentalis* L., *Quercus bicolor* Willd., and *Fagus sylvatica* 'Purpurea' showed the highest PF values (> 3), and *Ginkgo biloba* L. and *Acer rubrum* L. showed the lowest PF values (< 2) among sampled species. Findings from this study can help inform tree management strategies and policies to increase UV protection in schoolyards and other public settings.

1. Introduction

Trees provide natural shade and protect humans from solar ultraviolet (UV) radiation. Public programs to raise awareness to the hazards of solar UV radiation have been successful in promoting the use of personal UV protection, such as sun-protective clothing, hats, sunscreens, and sunglasses. However, the primary focus of most public health programs is to modify the environment to provide shade (Armstrong and Kricker, 2001). Currently, there are only a few municipalities (including Toronto, Ontario; Waterloo, Ontario; Victoria, Australia) that have a "Shade Policy", that aims to provide and target possible opportunities for construction of natural and built shade structures to prevent skin cancer (Ontario Sun Safety, 2018). In many municipalities, non-living shade structures are being placed in primary schools and parks to provide safe areas where children can undertake outdoor activities (Holman et al., 2018). A study by Gies and Mackay (2004) evaluated the effectiveness of artificial shade structures in providing UV radiation protection and found that these structures often reflect incoming solar UV radiation, and also absorb and re-emit UV and visible radiation as heat. As a result, urban heat island effects may be enhanced by artificial shade structures. Shade trees provide an alternative that is cost-effective and also have additional environmental and aesthetic benefits.

The sun's UV radiation can be divided into three different wavelength segments; UV-A (315 – 400 nm), UV-B (280 – 315 nm), and UV-C (100 – 280 nm), with shorter wavelengths emitting greater energy as described by the Planck-Einstein equation (Yoshimura et al., 2010). Due to their high energy, the UV-B and UV-C wavelengths cause the most biological damage, which can result in premature skin aging, skin erythema, cancer (Urbach, 1980), cataracts (Ayala et al., 2000), and can suppress the body's immune system (Hart et al., 2011). Stratospheric ozone partially absorbs incoming solar radiation, including nearly all high-energy UV-C rays, but appreciable levels of UV-B reach the earth. Recent studies have reported some biologically relevant UV-C at ground level, however, these findings have been questioned and were likely caused by instrument biases (D'Antoni et al., 2007; Flint et al., 2008).

In urban areas, solar UV radiation reflects off built structures and hard ground surfaces. Sliney (1986) found that UV reflectance from surface materials like sand and concrete contributes far more to UV

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exposure than that from green vegetation. One way to reduce effects of UV reflectance is to increase tree canopy cover; this is particularly important in urban areas where concrete and other hard surfaces pose heightened UV exposure risks to humans. *In-situ* measurements indicate that urban trees provide substantial protection against UV (Parisi et al., 1999; Grant et al., 2002; Gies et al., 2007), however, few such measurements exist, and variation among tree species has been poorly characterized. While leaf optical parameters (*i.e.*, leaf transmittance, reflectance, and absorptance) are important to some extent, UV attenuation patterns are thought to be mainly a function of the crown form and structure of a tree (Parisi et al., 1999; Gies et al., 2007).

Canopy gap fraction and within-tree leaf area index (LAI) varies among tree species (Horn, 1971); thus, it is likely that solar UV radiation penetrating below the canopy also varies among tree species. In general, shade-intolerant tree species that show higher growth rates also exhibit lower canopy gap fraction and higher light transmittance than shade-tolerant tree species (Canham et al., 1994; Valladares and Niinemets, 2008; Quinn and Thomas, 2015). This pattern is thought to be an evolved consequence of differences in leaf-level respiration and light compensation point, and co-evolved traits along the leaf economics spectrum (Wright et al., 2004). Trees are predicted to retain self-shaded leaves to the extent that these contribute to increased net carbon gain. Other aspects of canopy form, such as canopy depth, relative crown width, branching patterns, and leaf angular distributions, are also likely to show systematic variation along this ecological axis (Verbeeck et al., 2019).

Due to scattering effects and marked differences in optical properties of UV and visible wavebands, patterns of UV transmittance below tree canopies are not expected to correspond closely to visually perceived shade. UV radiation is highly scattered in the atmosphere and predominantly diffuse rather than direct (Frederick et al., 1989), even under cloudless conditions (e.g., Parisi et al., 2001). Although modeled estimates of UV attenuation have been applied in the context of urban forests (*e.g.,* Grant et al., 2002), there have been only a few empirical studies on patterns of UV attenuation underneath tree canopies (Parisi et al., 1999; Gies et al., 2007). There also remain few quantitative data pertaining to tree shading effects on solar erythemal UV, which is the spectral weighting pattern that matches the erythemal (skin burning) action spectrum. To date, most studies of tree attenuation of UV radiation have taken place in Australia (Parisi et al., 1999, 2000; Gies et al., 2007) and have focused on measuring primarily UV-A and some UV-B radiation below tree canopies. Very few studies have incorporated erythemally weighted UV below tree canopies (Parisi et al., 1999; Gies et al., 2007; Ysasi and Ribera, 2013; Downs et al., 2019). As well, existing municipal shade policies tend not to incorporate direct UV measurements when recommending potential tree species for planting. Where interspecific differences are considered, McPherson's shade factor (McPherson, 1984), defined as the percentage of sky obscured by foliage and branches within the perimeter of the tree crown, has loosely been used as a basis for recommendations. Many shade policies and guidelines promote the planting of dense and large canopies (SunSmart Victoria, 2015; UVR working group, Toronto Cancer Prevention Coalition, 2010), however they provide no species-specific recommendations due to the lack of information on their respective UV benefits.

In addition to variation among species, individual trees are likely to show variation in crown structure that may affect UV attenuation patterns. For example, canopy openness and within-crown LAI of individual trees generally declines with tree age following reproductive maturity, thereby increasing light transmission as canopy trees grow and mature (Nock et al., 2008; Quinn and Thomas, 2015). Trees also generally show increases in canopy transparency in response to drought and other stress factors (Zarnoch et al., 2004). Patterns of leaf senescence vary systematically among trees of varying shade tolerance (Koike, 1990) suggesting seasonal changes in crown structure that would affect UV attenuation. In urban environments, patterns of tree pruning and maintenance may likewise have important effects on crown structure and UV attenuation.

Table 1
List of study species, and their respective UV protection factor (PF) values averaged across individual trees, and their shade tolerance scores based on Niinemets, Ü., & Valladares, F. (2006) sampled in Toronto, Ontario during June to August in the years 2015 and 2016.

Species	PF	Standard error	Shade tolerance	n
Acer x freemani E. Murray.	2.43	0.081	3.52	7
Acer platanoides L.	2.76	0.432	4.20	6
Acer platanoides 'Crimson King'	3.39	0.127	4.20	3
Acer rubrum L.	1.31	0.070	3.44	5
Acer saccharinum L.	2.02	0.134	3.60	4
Aesculus hippocastanum L.	2.89	0.599	3.43	4
Celtis occidentalis L.	3.17	–	3.17	1
Fagus sylvatica 'Purpurea'	3.00	0.279	4.56	5
Ginkgo biloba L.	1.33	0.138	1.34	3
Juglans nigra L.	2.48	0.254	1.93	2
Pinus nigra Arnold.	1.93	0.304	2.10	5
Pinus strobus L.	2.39	0.246	3.21	6
Platanus occidentalis L.	2.40	0.049	2.86	2
Quercus bicolor Willd.	3.05	0.131	2.98	4
Quercus rubra L.	2.67	0.254	2.75	3
Tilia cordata Mill.	2.86	0.541	4.18	3

The present study focuses on measuring the penetration of erythema-causing UV wavelengths of 280–320 nm under common urban tree species in Toronto, making use of recently developed logging dosimeters for measurements. We address the following questions: (1) Does sub-canopy penetration of UV-erythemal radiation vary among tree species? (2) If so, what traits best predict variation in UV exposure beneath trees? and (3) Do shade-tolerant species with deeper canopies and lower gap fraction show higher UV attenuation than shade-intolerant species?

2. Materials and methods

2.1. Tree selection and measurements

During two summer seasons (June to August in the years 2015 and 2016), 64 individuals of 16 common urban tree species (Table 1) were sampled across nine urban schools and four public parks in Toronto, Ontario, Canada. Trees sampled were selected to meet the following criteria: (1) species commonly found in urban areas of Toronto; (2) trees located away from other buildings (minimum 15 m), substantial structures, and other trees to avoid obstruction of sky view from the observation point; (3) trees with healthy and symmetrical crowns; and (4) trees had crown radii ranging from 2 – 5 m. Considering the limitations and difficulties finding healthy isolated urban trees, the number ranged from 1 to 4 individuals within each species; in a few cases sample size was increased.

For each tree sampled, crown symmetry was estimated visually using a scale of 1–5 (1 being the least symmetrical, 5 being the most asymmetrical), and crown transparency was recorded as a mean of three transparency measurements at three separate locations beneath each tree crown using a "moosehorn" densiometer (Garrison, 1949; exact specifications of the instrument used are given by Quinn and Thomas, 2015). Tree height and crown depth were measured using angle (inclinometer) and distance measurements, while crown radius was measured as the mean of 3 measurements. These data were then used to calculate the ratio of crown radius to height to live crown (CR/HLC), which we hypothesized would be positively related to the UV protection factor under conditions of high radiation scattering. Visual estimates were also made of proportion crown dieback, proportion leaf chlorosis, and crown form index for each sampled tree (following Zarnoch et al., 2004). Diameter at breast height (DBH) was recorded for each tree using a diameter tape at 1.3 m height. Species shade tolerance scores were treated as the means reported in a prior review (see Table 1, Niinemets and Valladares, 2006). Shade factor was calculated for all individual trees based on DBH and shading coefficient, accounting for species and climate effects (following McPherson et al., 2018, using the closest available climate zone in the US for estimates for each species). Shading coefficient estimates were not available for *Fagus sylvatica* 'Purpurea', *Quercus bicolor* Willd., *Aesculus hippocastanum* L., *Acer x freemani* E. Murray. and *Pinus strobus* L., thus they were excluded from shade factor calculations.

2.2. UV measurements

Solar UV radiation exposure data were collected using electronic dosimeters (Scienterra, Otago, New Zealand). These devices are battery-powered UV detectors consisting of an aluminum gallium nitride (AlGaN) photodiode with logging capability (Allen and Mckenzie, 2005; Wright and Reeder, 2005). The detectors have a spectral response that closely matches the erythemal (skin burning) action spectrum in the 230 − 320 nm waveband (McKinlay et al., 1987) and very low temperature sensitivity (Allen and McKenzie, 2010; Scienterra, 2015). The dosimeters contain a processor with an analog converter allowing the reading of UV irradiance at pre-specified intervals (Sherman, 2018). The dosimeters were cross-calibrated with a Brewer spectrophotometer (Environment Canada, 2015) in July 2015. The spectrophotometer measured spectral UV irradiation between 290 and 325 nanometers every 10 − 20 min during daylight hours and provided the integrated CIE (Joules m^{-2}), which is the erythemal solar UV (UV_{Ery}) weighted to the erythema action spectrum for human skin (Commission Internationale de l'Eclairage (CIE), 1998).

The dosimeters were programmed to take a measurement once per minute between the hours of 11:00 am to 2:00 pm to capture solar noon (1:17 pm to 1: 25 pm) in this region. The solar zenith angles (SZA) around 12:00 pm ranges from 20.5°-26.6° for our sampling period (Environment Canada, 2015, 2016). Each per-minute measurement was converted to UV_{Ery} (Joules m^{-2}) using dosimeter-specific calibration curves. To express the protective influence of a tree, defined as the Protection factor (PF), the measured erythemal solar radiation beneath an individual tree was expressed as relative to the available ambient erythemal radiation. The mean of the three dosimeters underneath each respective tree was expressed as a PF.

$$PF = \frac{UV_{Ery(a)}}{UV_{Ery(tree)}}$$

Where PF stands for Protection Factor, $UV_{Ery(a)}$ or the total erythemal solar UV measured in the nearby open space (control), and $UV_{Ery(tree)}$ is the total erythemal solar UV underneath the sample tree.

Three dosimeters were placed under each tree equal distance apart, approximately 1 m away from the tree base (Gies et al., 2007) and 1 m above the ground using PVC tube stands, thus mimicking the height of a small child, the most vulnerable demographic group. Each dosimeter was fastened with a zip tie to a small tripod attached to the PVC tube and placed horizontally at 180° (using a circular level) to the ground. The study protocol was designed to capture children's high exposure times. All dosimetry measurements were taken during sunny or partially cloudy days, between 11:00 am to 2:00 pm. Two dosimeters were set in nearby open spaces to obtain temporally matched open space control measurements. General metrological conditions were noted each morning of the study (Environment Canada, 2015 and 2016).

Additional measurements were made of leaf-level UV optical parameters, leaf morphology, and leaf angle distributions for a subset of deciduous broadleaf species sampled. Full details of leaf optical measurements are presented in a companion paper (Sivarajah et al., submitted 2020). Leaf-level UV reflectance and transmittance of both adaxial and abaxial sides of leaves were measured in a double integrating sphere system, with illumination provided by a pulsed xenon light source capable of collecting spectral measurements between 220 − 400 nm. We hypothesized that the abaxial UV reflectance might affect canopy-level UV attenuation by reflecting scattered radiation beneath tree canopies. Leaf tissue density (g/cm^3) was calculated as the ratio of leaf dry biomass (g) and leaf lamina volume (cm^3), the latter estimated as the product of leaf area and leaf lamina thickness (Sivarajah et al., submitted 2020). Leaf angles were measured on site for a minimum of 20 leaves collected from the top-most and bottom-most branch of each sampled tree using a SUNTO inclinometer to the nearest 1°. All branches were held in place to recreate orientation in the canopy and measured within 5 min of branch clipping. During the leaf-level measurements, leaves were sampled from each individual tree collected from each stratum.

2.3. Statistical analysis

All statistical analyses were performed using R v.3.3.0 (R Foundation for Statistical, Vienna, Austria). ANOVA and Tukey honest significant difference (HSD) post-hoc tests were used to compare mean PFs among species. Total tree height was highly correlated to crown depth ($r = 0.959$), therefore, it was omitted from analyses. During preliminary analyses, multiple regression models were used to analyze PF as a function of species, crown depth, diameter at breast height, shade tolerance, crown transparency, crown radii, height to live crown, ratio of crown radius to height to live crown (CR/HLC), and the interaction of these terms. A global linear model was constructed to assess the variability in mean PF among individual trees as a function of crown depth, crown transparency, diameter at breast height, ratio of crown radius to height to live crown, shade tolerance scores, and the interaction of these factors. The global model was fed into an automated stepwise regression model selection, which was constructed using a 'step' (forward and backward selection) function to select the best model to explain the observed means of PFs minimizing Akaike's information criterion (AIC). To confirm the validity of the automated models, the corrected Akaike's information criterion (AICc) was generated and compared for the last three models (Burham and Anderson, 1998). An additional Pearson coefficient of determination test was used to compare the relationship between shade factors (used as a proxy for visible shade) and UV PFs.

3. Results

The estimated UV protection factor (PF), measured as the ratio of measured erythemal UV beneath a tree to erythemal UV temporally matched in open spaces (control), varied significantly among tree species ($F = 3.494$; $p < 0.001$). PF was significantly correlated to species shade tolerance: species with higher shade-tolerance scores showed higher PF values ($r = 0.395$; $p = 0.001$). PF values ranged from 1.07 to 4.14 among sampled individual trees; the overall mean PF was 2.46 ± 0.10, with species mean values varying from 1.31 to 3.39 (Table 1). Among sampled trees, crown depth ranged from 3.30 to 10.14 m, with a mean of 7.08 ± 0.29 m (±1 SE); crown transparency ranged from 0.00–13.00%, with a mean of 5.88 ± 0.80 %; and crown radius ranged from 2.00–5.67 m, with a mean of 3.72 ± 0.11 m. Total tree height ranged from 4.30 to 16.00 m, with a mean of 8.66 ± 0.21 m, and height to live crown ranged from 0.5 to 4.0 m, with a mean of 1.58 ± 0.08 m. Diameter at breast height (DBH) ranged from 13.00–50.00 cm, with a mean of 25.53 ± 1.12 cm. Mean values of ratio of crown radius to height to live crown ranged from 0.92 to 7.10 m, with a mean of 2.70 ± 0.15 m.

Multiple linear regression analysis revealed that a tree canopy's PF is best predicted by crown transparency (%) ($p = 0.004$), the ratio of crown radius to height to live crown (CR/HLC) ($p = 0.020$), and species shade tolerance scores ($p = 0.021$), which together explained 30 % of observed variance (Table 2). The next lowest model AICc score (which included a term for the interaction of crown transparency and CR/

Table 2
Independent variables chosen by stepwise model selection using minimized AICc, their P-values explaining the variation in protection factor (PF) beneath urban trees in Toronto, Ontario during June to August in the years 2015 and 2016. R^2 values are partial coefficients of determination explaining the total proportion of variance for chosen model, which shows the minimum AICc values (n = 64).

Parameters	Model R = 0.298, p = 0.0001			
	Est.	Standard error	p-value	Partial R^2
Crown Transparency (%)	−0.043	0.014	**0.004**	0.107
Crown Radius:height ratio to live crown	0.182	0.076	**0.020**	0.068
Shade tolerance	0.260	0.110	**0.021**	0.067

*All significant predictors are in bold.

HLC), differed by 11.11 AICc units. Crown transparency was negatively related to PF, whereas CR/HLC and shade tolerance scores were positively related to PF (Fig. 1; Table 2). Among species, *Acer platanoides* 'Crimson King', *Celtis occidentalis* L., *Quercus bicolor* Willd., and *Fagus sylvatica* 'Purpurea' showed the highest PF values (>3) but were not distinguishable by Tukey HSD post-hoc tests (Fig. 2). *Ginkgo biloba* L. and *Acer rubrum* L. showed the lowest PF (<2) among the sampled species.

Tests for relationships between leaf-level parameters and PF were not significant (Fig. 3), although sample sizes, and thus statistical power were small. Mean leaf angle was expected to be negatively related to PF due to effects of radiation transfer through the canopy; the observed correlation was negative but not significant (Fig. 3a: r = -0.313, p = 0.198). UV-A reflectance of the abaxial leaf surface might be expected to be negatively related to PF due to a radiation "trapping" effect; the observed correlation was likewise in the expected direction, but not significant (Fig. 3b: r = -0.232, p = 0.485). Leaf tissue density was expected to be positively related to PF, and again the correlation was in the expected direction, but not significant (Fig. 3b: r = 0.190, p = 0.286). There was also a weak but significant relationship between canopy-level shade factors and UV PFs (r = 0.351; p = 0.033) (Fig. 4).

4. Discussion

We present here the first direct measurements of protection factors for erythemal UV in common urban trees from North America. The data provide support for our hypothesis that UV protection factors vary substantially among tree species, with mean PF values showing ~2.6-fold variation ranging from 1.31 to 3.39. The values are broadly consistent with previous estimates from studies in Australia (Gies et al., 2007; Downs et al., 2019). Downs et al. (2019) recently presented model estimates that suggest UV protection factors range from 1.05 to 4.98 among tree species. Gies et al. (2007) estimated annual PF values between 2.30–10.40 based on empirical measurements; however, the highest values from their study are likely overestimates explained by biases arising due to use of chemically degrading polysulphone badges. Our results also confirm only weak relationships between visibly perceived shade (using shade factor as a proxy) and below-canopy UV protection (Fig. 4).

Consistent with our general hypothesis, the results suggest that the main factors driving variation in UV protection among trees are related to crown geometry. Specifically, crown transparency and the ratio of crown radius to height to live crown (CR/HLC) were identified as the best predictors of PF values among individual trees (Table 2). Previous studies have noted a relationship between estimated PF values and canopy gap fraction (Parisi et al., 1999; Gies et al., 2007; Downs et al., 2019), but have not examined potential relationships with other aspects of canopy macrostructure. Correlations between leaf-level parameters and PF values were in the expected directions, with the highest correlation observed for mean leaf angle (Fig. 3a). Thus, our data suggest that other aspects of canopy geometry and leaf optics may contribute to UV attenuation, but a considerably larger sampling effort would be necessary to rigorously test for such effects.

We also found that tree species with higher shade-tolerance scores were generally the most effective at screening UV (Fig. 1C): *i.e.,* that shade-tolerant trees (e.g., *Acer platanoides* L., *Fagus sylvatica* 'Purpurea') show the greatest attenuation of UV radiation. This is in part explained by the fact that shade tolerance predicts canopy gap fraction and canopy depth (Canham et al., 1994; Valladares and Niinemets, 2008; Quinn and Thomas, 2015), which we identified as the best predictors of UV attenuation (Table 2, Fig. 1). However, the multiple regression model included shade tolerance scores as a predictor together with canopy transparency and CR/HLC suggesting that additional leaf and canopy architecture traits correlated with shade tolerance contribute to this pattern as well.

The logging UV dosimeters used in our study are a recent methodological innovation. Dosimeters of this type have previously been used

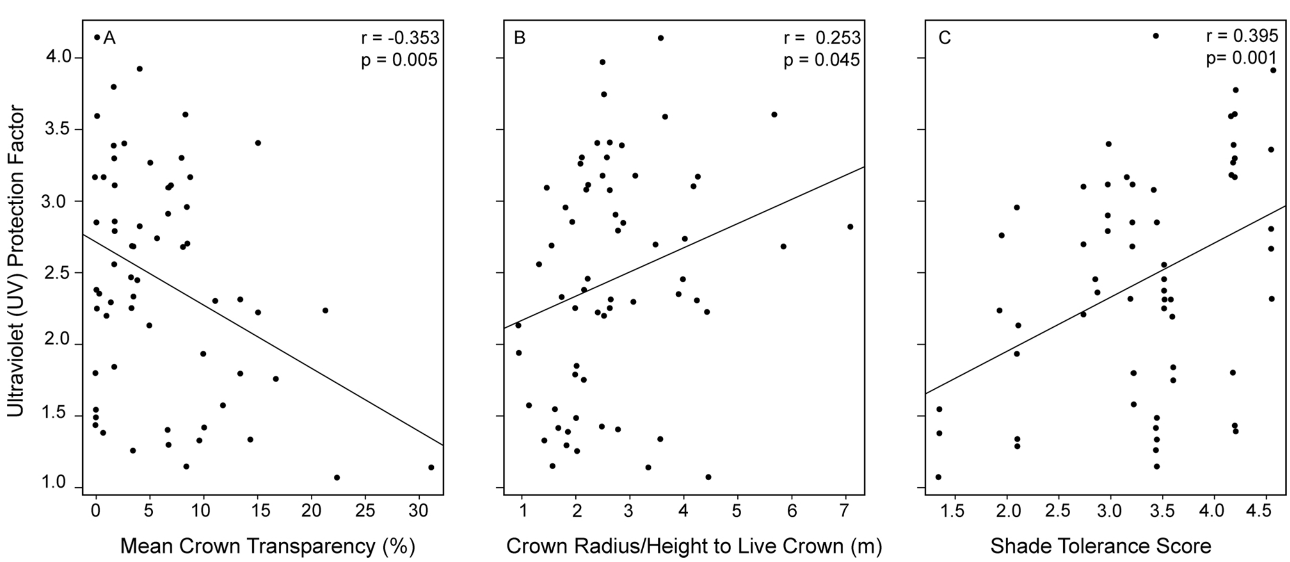

Fig. 1. Correlation plots illustrating the relationships between mean protection factors (PF) and A) Mean crown transparency (%), B) crown radius:height ratio to live crown (m) C) shade tolerance for individual urban trees (n = 64) sampled across urban schoolyards and public parks within Toronto, Ontario, Canada during June to August in the years 2015 and 2016.

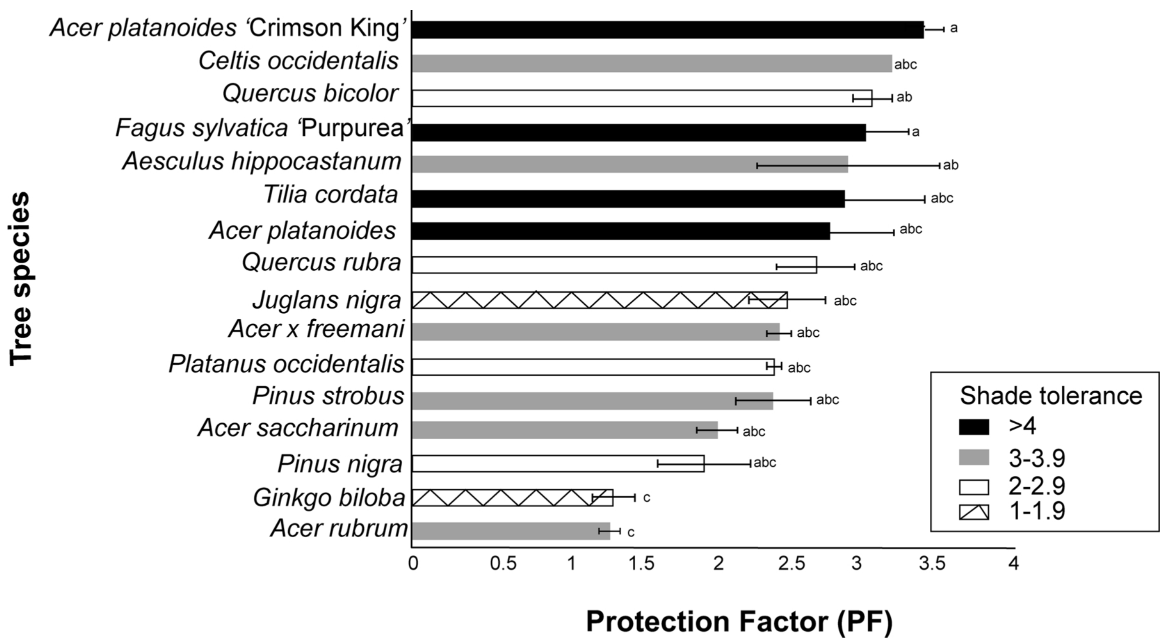

Fig. 2. Mean UV protection factor (PF) shown for urban tree species (n = 64) sampled across urban schoolyards and public parks within Toronto, Ontario, Canada during two periods of June to August in the years 2015 and 2016. Letters refer to Tukey post-hoc tests used to test for species-specific differences using comparisons of means with 95 % confidence level.

in behavioral studies to measure personal UV exposure (Allen and McKenzie, 2010; Cargill et al., 2013; Køster et al., 2015, 2016; Peters et al., 2016; Cox et al., 2018). Most of the previous studies accounting for UV beneath tree canopies have used polysulphone badges (Gies et al., 2007), spot measurements with ambient UV meters (Parisi et al., 2000) or have applied solar UV radiation models (Downs et al., 2019). Logging dosimeters represent a substantial improvement from integrated analog badges or instantaneous meter readings. Polysulphone badges have a logarithmic response to UV exposure (rather than linear), show rapid saturation, are affected by ambient temperature, and fit less closely to the UV erythemal spectrum (Allen and Mckenzie, 2005).

Dosimeter data indicate large differences in UV protection factors among tree species in a North American urban setting that can be explained, in part, by differences in species canopy morphology. These data are directly applicable to planning for outdoor spaces to enable choice of tree species that provide increased UV protection. Data from our study can also potentially be used in nursery settings, where breeders and arborists can select for phenotypes that enhance UV protection (*e.g.,* low branching height and dense canopies). In urban spaces, choosing and planting specific tree species is often one of the few factors that can be controlled in a pre-existing built environment to improve urban spaces. Given that tree morphology is a strong predictor of UV attenuation and there is considerable variation among species (*e.g.,* about 179 species among city-owned trees in Toronto (KBM Resources Group et al., 2019)), the research herein can be used to select for these traits in the local tree species pool.

Although UV attenuation is an important consideration, urban tree planning should be based on an assessment of multiple objectives. For example, our results indicate that the non-native *Acer platanoides* 'Crimson King' is particularly effective at shielding pedestrians from high UV (Fig. 2); however, *Acer platanoides* L. is a non-native, invasive species in the region, and thus a potential cause of economic, social, and ecological damage (Molina-Montenego et al., 2012; Simberloff, 2014; Essl et al., 2011). Even in a street tree setting, native species can have considerable advantages, such as supporting higher bird species richness compared to non-native trees (Shackleton, 2016). This suggests that the focus should be on native species with high PF values *(e.g., Celtis occidentalis* L.*, Quercus bicolor* Willd.*)* or selected non-native but non-invasive species (*e.g., Aesculus hippocastanum* L.*, Tilia cordata* Mill., *Fagus sylvatica* 'Purpurea'). Finally, we note that the present study was limited to measurements of isolated trees of select common species in the summer during peak UV exposure conditions. Future research could

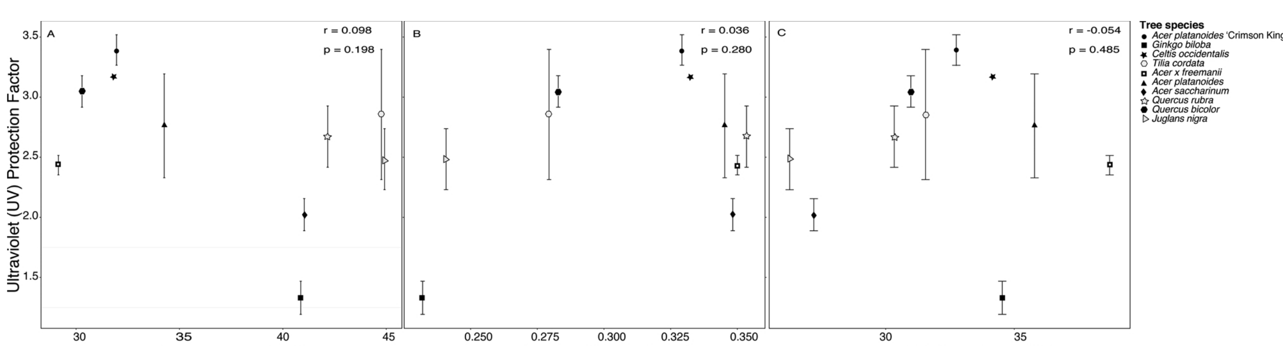

Fig. 3. Scatterplots of mean protection factor (PF) as a function of A) Mean leaf angle (°), B) mean leaf tissue density (g/cm^3) C) UV-A reflectance (abaxial leaf surface) for a subset of species (n = 11) sampled across urban schoolyards and public parks within Toronto, Ontario, Canada during June to August in the years 2015 and 2016. The following species are used in this analysis: *Acer platanoides* 'Crimson King'*, Acer platanoides* L.*, Ginkgo biloba* L.*, Celtis occidentalis* L.*, Tilia cordata* L.*, Acer x freeman* E. Murray.*, Acer saccharinum* L.*, Quercus rubra* L.*, Quercus bicolor* Willd.*, and Juglans nigra* L.

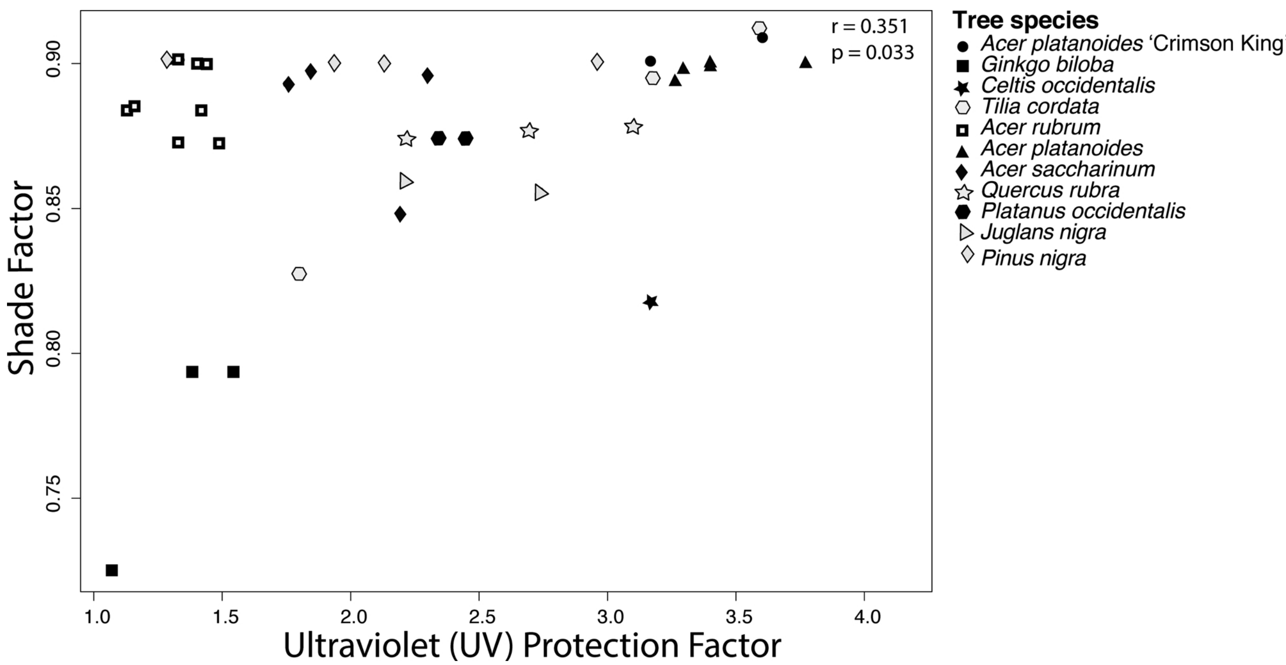

Fig. 4. Scatterplot of mean protection factor (PF) as a function of shade factor for individual urban trees (n = 37) sampled across urban schoolyards and public parks within Toronto, Ontario, Canada during June to August in the years 2015 and 2016. The following species are used in this analysis: *Acer platanoides* 'Crimson King', *Acer platanoides* L., *Ginkgo biloba* L., *Celtis occidentalis* L., *Tilia cordata* L., *Acer saccharinum* L., *Pinus nigra* Arnold., *Platanus occidentalis* L., *Acer rubrum* L., *Quercus rubra* L., and *Juglans nigra* L.

include more extended species surveys under multiple seasons, assessment of effects under clusters of single and multiple tree species, ontogenetic effects, positioning of trees relative to built structures, and testing and refinement of modeling frameworks.

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CRediT authorship contribution statement

Sivajanani Sivarajah: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Sean C. Thomas:** Funding acquisition, Supervision, Methodology, Resources, Formal analysis, Writing - review & editing. **Sandy M. Smith:** Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2020.126679.

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