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RESEARCH ARTICLE

The mitigating effect of street trees, urban flora, and the suburban environment on seasonal peak UV indices: A case study from Brisbane, Australia

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Abstract

Tree shade, particularly shade that obscures direct sunlight near peak periods of midday solar exposure can have a pronounced effect on potentially harmful ultraviolet radiation, and in turn, strongly influence the maximum daily UV index (UVI). In this study, the seasonal influence of tree shade on the UVI is evaluated from 210 hemispherical sky view images collected alongside public walkways and footpaths from 10 residential Brisbane suburbs. The effective sidewalk UV index is calculated underneath planted tree canopies, adjacent residential gardens, buildings and background tree species. Results are presented with respect to seasonal variations in the diurnal solar elevation for each month of the year at Brisbane's latitude. The research also examines the total reduction in UVI due to the presence of individual tree species, showing reductions in the midday UVI of up to 91% of an equivalent unimpeded sky hemisphere when overhead tree canopies are present. Important footpath tree species for peak midday UVI mitigation include *Pongamia pinnata*, *Xanthostemon chrysanthus*, *Senna siamea*, and *Libidibia ferrea*. The planting and maintenance of existing tree species already growing alongside residential Brisbane streets will improve the shade characteristics of suburbs and enhance UV protection for local residents.

KEYWORDS

Brisbane, erythema, shade, tree, UVI

INTRODUCTION

Brisbane (27.5°S, 152.5°E) is a large, relatively low-density state capital of approximately 1.2 million residents situated in the south-eastern corner of subtropical Queensland, Australia. The city occupies an area of approximately 1163 km[21] adjacent to the Pacific Ocean and has grown progressively westward along the Brisbane

Abbreviations: ARPANSA, Australian Radiation and Nuclear Safety Authority; CBD, Commercial Business District; PF, Protection Factor; SPI, Shade Protection Index; UV, Ultraviolet; UVI, Ultraviolet Index.

River, extending as far as the city of Ipswich (27.7°S, 152.8°E). Coastal suburbs are of low elevation and are situated to the north and east of the commercial business district (CBD), which is located on the northern bank of the Brisbane River approximately 10 km inland of the Moreton Bay estuary. Surrounding the CBD are fringing suburbs of mixed, medium density housing. These include single residential dwellings and light commercial districts. Toward the south and west of the CBD, the suburban elevation increases and includes the fringe suburbs of Coorparoo, Mt Gravatt, and Tarragindi that extend south and west toward eucalypt green spaces. Outer Brisbane districts adjacent to these southern fringe suburbs include the well vegetated low-density residential development of Forest Lake and further west, the outer suburban Master Planned Community of Springfield (27.7°S, 152.9°E).

Previous assessment of the vegetative cover of Brisbane and its surrounding suburbs employing remote satellite sensing and aerial surveys has highlighted the environmental and social impacts of continued urbanization.[2–4] Urban consolidation, introduced in the 1980s by state and local government to encourage the development of higher density vertical residential zoning within centralized Brisbane suburbs, has been instigated to mitigate the effect of urban sprawl.[5] Brisbane is Australia's fastest growing city.[6] Urban consolidation and the displacement of city residents, alongside the nation's housing affordability crisis, are playing a direct role in altering equitable access to space and shade.[6,7] Development policy that encourages urban density naturally reduces the size of residential property allotments, space for private gardens, and open green space within an urban community. Subsequently, street side footpaths and public walkways become increasingly important public green spaces for residents.[7,8]

Potentially, increased development density may benefit city liveability and walkability by improving access to amenities, services, and centralized infrastructure, including transport.[5,9] Walkability assessments[10] can enable the investigation of integrated physical factors that affect personal attitudes to health, safety, and the overall quality of neighborhoods. Walkability assessments of public footpaths may examine their overall physical condition, their potential for heat mitigation, and influence on personal comfort through the provision of shade provided by awnings, tree canopies, and surrounding buildings.[11–13] However, there has been limited research that has investigated the potential of solar ultraviolet (UV) radiation on walkability indices designed for an urban landscape.[14–16] The presence of UV on suburban walkways and the urban environment is of concern and has previously been examined with respect to tree canopy cover and urban surroundings.[14,17–19]

In Australia, noticeable erythema (sunburn) can be achieved by exposure of unprotected skin in 12 min,[20] with this time varying depending on skin type. Sunburn and exposure to UV radiation are established causative factors for the development of melanoma skin cancer.[21] Nationally, in 2021, 55 per 100,000 Australians were diagnosed with a melanoma skin cancer.[22] Sun protection is especially important in Queensland given the state reports the highest melanoma skin cancer rate in Australia at above 3600 cases per year.[23] Skin cancer prevention groups recommend the application of sun protection strategies when the UV index reaches or exceeds 3.[24–26]

The UV index (UVI) was first established in 1992[27] and later adopted as an international standard for reporting UV radiation that has the potential to cause damage to human skin.[28] It is a unitless index, often divided into five broad hazard categories. UV index categories range from low (<2), moderate (3–5), high (6, 7), very high (8–10), and extreme (11+). The maximum daily UV index and hazard rating is often reported alongside routine weather forecasts, providing an easy-to-understand metric to enable public assessment of the day-to-day solar UV hazard. Strategies implemented to mitigate exposure to solar UV radiation include the use of sun-protective clothing, hats, sunglasses, sunscreen, and behavior modification to seek shade where possible.[23] The UV index is affected by the presence of cloud cover, total stratospheric ozone column thickness, and atmospheric aerosol concentration including smoke particulates, dust and local airborne pollutants. Forecasts of the UV index often do not take variations in cloud cover or aerosol concentration into account. However, the day-to-day UV index is monitored by a number of meteorological agencies worldwide. This includes the Australian Radiation and Nuclear Safety Authority (ARPANSA) who provide live daily charts of the UV index for each Australian state capital city, including Brisbane.[29]

Previous research[30] established the use of the Shade Protection Index (SPI) to quantify the protective impact of tree canopies using whole sky images collected from ground sites. The index has been applied to measure the protection of individual tree species located within the Local Government Areas of Queensland.[31] For metropolitan Brisbane, tree species identified in research conducted by statewide surveys are not always suitable for the urban environment where species are often limited to smaller sizes to reduce potential root damage to roads and underground water networks, mitigate the risk of falling tree limbs, and to reduce general maintenance of tree canopies in and around above-ground electrical infrastructure. In light of restrictions that limit the available tree species suitable to the urban environment, and in an effort to improve city green space, the Brisbane local government Neighborhood Shadeways tree planting program aims to provide 50% tree canopy cover over all public footpaths by 2031.[3] The SPI is modified and applied here to examine the impact of tree canopies already chosen by the local government and planted within urban and residential footpath zones on the daily UV index.

MATERIALS AND METHODS

Study site

The impact of tree canopy cover on the seasonal UV index is examined using hemispherical sky view data collected from Brisbane footpath sites during the winter months of June, July, and August 2022. Footpath site surveys were conducted for 21 Brisbane streets from across 10 residential suburbs (Figure 1). Hemispherical sky view images were taken for all 21 surveyed streets under cloud-free conditions. Sky view images were taken in the middle of each street footpath using a fish-eye EF 8–15 mm lens (Canon, Japan) orientated horizontally at a surface height of 1.5 m. Hemispherical site images represent a 180° sky view and have a resolution of 4480 × 6720 with each imaged hemisphere containing a total of 14,725,169 pixels.

Within each street a total of 10 hemispherical sky view images, classified as site A though to site J were collected. Sky view images were taken at approximately 10-m intervals along colinear footpath sections adjacent to an identified roadway (Table 1). For this research, a total of 210 upward facing cloud-free hemispherical site images were collected. Site survey data were ingested into the South-East Queensland AtmoSEQ online science images database,[32] curated through mdvine data management software. This database is publicly accessible using an ORCiD[33] identification and includes searchable hemispherical image metadata, site temperature, identified site tree species (including both common and scientific tree names), date, location, and survey time.

The predominant tree species, either planted or remnant, growing within a footpath along each 100-m street-side survey were identified and recorded. Tree species not planted on the footpath were classified as background species. This included tree species belonging to private gardens, parks, or nearby green spaces. Table 1 summarizes the predominate footpath tree species, survey sites, and identifying details of the Brisbane streets visited during the winter data collection period of 2022.

Calculation of the UV index

The UV index received at a given site depends on the solar spectral UV irradiance incident upon a horizontal plane, $E(\lambda,\theta)$ after weighting to the human biological action spectrum $S(\lambda)$ for erythema.[34]

$$\mathrm{UVI} = \frac{1000}{25}\int_{290}^{400} S(\lambda)E(\lambda,\theta)d\lambda \quad (1)$$

By definition, the biologically effective solar spectral UV irradiance incident at the earth's surface from 290 to 400 nm once integrated over the spectral range of the incident radiation, yields the weighted erythema irradiance in [$\mathrm{W\,m^{-2}}$]. The incident solar erythema irradiance varies according to solar elevation, θ, and in determining the UV index (Equation 1) is further weighted by a factor of $40\,\mathrm{m^2 W^{-1}}$. Thus, $25\,\mathrm{mW\,m^{-2}}$ is the equivalent of a UV index of one (Figure 2A). Over the course of a day, the horizontal plane

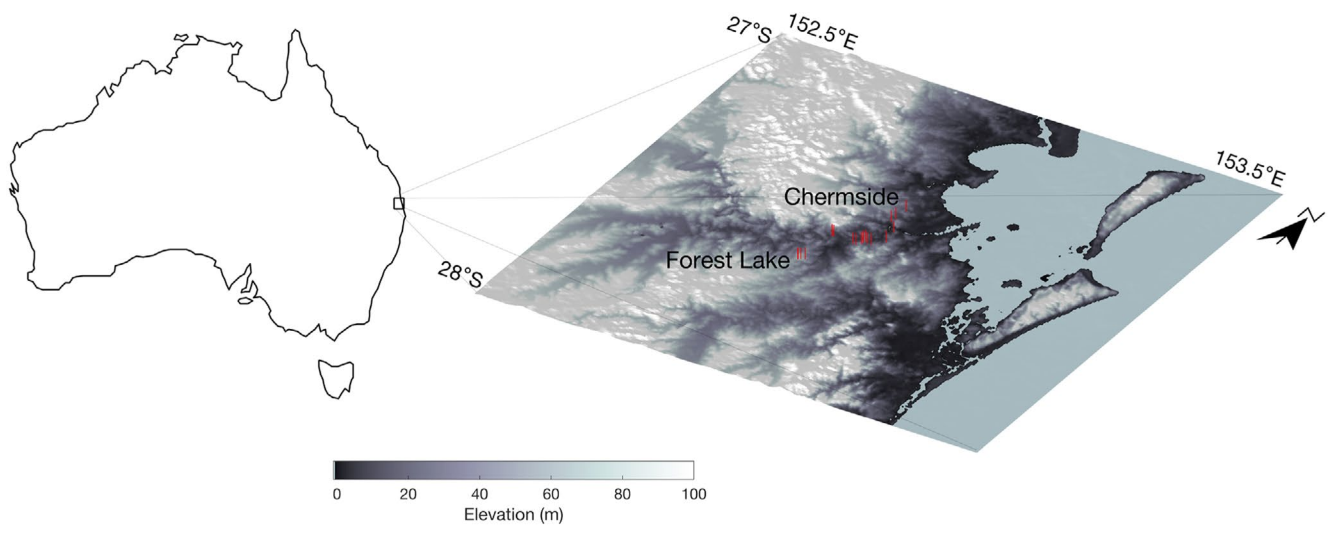

FIGURE 1 The study region of greater Brisbane, Australia situated between 27 and 28°S; and 152.5 and 153.5°E. Insert shows street survey locations (red stems) extending from the southern Brisbane residential suburb of Forest Lake, through to the northern suburb of Chermside. Table 1 lists the latitude and longitude for each street survey site shown in the figure.

solar UV index increases until reaching a maximum at solar noon and decreases again until sunset (Figure 2B).

As the UV index is a measure of the erythema irradiance with time of day, it is also affected by surface structures and shading by local tree canopies. The mitigating effect of tree canopies and surface objects on the UV index is derived by taking into account the time of day the direct solar beam is obstructed by a shading surface, and the total sky view visible at a given surface site.[30] Under the influence of a tree canopy, shading of the solar disc influences the direct component of the erythema irradiance, E_{dir}. The proportion of diffuse, blue skylight distributed across an isotropic hemisphere E_{diff} that is obstructed by surrounding surface objects contributes to the remaining total erythema irradiance at a given surface location. The effect of surface object shading on the available site UV index is calculated as the sum of both the direct and diffuse erythema irradiance according to Equation 2,

$$\text{UVI} = \frac{1000}{25}\int_{290}^{400} S(\lambda)\left(P_0 \bullet E_{\text{dir}}(\lambda,\theta) + F_{\text{s}} \bullet E_{\text{diff}}(\lambda,\theta)\right)d\lambda \quad (2)$$

where P_0 represents the condition of the solar disc at a given time of day, being 1 if unshaded and 0 if obstructed by a tree canopy. The factor, F_s represents the sky view or proportion of the visible blue sky unobstructed by tree canopies or surface objects at a given site. Using a hemispherical image, F_s is calculated in this research as the proportion of pixels classified as unobstructed sky pixels from the total number of pixels available in each hemispherical sky image.

In Figure 3A, the path of the sun is plotted for the expected diurnal solar elevation on 21 December 2023 over a processed hemispherical full sky image taken at a street footpath site located in Bishop street, Forest Lake (27.617°S, 152.962°E). Dips in the daily UV index are due to the presence of tree canopies obstructing the solar disc, including a large central *Eucalyptus tereticornis* canopy from approximately 9:00 am to midday (Figure 3B). The Bishop street site, which has an unobstructed sky view of 54% further reduces the available diffuse solar radiation. The resulting UV index on a footpath site, as shown in Figure 3B is, therefore, always lower than the expected unobstructed UV index modeled under a cloud-free atmosphere or the nationally reported UV index recorded at an open and unobstructed measurement site.[29]

Site image processing

The influence of tree canopies on the UV index for each hemispherical site image was determined according to Equation 2 for each month in the calendar year 2023. To do this, site images collected during the cloud-free winter months of 2022 were image processed into visible sky or surface object pixels by thresholding the Red, Green, and Blue (RBG) value of each pixel after the image of the solar disc itself was removed. To be classified as an unobstructed sky pixel, the ratio of B/R needed to exceed 1. This threshold ratio represents all image pixels with a higher blue saturation than red. An example of the image processing using this threshold classification is given in Figure 4A,B showing the same site imaged in Bishop Street, Forest Lake before and after processing.

In Figure 4B, the expected path of the solar disc is plotted for the summer and winter solstice and the southern hemisphere spring equinox showing the expected annual range in solar position relative to the Bishop street site and the expected change in UV index (Figure 4C). The solar disc position, which varies seasonally, was calculated for each site image in the current survey at Brisbane's latitude and longitude according to the Astronomical almanac's algorithm for solar position.[35] The resulting UV index, with the time of day derived according to Equation 2, was calculated using the Rundel[36] modification of the original direct and diffuse semi-empirical UV irradiance calculations of Green et al.,[37] Green et al.[38] and Schippnick and Green,[39] including seasonal correction for the earth–sun distance due to the earth's elliptical orbit.[40]

RESULTS

Tree species distribution

The study distribution of identified footpath tree species is included as Table S1. A total of 263 trees were identified as belonging to a footpath from the 210 hemispherical site images surveyed in this study with 31 site images containing no identifiable footpath tree species. Of the 263 footpath trees, a total of 48 individual species were classified. This included trees planted by local government, privately planted footpath trees, and established remnant species left standing within newly developed suburban areas. Predominate species of the 263 trees identified across all 10 Brisbane residential suburbs included Leopard trees, *Libidibia ferrea* (10.3%); Tuckeroo, *Cupaniopsis anacardioides* (9.1%); Indian beech, *Pongamia pinnata* (8.7%); Yellow cassia, *Senna siamea* (5.7%); and Golden penda, *Xanthostemon chrysanthus* (5.3%).

A total of 65 trees were identified as trees not belonging to a footpath zone (background species). Fewer tree species were identified in this zone due to difficulty in identifying species located at a distance from footpath study sites. Additionally, trees located within private gardens and nearby parks and green spaces were

TABLE 1 Brisbane street footpath survey observation summary.

Street	Suburb	Transect start	Survey time	Predominate species
Murray Pl	Forest Lake	27.617°S, 152.959°E	09 Jun 09:44 am	*C. anacardioides*
Bishop St	Forest Lake	27.617°S, 152.962°E	09 Jun 10:55 am	*C. anacardioides*
Banksia Cir	Forest Lake	27.613°S, 152.964°E	09 Jun 01:04 pm	*B. integrifolia*
Woodland Ave	Forest Lake	27.610°S, 152.971°E	09 Jun 01:55 pm	*T. rosea*, *M. bracteatum*
Wright St	Balmoral	27.458°S, 153.064°E	15 Jun 11:02 am	*S. siamea*
Fee St	Chermside	27.386°S, 153.044°E	23 Aug 08:32 am	*W. floribunda*
Mawarra St	Albion	27.429°S, 153.040°E	30 Jul 09:41 am	*P. pinnata*
McIntyre St	Wooloowin	27.418°S, 153.043°E	30 Jul 10:35 am	*J. mimosifolia*, *H. pendula*
Stephens St	Annerley	27.511°S, 153.035°E	15 Aug 10:00 am	*L. ferrea*
Bower St	Annerley	27.513°S, 153.035°E	15 Aug 10:15 am	*P. pinnata*, *A. oblongfolia*
MacKenzie St	Annerley	27.514°S, 153.033°E	15 Aug 10:22 am	*C. viminalis*
King St	Annerley	27.506°S, 153.036°E	15 Aug 10:30 am	*P. pinnata*, *L. ferrea*
Gibson St	Annerley	27.516°S, 153.034°E	15 Aug 10:53 am	*P. pinnata*, *B. celsissima*
Brian Ave	Coorparoo	27.512°S, 153.052°E	15 Aug 11:40 am	NIL
Pampling St	Coorparoo	27.510°S, 153.043°E	15 Aug 12:15 pm	*S. siamea*, *X. chrysanthus*
Garden St	Coorparoo	27.510°S, 153.043°E	15 Aug 11:15 am	*L. ferrea*
Bell Tce	Graceville	27.521°S, 152.972°E	25 Aug 10:26 am	*L. ferrea*
Laurel Ave	Graceville	27.519°S, 152.970°E	25 Aug 10:50 am	*C. camphora*
Honor Ave	Graceville	27.520°S, 152.975°E	25 Aug 11:18 am	*M. quinquinervia*
Nathan Tce	Yeronga	27.525°S, 153.020°E	13 Jul 11:03 am	*C. anarcardioides*
Zonnebeke St	Moorooka	27.524°S, 153.027°E	13 Jul 09:46 am	*X. chrysanthus*

Note: Details of site characteristics and identified tree species in each site image are included in the AtmoSEQ online database.[26]

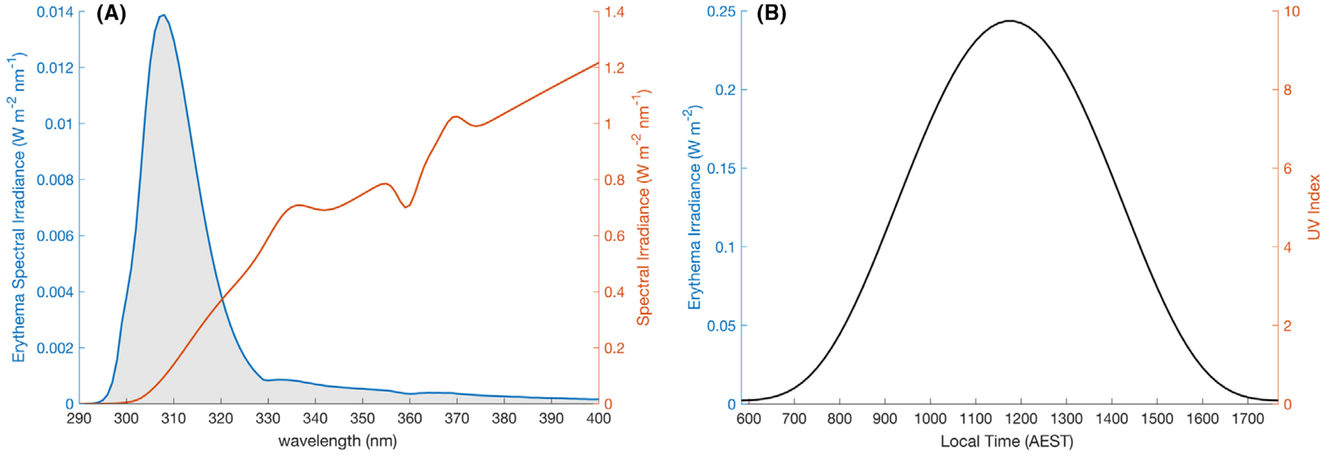

FIGURE 2 (A) The unweighted $E(\lambda,\theta)$ and erythema weighted $S(\lambda)E(\lambda,\theta)$ spectral UV irradiance modeled for Brisbane on 23 September 11:50 am[39]; (B) The corresponding UV irradiance $\int_{290}^{400} S(\lambda)E(\lambda,\theta)$ weighted to the erythema action spectrum and the associated UV index modeled for each minute of 23 September, Brisbane, Australia.

often mixed among existing vegetation and surrounding buildings making individual tree identification difficult. Subsequently, a total of 160 of the 210 hemispherical site images did not include a background tree species classification. The highest counts of background tree species that could be identified included Spotted gum trees, *Corymbia maculata* (12.3%); Tuckeroo, *Cupaniopsis anacardioides* (7.7%); Palms, *Archontophoenix* sp. (7.7%); and Frangipani, *Plumeria* sp. (6.2%). In addition, Pines, *Pinus* sp.; Poinciana, *Delonix regia*; Tulipwoods, *Harpullia pendula*; and Cocos palms, *Syagrus romanzoffiana*, collectively accounted for 4.6% of the identified

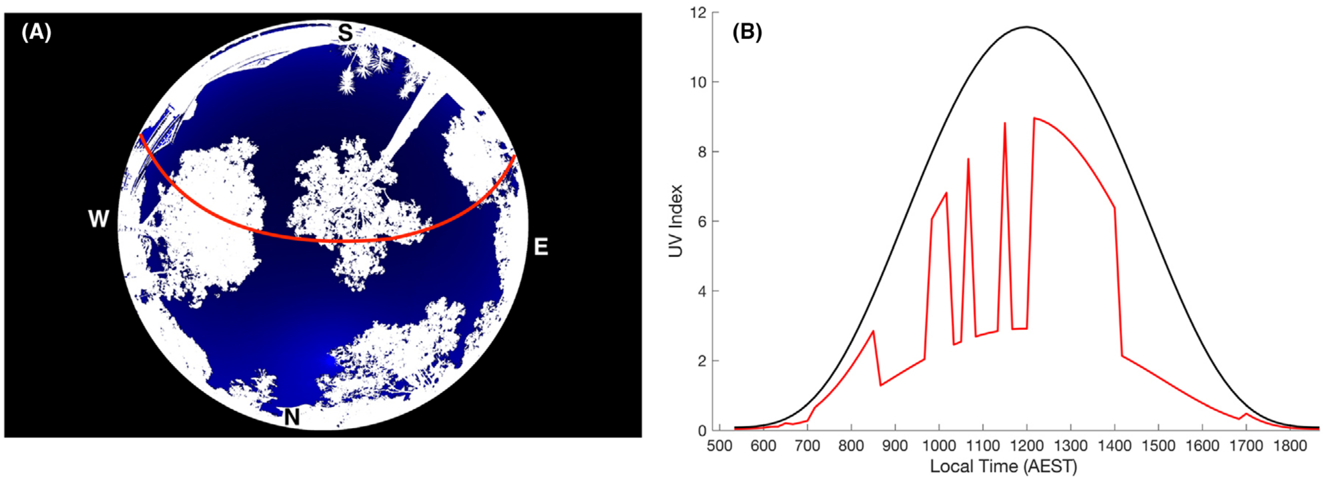

FIGURE 3 (A) Image processed site image from Bishop Street Forest Lake, 27.617°E, 152.962°S showing the diurnal solar path for 21 December 2023; (B) Unobstructed UV index (black) and the expected change in UV index with time of day (red) due to direct obstruction by overhead tree canopies and reduction in diffuse UV irradiance for a site of 54% sky view.

background tree species. These species represent the typical makeup of private gardens and parklands occupying Brisbane residential areas.

Seasonal influences

Table 2 lists the calculated median, maximum, and minimum monthly noon time UV index for each site located within each of the 21 residential streets included in the Brisbane survey. At Brisbane's latitude, the celestial equator is tilted at 27.5° from the zenith. Therefore, at either the spring or autumnal equinox, the sun will traverse a daily path along the celestial equator, rising due east (90°E azimuth). In winter, the sun will traverse a shorter path, rising in the north-east and in summer the sun will traverse a greater path rising in the south-east. These variations in solar path influence the position of the solar disc at noon, the seasonal solar elevation, and the likelihood that the sun will be blocked by an overhead tree canopy. In general, the seasonal influence of the solar path at noon can be observed across the tabled median UV index, which for each street peaks in January, falls to a minimum in June, and peaks again in December (Table 2). For streets with consistent sky view characteristics, the range in minimum and maximum noon UV index is minimal. Examples include MacKenzie Street, Annerley (27.514°S, 153.033°E) and Brian Avenue, Coorparoo (27.512°S, 153.052°S). Both of these streets had no overhead tree canopy cover and had consistent sky view characteristics, with the average being $74.2 \pm 8.4\%$ ($\pm 1\sigma$) and $51.6 \pm 8.4\%$ ($\pm 1\sigma$) for MacKenzie Street and Brian Avenue, respectively.

Table 2 also lists the annual average noon UV index for each street, calculated as the arithmetic mean of all 12 months in the calendar year. Streets belonging to suburbs with established trees were most likely to have canopies that blocked direct sunlight at noon. This, combined with generally lower sky views resulted in average annual noon UV indices of less than 3 in four of the 21 suburban streets included in the current survey. These streets included Woodland Avenue, Forest Lake; Zonnebeke Street, Moorooka; Wright Street, Balmoral; and Bell Terrace, Graceville. The annual average noon UV index for Woodland Avenue, Zonnebeke Street, Wright Street, and Bell Terrace was 2.6, 1.8, 1.6, and 1.5 respectively. Neighborhood sky view characteristics for each of these residential streets show that these locations were well protected by overhead tree canopies and surrounding flora with respective sky view averages of $26.1 \pm 13.1\%$ ($\pm 1\sigma$), $31.6 \pm 8.3\%$ ($\pm 1\sigma$), $41.2 \pm 12.9\%$ ($\pm 1\sigma$), and $35.0 \pm 10.3\%$ ($\pm 1\sigma$) at Woodland Avenue, Zonnebeke Street, Wright Street, and Bell Terrace.

The three streets with the lowest annual average noon UV index (Wright Street, Zonnebeke Street, and Bell Terrace) all maintained consistent and established footpath tree species plantings. In Wright Street, nine of the 10 footpath transect sites included established *Senna siamea* tree species. In Zonnebeke Street, seven of the 10 street side survey sites had *Xanthostemon chrysanthus* species and in Bell Terrace, nine of 10 survey sites included *Libidibia ferrea* species. Although the seasonal variation in the noon time UV index is dependent on local canopy position, shape, and the unique surroundings of each individual surveyed site, regular footpath tree plantings of consistent species of similar age and the surrounding neighborhood characteristics such as the presence of established gardens tend to influence the local sky view and, therefore, the neighborhood UV index pattern.

Figure 5 illustrates the seasonal variation in UV index at Brisbane's latitude and the mitigating effect of local footpath tree plantings and neighborhood sky view

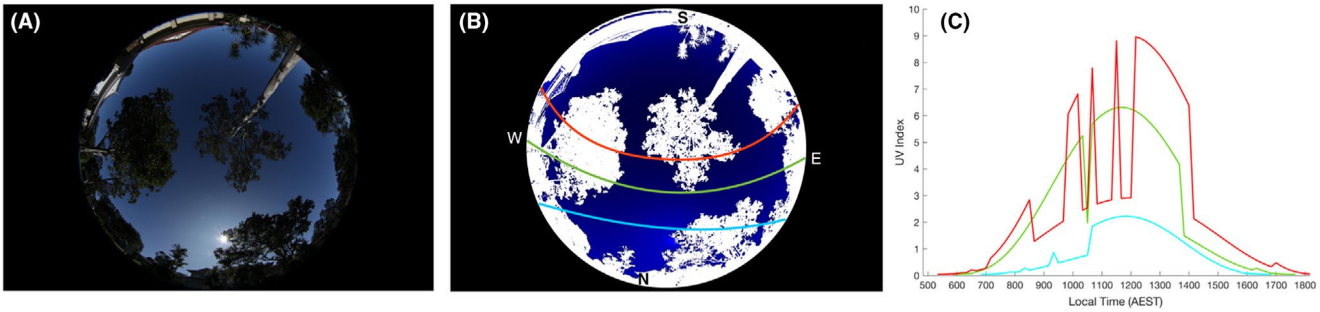

FIGURE 4 (A) Bishop Street Forest Lake, site H, 27.617°E 152.961°S; (B) Processed image showing solar paths on 21 June (blue), 21 December (red), and 23 September (green); (C) UV index at Bishop Street site H on 21 June (blue), 21 December (red) and 23 September (green).

characteristics on the UV index. The seasonal maximum UV index at Brisbane's latitude is plotted for each month in the calendar year,[36] where black dots show the maximum UV index measured on the 17 cloud-free days for Brisbane in 2022.[29] In the figure, the median and range in noon UV index is plotted for Bell Terrace, Graceville, and MacKenzie Street, Annerley. These two residential streets represent the greatest and least annual average reduction in the UV index at noon from the unobstructed open sky model.[36]

Both Mackenzie Street and Bell Terrace contained the highest and lowest respective monthly UV indices of all 210 study sites. The lowest study noon UV-index of 0.5 was calculated for 15 May at Bell Terrace site C (Figure 6A). This site has an open sky view of 20.2% and is protected by an overhead *Libidibia ferrea* canopy. *Delonix regia* tree species are present in nearby gardens at this site and would have also contributed to a reduction in the site sky view. The highest study UV index was calculated at MacKenzie Street site E (Figure 7A). The summer noon UV index calculated for 15 December at this site reached 10.7. This represents a 9.3% reduction in the expected cloud-free UV index of 11.8 (Figure 5) at that time of year. For MacKenzie Street site E, the high sky view and the absence of overhead tree canopies makes a clear contribution to the high noon UV index. Although the footpath at MacKenzie Street is planted with *Buckinghamia celsissima* saplings, their immaturity and limited height have no current effect on the UV index. As seen in Figure 7B, the sky view in MacKenzie street is predominantly protected by the presence of existing residential houses which can only shade public footpath sites in the late afternoon or early morning.

The noon UV index was shown to clearly correlate with the study sky view for all months of the year. Figure 8 shows the linear dependence of noon UV index with sky view calculated for the 15th day in each of the 12 months of 2023. Evident in the figure are two distinct monthly series. The lower monthly series shows the trend in noon UV index with sky view at sites where the solar disc at noon was blocked by an overhead tree canopy. Note, this lower series ranges from measured image sky views of 10 to 65%, indicating that where the solar disc was obscured at noon the total available sky view was also low. A likely explanation for this is that sites with overhead tree cover were also likely to cover a larger proportion of the total available sky hemisphere. At study sites where limited tree canopy cover was available, a higher proportion of the sky was visible. This is clearly indicated in Figure 8 where the site sky view upper series extends up to 90%. When not blocked by an overhead tree canopy, the UV index is higher and the rate of noon UV index increase with increasing sky view is also greater.

Influence of sky view

The study distribution of site sky view is shown in Figure 9. Sky view is normally distributed for the 21 residential Brisbane streets, indicating that footpath tree canopy cover greater than 50% occurs in approximately half of the Brisbane residential streets studied in the current survey. On average, the study sky view was $47.5 \pm 16.6\%$ ($\pm 1\sigma$) indicating that most Brisbane residential footpath sites cover slightly more than half of the available sky view.

The frequency of footpath tree species that contributed to site sky view less than 50%, that is, those sites that protected more than half of the available sky hemisphere are listed in Table 3. In the table, only sites identified as having a single tree species and no identified background species were included ($n = 47$ sites). A total of 21 tree species were identified as exclusive tree species footpath plantings. Of these, 15 species where identified from site images where the sky view was less than 50%. Predominate exclusively planted tree species that were on footpath sites with less than 50% sky view include *Pongamia pinnata* (11 sites); *Libidibia ferrea* (10 sites); and *Senna siamea* (7 sites). *Pongamia pinnata*, *Libidibia ferrea*, and *Senna siamea* were identified as established mature trees in Mawarra Street, Albion; Bell Terrace, Graceville; and Wright Street, Balmoral, respectively. Both Wright Street and Bell Terrace were identified as streets with the lowest average annual study noon UV index (Table 2).

TABLE 2 Median, minimum and maximum noon UV index of all 10 footpath sites for each residential Brisbane street calculated on the 15th of each month in the year 2023 ($\bar{x}$ is the annual average).

	J	F	M	A	M	J	J	A	S	O	N	D	$\bar{x}$
Murray St													
Median	8.6	2.8	4.3	1.8	2.7	0.9	1.1	1.5	5.2	2.7	8.1	9.0	4.0
Min	2.1	2.0	1.7	1.2	0.8	0.7	0.7	1.0	1.5	1.9	2.0	2.1	1.5
Max	9.6	8.9	7.3	5.0	3.2	2.4	2.7	4.0	6.2	8.2	9.4	9.7	6.4
Bishop St													
Median	8.5	8.2	6.7	4.6	3.0	2.2	2.5	3.8	5.7	7.6	8.4	5.8	5.6
Min	2.1	2.0	2.0	1.4	2.6	2.0	2.2	3.3	1.7	2.2	2.0	2.1	2.1
Max	10.2	9.4	7.7	5.3	3.4	2.6	2.9	4.3	6.6	8.7	10.0	10.3	6.8
Banksia St													
Median	8.1	5.1	6.4	4.3	2.7	2.1	2.3	3.5	5.4	7.2	5.3	8.2	5.0
Min	1.1	1.0	0.9	0.6	0.4	0.3	0.4	0.5	0.8	1.0	1.1	1.1	0.8
Max	9.1	8.4	6.9	4.7	3.0	2.3	2.5	3.8	5.8	7.7	8.9	9.2	6.0
Woodland Av													
Median	7.4	1.5	1.2	1.2	0.7	0.7	0.7	0.9	1.0	3.8	7.4	4.6	2.6
Min	0.5	0.5	0.4	0.3	0.2	0.2	0.2	0.3	0.4	0.5	0.5	0.5	0.4
Max	8.7	8.0	6.5	4.4	2.8	2.1	2.4	3.6	5.5	7.4	8.5	8.8	5.7
Wright St													
Median	2.1	1.9	1.7	1.3	0.9	2.0	0.7	1.1	1.4	1.9	2.0	2.2	1.6
Min	1.8	1.7	1.4	1.0	0.8	0.6	0.6	1.0	1.2	1.6	1.7	1.8	1.3
Max	10.4	9.6	7.9	5.4	3.5	2.7	3.0	4.4	6.7	8.8	10.1	10.5	6.9
Fee St													
Median	9.8	9.0	7.4	5.1	3.3	2.5	2.8	4.1	6.3	8.3	9.5	9.8	6.5
Min	1.5	1.4	1.9	0.9	0.6	0.5	0.5	0.8	1.1	1.3	1.5	1.5	1.1
Max	11.0	10.1	8.3	5.8	3.8	2.9	3.2	4.7	7.1	9.4	10.7	11.0	7.3
Mawarra St													
Median	8.8	8.1	6.5	1.9	2.0	0.9	1.0	2.6	5.6	7.3	8.6	8.9	5.2
Min	0.7	0.6	0.5	0.4	0.3	0.2	0.2	0.3	0.5	0.6	0.6	0.7	0.5
Max	10.1	9.3	7.6	5.3	3.4	2.6	2.9	4.3	6.5	8.6	9.8	10.2	6.7
McIntyre St													
Median	9.9	9.1	7.4	5.1	3.3	2.5	2.8	4.2	6.3	8.4	9.6	9.9	6.5
Min	2.3	2.2	2.4	1.8	2.7	0.9	2.3	1.5	1.6	2.0	2.3	2.3	2.0
Max	10.2	9.4	7.7	5.3	3.5	2.6	2.9	4.3	6.6	8.7	9.9	10.3	6.8
Stephens St													
Median	8.9	8.1	6.6	4.5	2.9	2.2	2.4	3.6	5.6	7.5	8.6	8.9	5.8
Min	1.8	1.7	1.5	1.1	0.8	0.6	0.6	0.9	1.3	1.6	1.8	1.9	1.3
Max	10.1	9.3	7.6	5.2	3.4	2.6	2.9	4.3	6.5	8.5	9.8	10.1	6.7
Bower St													
Median	9.3	8.6	7.0	4.8	3.1	2.3	2.6	3.9	6.0	7.9	9.1	9.4	6.2
Min	2.5	2.3	2.0	1.4	1.0	0.8	0.9	1.2	1.7	2.2	2.4	2.5	1.7
Max	10.4	9.6	7.9	5.4	3.5	2.7	3.0	4.4	6.7	8.9	10.2	10.5	6.9
MacKenzie St													
Median	10.4	9.6	7.9	5.4	3.5	2.7	3.0	4.4	6.7	8.9	10.2	10.5	6.9
Min	9.3	8.6	2.6	1.9	1.3	1.0	1.1	1.6	2.2	2.8	9.1	9.4	4.2

TABLE 2 (Continued)

	J	F	M	A	M	J	J	A	S	O	N	D	$\bar{x}$
Max	10.6	9.7	8.0	5.5	3.6	2.7	3.0	4.5	6.8	9.0	10.3	10.7	7.0
King St													
Median	8.7	8.0	6.5	4.4	2.9	2.2	2.4	3.6	5.5	7.4	8.4	8.5	5.7
Min	1.0	0.9	0.8	0.6	0.4	0.3	0.4	0.5	0.7	1.5	1.0	1.0	0.8
Max	9.9	9.1	7.4	5.1	3.3	2.5	2.8	4.2	6.4	8.4	9.7	10.0	6.6
Gibson St													
Median	1.9	4.6	3.8	4.0	2.5	1.8	2.0	3.1	3.2	4.2	1.9	4.7	3.1
Min	1.1	1.0	0.9	0.7	0.5	0.4	0.4	0.5	0.8	1.0	1.1	1.3	0.8
Max	9.8	9.0	7.4	5.1	3.3	2.5	2.8	4.1	6.3	8.3	9.5	9.9	6.5
Brian Av													
Median	9.2	8.5	6.6	4.7	3.0	2.3	2.6	3.8	5.6	7.8	8.9	9.3	6.0
Min	8.4	7.7	2.5	4.2	2.7	2.0	2.3	3.4	2.2	7.1	8.2	8.5	4.9
Max	9.5	8.7	7.2	4.9	3.2	2.4	2.7	4.0	6.1	8.1	9.2	9.6	6.3
Pampling St													
Median	8.1	5.0	1.9	4.1	1.9	1.9	2.3	3.2	5.0	4.6	7.9	8.2	4.5
Min	1.6	1.5	1.3	1.0	0.7	0.6	0.6	0.8	1.1	1.4	1.6	1.6	1.2
Max	10.0	9.2	7.5	5.2	3.4	2.6	2.8	4.2	6.4	8.5	9.7	10.1	6.6
Garden St													
Median	5.2	4.6	5.7	2.7	0.9	1.5	2.0	2.2	3.3	4.4	5.3	8.3	3.8
Min	1.4	1.3	1.2	0.8	0.6	0.5	0.5	0.7	1.0	1.2	1.4	1.4	1.0
Max	9.7	8.9	7.3	5.0	3.0	2.3	2.8	4.1	6.2	8.3	9.5	9.8	6.4
Bell Tce													
Median	2.1	1.8	1.6	1.2	0.8	0.8	0.8	1.0	1.5	1.7	1.9	2.3	1.5
Min	1.0	0.8	0.7	0.5	0.3	0.4	0.4	0.4	0.7	0.7	0.8	1.2	0.7
Max	6.8	6.3	5.1	3.4	2.1	1.4	1.7	2.7	4.2	5.8	6.8	6.7	4.4
Laurel Ave													
Median	8.2	5.1	6.2	1.5	1.2	2.0	1.6	1.2	3.5	4.2	2.4	4.9	3.5
Min	1.1	0.6	0.5	0.4	0.3	0.2	0.2	0.3	0.4	0.5	0.6	1.1	0.5
Max	9.7	9.0	7.4	5.0	3.3	2.5	2.8	4.1	6.3	8.3	9.5	9.8	6.5
Honor Ave													
Median	9.4	8.7	7.0	4.8	3.1	2.4	2.6	3.9	6.0	8.0	9.1	9.4	6.2
Min	1.3	1.2	2.7	0.8	0.9	0.7	0.5	0.6	0.9	1.1	1.3	1.3	1.1
Max	9.7	9.0	7.4	5.0	3.3	2.5	2.8	4.1	6.3	8.3	9.4	9.8	6.5
Nathan Tce													
Median	2.7	5.5	6.3	1.8	2.9	2.1	2.4	3.6	5.6	7.2	8.6	2.8	4.3
Min	1.4	1.3	1.1	0.8	0.6	0.9	0.5	1.0	1.0	1.2	1.4	1.4	1.0
Max	9.9	9.1	7.5	5.1	3.3	2.5	2.8	4.2	6.4	8.4	9.6	10.0	6.6
Zonnebeke St													
Median	1.8	1.7	1.4	2.5	1.6	1.2	1.4	3.1	1.3	1.6	1.8	1.8	1.8
Min	0.9	0.9	0.8	0.6	0.4	0.3	0.3	0.6	0.7	0.8	0.9	1.0	0.7
Max	8.6	7.9	6.4	4.3	2.8	2.1	2.3	3.5	5.4	7.2	8.3	8.6	5.6

Figure 10 lists the median and street survey range in the peak solar noon UV index for all exclusively planted footpath tree species. Species listed in the figure are those that were identified as the only identifiable footpath and background species at a study site ($n = 95$ sites). For each species, two box plots are given, showing the range in UV index for an individual species when the solar disc at noon was not blocked (blue), and the range in UV index when the solar disc was

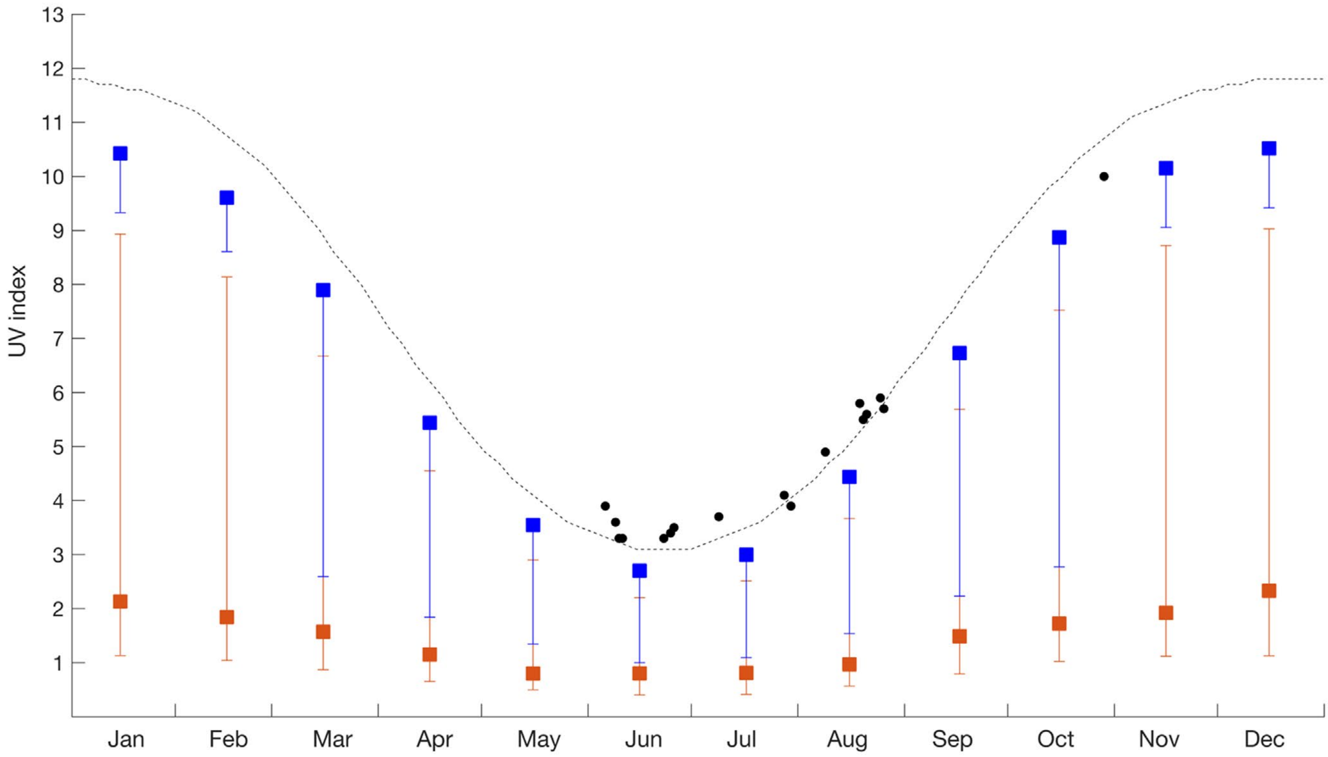

FIGURE 5 Seasonal variation in cloud-free noon UV index[36] at Brisbane's latitude (dashed line). Black dots represent ARPANSA[29] UV indices measured on cloud-free days in 2022. Median noon UV index for all 10 survey sites located in Bell Terrace, Graceville (red squares) and MacKenzie Street, Annerley (blue squares). Error bars show maximum and minimum street noon UV index for Bell Terrace and MacKenzie Street, respectively.

blocked at noon (red). Tree species are listed in the figure in ascending order of the unobscured noon UV index median. *Xanthostemon chrysanthus*, and *Senna siamea* had the lowest unobscured noon UV index study medians which ranged between 4 and 5, respectively. UV indices for all other individual tree species ranged between 5 and 8 when unobscured. However, when obscured at noon, the median UV index for all individual tree species was found to be less than 3. This indicates that public footpaths protected by overhead tree canopies would provide good protection from solar UV radiation in Brisbane residential suburbs.

DISCUSSION

The UV index at solar noon has been derived in this research from 210 hemispherical footpath site images collected under cloud-free conditions. Analysis of the peak noon UV index has been presented for each month in the 2023 calendar year. The techniques described have allowed the derivation of noon UV indices from the publicly accessible South-East Queensland AtmoSEQ online database.[32] This database of footpath site images retains a publicly accessible record of over 1000 Brisbane street site images, of which 210 cloud-free images have been utilized here to examine the influence of site sky view and solar position relative to local tree canopies growing and being maintained within the public footpaths of 10 residential Brisbane suburbs. The study has provided the first objective measure of the effectiveness of established tree canopies, gardens, and the surrounding surface objects at mitigating direct and diffuse sunlight and UV radiation on public footpaths located within the dry sub-tropics of Brisbane, south-eastern Queensland, a region that shares Australia's highest melanoma skin cancer incidence.[41] In the absence of tree canopies, the UV index is higher in the summer than in the winter. This preliminary research of 21 Brisbane streets has shown that effective protection from UV by tree canopies is most effective during the peak summer season when the sun is directly overhead at noon as such canopies will block direct sunlight. This research has also shown that the presence of overhead tree canopies and the distribution of those canopies with respect to the available sky view and tree species themselves can have a mitigating effect throughout the year.

Tree shade and the planting of street trees in the urban environment has clear benefits in mitigating against heat and climate change by reducing the available ambient solar radiation, increasing humidity, and regulating air quality.[42] Additional benefits may include increased capacity for carbon sequestration.[43] Public health benefits

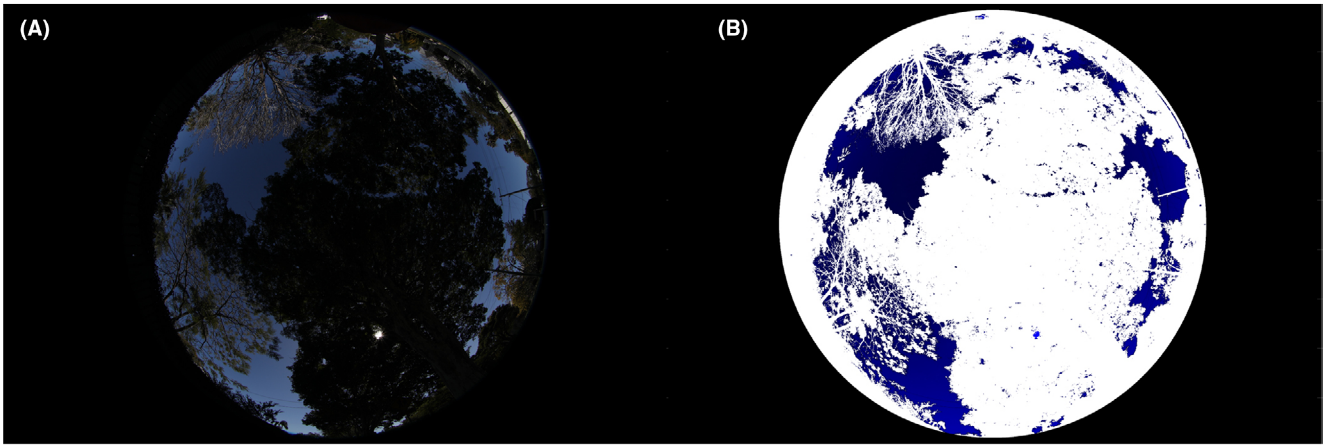

FIGURE 6 (A) Bell Terrace, Graceville, site C, 27.52129°S, 152.97221°E; (B) Processed Image noon UV index is 0.5 on 15 May, sky view 20.2%. This site is protected by an established *Libidibia ferrea* canopy and background *Delonix regia* species.

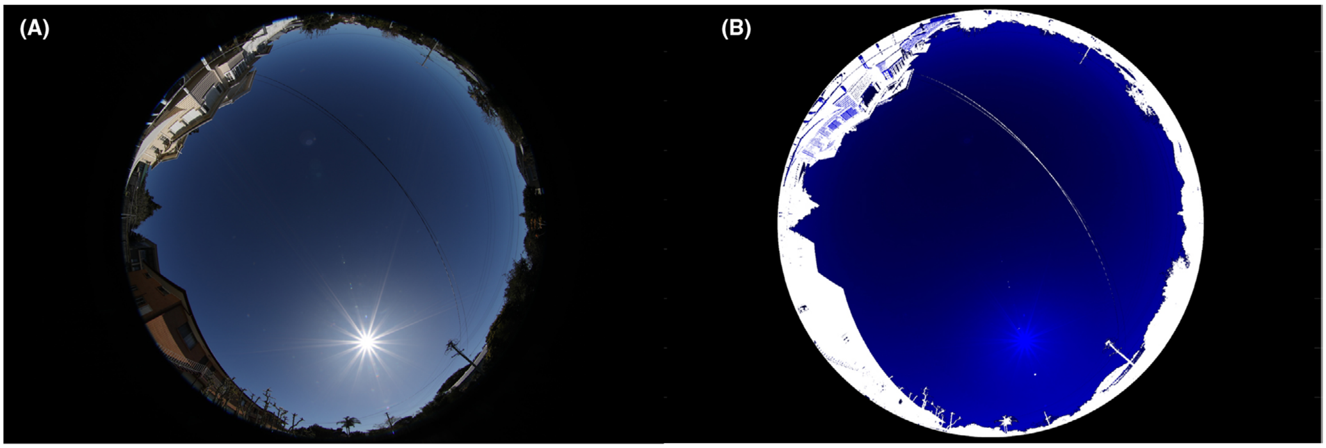

FIGURE 7 (A) MacKenzie Street, Annerley, site E, 27.51434°S, 153.03337°E; (B) Processed Image noon UV index is 10.7 on 15 December, sky view 80.1%. The footpath is planted with *Buckinghamia celsissima* saplings under 2 m in height. Background trees include *Dypsis lutescens* and *Archontophoenix* sp.

often include improving urban aesthetics and increasing overall access to green space.[44] These benefits can clearly influence psychological health. In this research, the focus has been to investigate the mitigating effect of tree canopies at solar noon on the UV index. The current study, therefore, seeks to examine the potential physical benefit of street side tree plantings. This was achieved by predicting the path of the sun in each month of the year 2023 from overhead site images taken during the winter survey period of June, July, and August 2022.

Using upward facing hemispherical images to derive the local site UV index has some advantages over using a UV radiometer. This includes ease of use without the need for calibration or training on behalf of the surveyor. A single image taken during a survey period can be applied to calculate the UV index at any time of year. Limitations of any sky view analysis include seasonal changes in tree foliage, changes that may influence the maintenance of trees or footpaths to retain accessibility, local development, and changes to private gardens or public parks and green spaces. In Brisbane's subtropical climate, many street trees are either evergreen species or semi-deciduous species. Patterns in local foliage densities predicted here throughout the year are likely to be stable and representative of seasonal changes to the site UV index. This is an avenue for future research. Similar studies that utilize site sky view under tree canopies located within temperature climates are likely to yield different seasonal UV index patterns.

Variability in site canopy density and seasonal dependencies can be examined using site series surveys conducted during different times of the year. Patterns in hemispherical site foliage may also be examined using machine learning techniques. In this research, footpath site images were collected in winter, a period when cloud cover and foliage density is minimal. The UV index on each of the streets examined in the current survey are, therefore, likely to be lower in the summer, when cloud and tree foliage density increases.

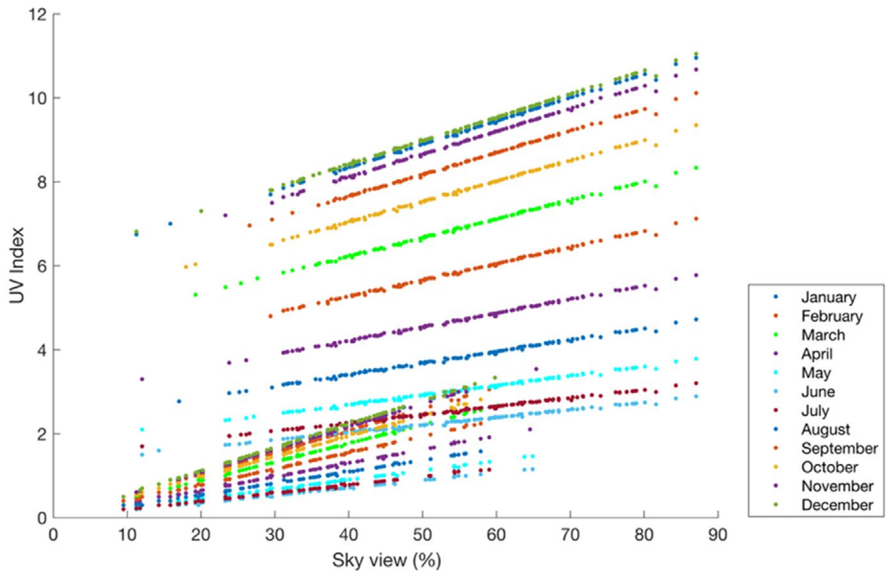

FIGURE 8 Maximum cloud-free noon UV index versus hemispherical sky view for each month in the calendar year. Note the emergence of two distinct series for images where the solar disc is not obscured at noon (upper series) and images where the solar disc is obscured by a tree canopy (lower series).

Seasonal UV mitigation under established canopies

In 2007, Gies et al.[45] measured the UV protection factors (PF) of six tree species used commonly in Australian urban environments, including three of the species encountered in the current Brisbane survey of *Lophostemon confertus*, *Koelreuteria paniculata*, and *Jacaranda mimosifolia*. The seasonal dependence and range in UV protection under tree canopies protected by well-established species on Brisbane footpaths are similar to the UV site measurements taken underneath tree canopies described by Gies et al.[45] (20%–10%, PF 5–10), Parsons et al.[46] (29%–18%, PF 3.5–5.5), and Parisi et al.[47] (50%–5%, PF 2–20). Grant et al.[17] established similar findings using a computer model to derive the canopy PF under changing sky view proportions. Similar to the research findings presented here (Figure 8), Grant et al.[17] found that for trees that obscured 90% of the available sky hemisphere, a PF of 10 could be achieved (90% reduction). For trees that obscured less than 50% of the available sky view, the PF fell to less than 2 (50% reduction).

This research concluded that local tree canopies could reduce the cloud-free erythemally effective UV in summer by 90% (PF 10) at midday when the sun is obscured by an overhead canopy and 40% (PF 1.7) when not blocking the sun. The results showed that protection depended on the season and the tree species, and that maximum UV protection generally occurred in the height of summer when the sun reached its highest elevation (Figure 5). At Brisbane's latitude, the sun will traverse its most northerly celestial path on 21 June (winter solstice). Conversely, in the southern hemisphere summer the sun reaches its maximum southern celestial declination of −23.44°S on 21 December resulting in a maximum noon time solar elevation of 85.9°. This research confirms that the greatest reduction in UV index from Brisbane footpath tree canopies occurs near the annual summer solstice. For this to occur, tree canopies located in Brisbane must cover the summer noon solar elevation at 85.9°, almost directly above a given footpath site. Planting programs that aim to preserve street sides where established tree canopies are present will subsequently have the most influence on reducing UV radiation in summer. New street plantings that encourage fast-growing species able to provide overhead cover are also important for effective UV mitigation.

In addition to the importance of retaining street trees with established overhead canopy cover, protection from peak noon UV radiation was found here to also depend on the street (Table 2) and tree species itself (Figure 10). All 21 surveyed streets reduced the UV index from the expected unobstructed monthly maximum. On average, all 210 surveyed footpath sites reduced the annual UV index to 4.6 from the unobstructed annual Brisbane average of 7.9, representing a noon UV index mitigation of 42%.

Maximum protection was found to occur in the current study of 21 streets in Bell Terrace underneath an established *Libidibia ferrea* canopy. On 15 December, Bell Terrace, site C reached a maximum UV index of only 1.1. This represents a 90.7% reduction from the expected open sky UV index of 11.8. The median noon UV index on Bell Terrace on 15 December (including all 10 street sites) was 2.3 (an 80.5% reduction). For Wright Street, Balmoral, the

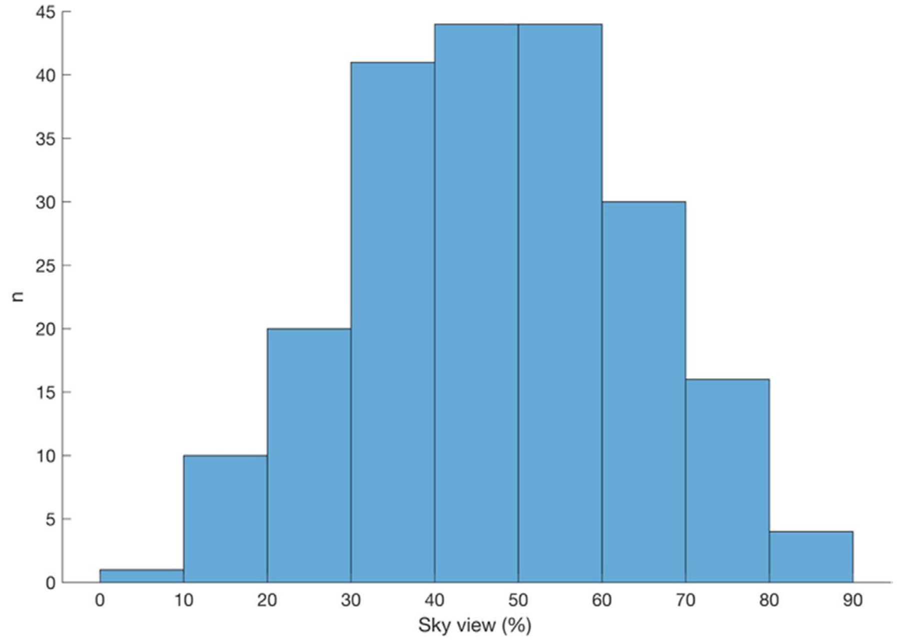

FIGURE 9 Distribution of hemispherical sky view for all 21 streets included in the Brisbane survey. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Frequency of singular footpath tree species imaged in sites with less than 50% sky view.

Footpath sites identified with a singular tree species	Frequency of sites with <50% sky view, *n*
Pongamia pinnata	11
Libidibia ferrea	10
Senna siamea	7
Callistemon viminalis	3
Cinnamomum camphora	3
Xanthostemon chrysanthus	2
Cupaniopsis anacardioides	2
Delonix regia	2
Waterhousia floribunda	1
Banksia integrifolia	1
Harpullia pendula	1
Buckinghamia celsissima	1
Pheltophorum pterocarpum	1
Eucalyptus microcorys	1
Ficus obliqua	1
Lophostemon confertus	0
Eucalyptus torelliana	0
Eucalyptus tessellaris	0
Acronychia oblongifolia	0
Melaleuca quinquinervia	0
Jacaranda mimosifolia	0
Total	47

15 December median was 2.2 (an 81.4% reduction) and for Woodland Avenue, Forest Lake, the median December UV index was 4.6 (a reduction of 61.0%). These three streets recorded the lowest annual mean noon UV index, and each of these streets recorded an annual mean less than 3.

Opportunities for UV mitigation and challenges

Approximately 4.8% of Brisbane's total tree cover is supported by road reserve land.[3] This land includes footpath zones adjacent to city streets and roads that extend over 4800 km within Brisbane alone, shading approximately 35% of the available area.[3] In this study, the effect of these planted trees, local residential buildings, and surrounding vegetation was examined using surface site measurements. The difference in daily UV protection between summer and winter was modeled using the expected solar path visible at each individual survey site. This analysis has shown clearly that there is a difference in the level of UV protection afforded to pedestrians who utilize different footpaths and public walkways across each of the 10 studied Brisbane suburbs. This level of protection is not only a result of footpath tree planting alone but also a result of the presence of street side awnings, retaining walls, local gardens, fences, and urban surface structures that can each attenuate the available ambient solar UV, and hence block the available sky view. The use of UV indices derived as an assessment metric using the techniques

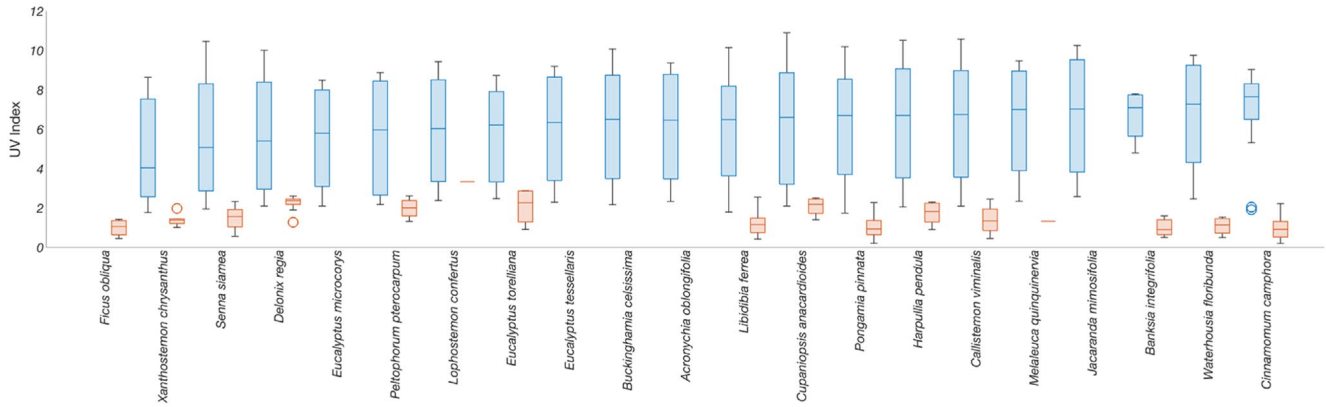

FIGURE 10 Cloud-free noon UV index for hemispherical images classified with respect to tree species for all months in the year 2023. UV index is listed for species that obstructed the solar disc at noon (red) and images that did not obstruct the solar disc at noon (blue).

demonstrated here may potentially enhance existing urban walkability and enhance population skin cancer risk models. In this research, the path of the sun was calculated at noon, but in future studies could be taken into account over a full day to model the effective total UV exposure at each site.

Tree plantings encountered during the field survey, including the position of each tree on a footpath, the spacing between trees, the species of tree used, their height, and canopy diameter showed some regularity across each Brisbane street and suburb. In general, it was noted that trees tended to be planted to the right of the middle of a footpath (for the left or western side of a north facing street). Plantings were typically no more than 2 m from the street side curb and were placed in an approximate linear path. Electrical infrastructure was located on both the left and right side of surveyed streets. In some cases, trees may have been clipped to allow clearance for power lines. The necessity for tree clipping and utilization of trees that do not encroach on existing city infrastructure is likely to limit the total species and tree characteristics that may be considered optimal for UV protection within an urban landscape such as Brisbane.

Many trees encountered in the current survey were not purposefully planted on footpaths. In suburbs such as Forest Lake, large indigenous tree species including *Eucalyptus*, *Callistemon*, and *Acacia* species remained in place at irregular intervals, possibly as the suburb was developed. Large background tree canopies from nearby parklands, private properties, gardens, and road islands adjacent to a surveyed footpath also contributed to the noon UV index site results. Many tree canopies, especially for closely planted trees or trees planted in proximity to a garden, or existing parkland were merged in groups making individual tree canopy diameter, height spacing, and species identification challenging. Thus, these characteristics were not routinely included in the current study database, but each have the potential to be measured in the future.

CONCLUSIONS

This research has studied the potential influence of trees and the surrounding environment in reducing the available ambient UV by in situ site image surveys. Trees that have a high leaf volume year-round, provide a broad stable canopy and room for accessibly by pedestrians will provide optimal protection from solar UV.[31] However, based upon current planting practices along footpath zones, the optimum tree specifications for UV mitigation in Brisbane are likely to be a range of different tree species, such as those encountered during the field survey as often a mixture of different tree species were found in a single street. Local tree species that grow to a height of 8 m and can be easily pruned are recommended by the Brisbane City Council.[48] The planting of similar medium-sized trees and the continuing maintenance of residential streets that are already protected by established tree canopies will improve the shade characteristics of Brisbane suburbs and enhance UV protection for local residents.

ACKNOWLEDGMENTS

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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