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Measuring the Luminous and Spectral Characteristics of Light Transmitted through deciduous trees Indoors

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1 Abstract

This paper examines the impact of a deciduous Beech tree on indoor daylight quality in a room where the window is fully obscured by the tree. Trees, with their complex geometries, act as fenestration systems that modulate the quantities and spectral characteristics of daylight. The Beech tree's geometry and leaf colour change with the seasons, losing leaves in winter and changing leaf colour from summer to autumn. To capture these variations and understand how a Beech tree modulates daylight, the study measures luminance, spectral irradiance, and spectral radiance across spring, summer, winter, and autumn. Findings illustrate how the spectral and photometric qualities of daylight change with the tree's seasonal variations.

2 Introduction

Trees are essential in creating sustainable urban environments as they provide numerous environmental and social benefits. Trees outside buildings can modify the light entering indoor spaces through windows by transmitting, attenuating, scattering, and reflecting light [1]. However, accurately characterizing the impact of trees on indoor daylight quality can be challenging due to varying spatial arrangements, density and seasonal changes of the components of trees.

Deciduous trees, including Beech trees, show seasonal variations in their spectral characteristics influenced by canopy coverage percentage [2]. Factors such as canopy dimensions, leaf density, leaf drop and regrowth, and branch patterns also affect daylight levels [3]. These factors are usually tested through simulations in the field of lighting and building science because quantifying a tree's light characteristics, for example with a classical goniophotometer is challenging in laboratory settings. While methods exist for measuring tree transmittance, measuring their reflectance remains difficult [1]. Additionally, the spectral power distribution of daylight in the presence of plants or trees displays unique patterns that are distinct in the urban environments [4].

Hence the aim of this paper is to describes a field study to characterize the spectral and photometric quantities of daylight through a Beech tree in an indoor environment. The study focuses on a room with a window area entirely obscured by a deciduous Beech tree outside, whose colour of leaves and geometry changes across seasons. Luminance images, spectral irradiance, and spectral radiance measurements are carried out across the room.

3 Methodology

Measurements were collected at distinct times during three seasons --- summer, autumn, and winter (Table 1). The study was conducted in a rectangular office room measuring approximately 3 m wide and 6 m deep with a west facing window at the Technical University of Berlin, Germany. The office contains three work desks equipped with monitors and chairs, as well as storage cabinets, whiteboards, and chalkboards, as shown in Figure 1a and 1b. The room features white plastered walls and dark grey linoleum flooring. The west facing wall with the window is flanked by a three-sectioned window and the Beech tree that grows outside the window covers the entire widow area filtering all the daylight entering the office space (Figure 1a, 2a). For all measurements the interior lighting is switched off. Only daylight filtered through the trees and window glass illuminates the room.

Figure 1a: Room with view to the window.

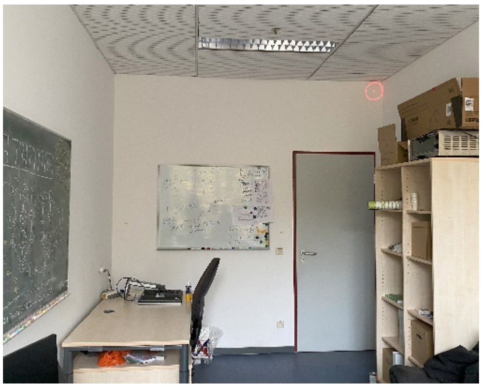


Figure 1b: Room with view to the backwall

Figure 2a: Beech tree in front of the office (red circle)

Figure 2b: Measurement position and setup

3.1 Description of measurement devices and setup

Luminance images were captured using the LMK 5 camera from TechnoTeam, which can measure spatially resolved luminance images and melanopic lux. Spectral radiance and irradiance measurements were conducted with the Specbos 1201 spectrophotometer from JETI Technische Instrumente GmbH. This device can measure radiation density within a 5° spatial angle when assessing spectral radiance.

Figure 3a: Measurement setup with the LMK 5 and JETI spectroradiometer

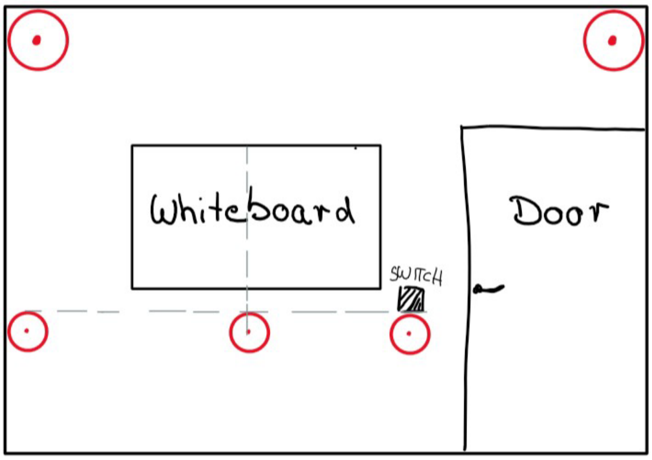


Figure 3b: Sectional sketch of the back wall with red circles indicating points of spectral radiance measurements

The measurement setup, as shown in Figure 3a, includes the LMK camera and the JETI spectroradiometer mounted side by side on a tripod using a custom-made aluminium plate. This plate ensures that both devices are positioned at the same horizontal level. The setup is arranged between two tables, allowing the LMK camera to capture the full width of the window and the viewing points of the two office desks by the window. Measurements are taken from this fixed position approximately 1.30 m from the window, directed towards the window (referred to as window), 90 degrees to the left (referred to as left side) and right walls (referred to as right side), and towards the back of the room (referred to as back wall). Additionally, five spectral radiance measurements are taken on the back wall, as shown in Figure 3b. The height of the setup is set at 1.20 m, measured from the floor to the centre of the sensor areas.

Outdoor daylight illuminance data for further photometric analysis (Section 4.1), including global and vertical illuminances in the four cardinal directions (North, South, East, and West), were obtained from the daylight measuring site located on the rooftop of the EN-building at TUB.

The measurement data was evaluated using the software tools of the measuring device manufacturers in combination with Matlab.

3.2 Seasonal, daylight and sky conditions for analysis

Table 1 provides an overview of the dates, times, sky conditions, seasons, and solar angles at the time of the measurements. The ability to create a fully comparable dataset was limited due to factors such as weather conditions, space accessibility, and the availability of measuring devices. However, measurements taken under hazy to cloudy sky conditions at 12:00 noon across three different seasons form a complete dataset, which will be the focus of comparison in this paper (highlighted in green in Table 1).

Table 1: Date, time, season and solar angles information of measurement periods.

Season/Date	Time [hh:mm]	Sky condition	Sun elevation [°]	Sun azimuth angle [°]
Summer				
21.08.2022	09:00	cloudy	26,23	104,95
	12:00	cloudy	47,19	154,46
	15:00	clear	43,87	218,88
	17:00	clear	28,97	250,65
Autumn				
21.10.2022	12:00	cloudy	25,81	166,65
Winter				
27.02.2023	12:00	hazy/cloudy	27,53	174,52

The three sky conditions during the 12 noon measurements across the three seasons are shown in Figure 4a-c. The pictures are taken by a fisheye camera on the daylight measuring site of the EN-building rooftop at TUB.

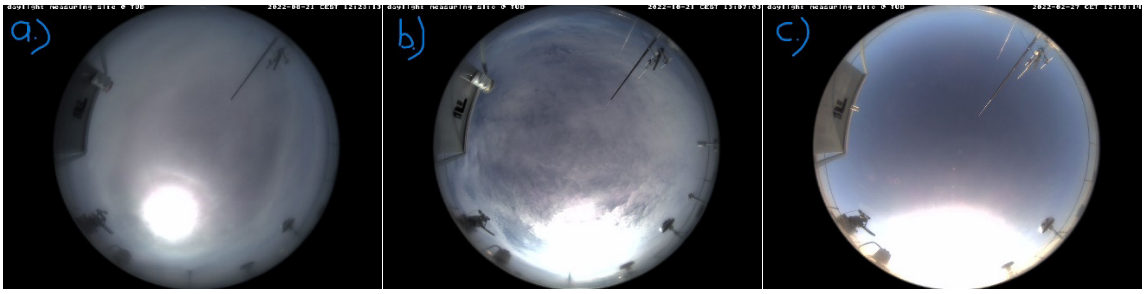


Figure 4: Sky conditions at noon: a) August 22, 2022 b) October 21, 2022 c) February 27, 2023

4 Results

The first part of the results presents absolute quantities, aiming to describe the general photometric conditions both indoors and outdoors, with comparisons made between seasons and measurement locations. The second part focuses on the spectral irradiance analysis taken indoors. The final part of the results will present the colorimetric and non-image forming potential of daylight through trees.

4.1 Photometric analysis

Figure 5a charts the illuminance measured at various locations during the three seasons. Across all seasons, illuminance is highest at the window view, peaking at 1,954 lx in autumn. The lowest illuminance levels are recorded at the rear wall, with all values below 100 lx. The difference between the right and left sides reaches up to 200 lx. The variation in illuminance at the window and rear wall is primarily due to their distance from the daylight source. According to the inverse square law, illuminance decreases proportionally to the square of the distance from the light source.

Table 2 shows the values of the outdoor west-facing vertical daylight illuminance measured at the TUB rooftop at the same time stamps when indoor measurements were taken at each viewpoint (window, right side, left side, backwall) in summer, autumn and winter.

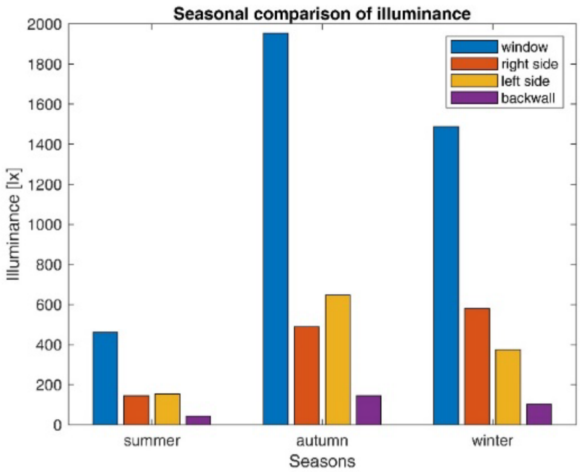


Figure 5a: Illuminance levels for the four indoor measurement views during summer, autumn, and winter

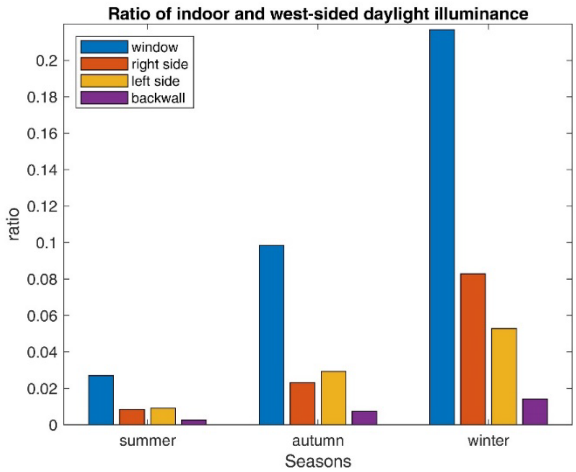


Figure 5b: Ratio of indoor illuminance to outdoor vertical illuminance measured west-facing at the daylight measurement site on the TUB rooftop

Comparing the outdoor illuminance values in Table 2 with the indoor illuminances shown in Figure 5a (comparing summer and winter conditions), it is clear that the highest outdoor illuminance does not always lead to the highest indoor illuminance at the window, particularly when complex geometries like trees are outside. This underscores the significant impact that leaves have on the room's photometric properties and to consider modelling trees when planning for daylight indoors.

In summer, the measured illuminance at the window view is only 2.7% of the outdoor illuminance. In winter, this increases to 21.68%, while in autumn, it is 10%. Figure 5b illustrates this relationship by showing the ratio of indoor to outdoor vertical daylight illuminance. The figure highlights that indoor vertical daylight levels are lowest in summer and highest in winter, with winter achieving the greatest indoor daylight levels relative to outdoor availability.

Table 2: Outdoor west-facing vertical daylight illuminance measured at the TUB rooftop

Season	Window	Right side	Left side	Backwall
Summer	17074 lx	17074 lx	17041 lx	16918 lx
Autumn	19845 lx	21228 lx	21975 lx	19375 lx
Winter	6863 lx	7005 lx	7098 lx	7222 lx

4.2 Spectral analysis

To analyse the spectral characteristics of light filtering through trees, the relative spectral irradiance normalized at 560 nm across all three seasons towards the window view are shown in Figure 6a. The most pronounced spectral effect is observed in summer. In this season, the near-infrared range (700 nm – 780 nm) is particularly highlighted, with a peak at 751 nm. The intensity drops at 775 nm but increases again afterwards. This range (>680 nm), known as the 'red edge,' is where chlorophyll in the leaves reflects light to minimize heat absorption and prevent cell overheating. [5]. There is also a decreasing intensity slope from 550 nm to 380 nm and to 680 nm.

In autumn, the spectrum resembles that of summer, but the decreasing intensity slope between 550 nm and 680 nm is less pronounced, and the 'red edge' effect diminishes. The winter measurement closely matches the CIE D65 spectral curve, which represents average daylight with a color temperature of approximately 6500 K. This highlights the distinct spectral patterns of leaf colour changes during summer and autumn, with minimal effect in winter due to the absence of leaves (Figure 6b)

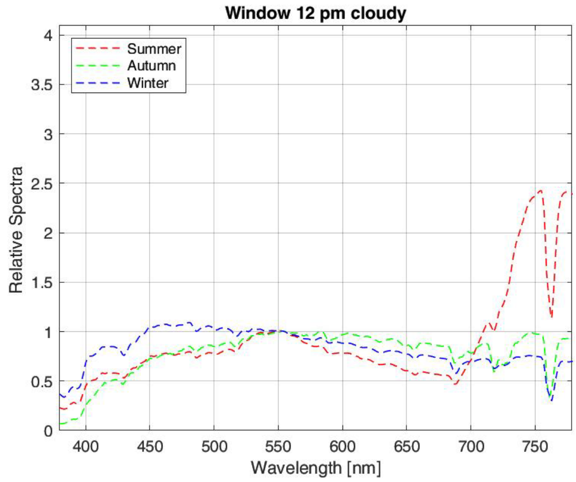


Figure 6a: Comparison of the relative spectral irradiance measured over three seasons towards window view

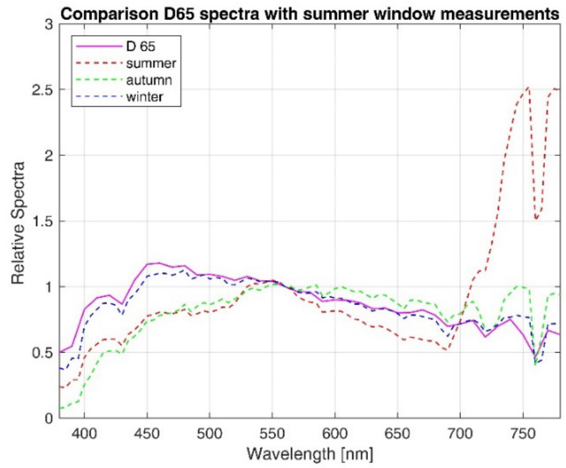


Figure 6b: Comparison of normalised D65 spectra with the spectral irradiance measured towards window

Figure 7 compares all the four the measurement views across the three seasons. The spectral characteristics of each season shown in Figure 6a, aligns with all the viewpoints. Summer measurements at each view exhibit the 'red edge,' and decreasing slop on either side from 550 nm, while winter measurements show increased intensity at shorter wavelengths and alignment to the CIE D65 spectral characteristics. The higher proportion of the red region (from 750 nm) observed in the back wall view across the seasons, and especially the autumn and winter may be attributed to object-specific reflectance in the room, such as from the large wooden shelves on the back wall (Figure 1b).

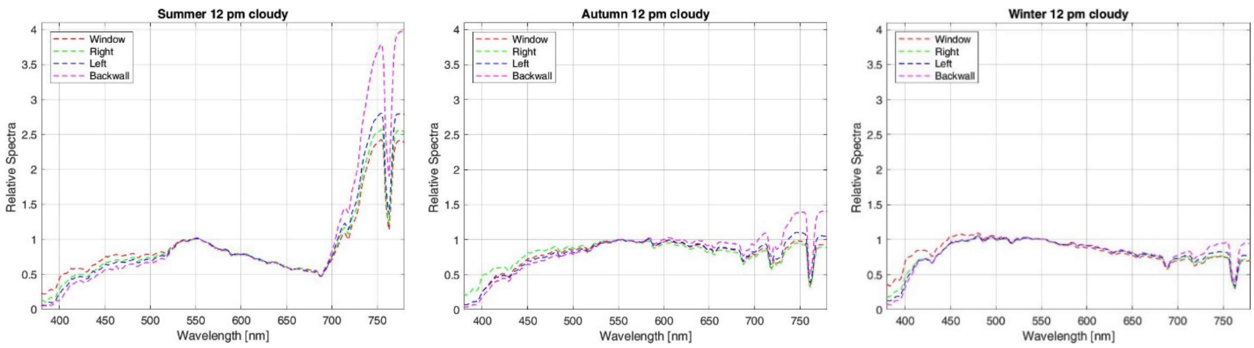


Figure 7: Comparison of the measurement viewpoints across the three seasons (left: summer, middle: autumn and right:winter)

4.3 Colorimetric analysis

Table 3 summarizes the colorimetric data for all measurement viewpoints across the three seasons. The Color Rendering Index (CRI) shows a consistent pattern: it is lowest in summer when trees are covered with green leaves and highest in winter when the trees are bare. The greatest variations in CRI across different viewpoints are observed in summer, compared to autumn or winter.

The Correlated Color Temperature (CCT) at the window view is lower in summer and autumn compared to winter, indicating that the presence of leaves may affect the CCT of daylight filtered indoors. Simultaneous spectral irradiance measurements or colorimetric measurements of daylight outside the window or on the rooftop were not recorded; hence, the effect of sky conditions on the CRI and CCT variations cannot be ruled out.

Table 3: CCT and CRI data of the measurements at different viewpoints indoors across the seasons.

Season	**Window**		**Right side**		**Left side**		**Backwall**	
	CCT [K]	CRI [%]	CCT [K]	CRI [%]	CCT [K]	CRI [%]	CCT [K]	CRI [%]
Summer	5580	88,25	5197	86,79	5117	85,54	4917	83,86
Autumn	5035	96,37	4703	95,31	4578	95,11	4341	95,68
Winter	6185	98,23	5664	97,58	5707	97,36	5707	97,93

4.4 Melanopic Equivalent Daylight Illuminance (MEDI)

To evaluate the impact of trees on non-image forming effects, Melanopic Equivalent Daylight Illuminance (MEDI) was calculated using spectral irradiance measurements taken towards the window across three seasons. MEDI values, determined using melanopic spectral sensitivity and the CIE S 026/2018 standard [9], are compared to photopic illuminance values in Table 3. In summer and autumn, MEDI values are lower than photopic illuminance, indicating that daylight filtered through trees somewhat reduces its non-image forming potential. However, the change in leaf color from summer to autumn does not significantly influence this reduction. In winter, the MEDI-to-photopic ratio of 0.99 suggests no substantial decrease in non-image forming potential, due to absence of leaves. It is important to note that in this case, daylight is filtered through both the trees and the window glass, and the reductions quantified in Table 3 reflect the combined effects of both factors.

Table 4: Comparison of MEDI and photopic illuminance towards the window view across the three seasons

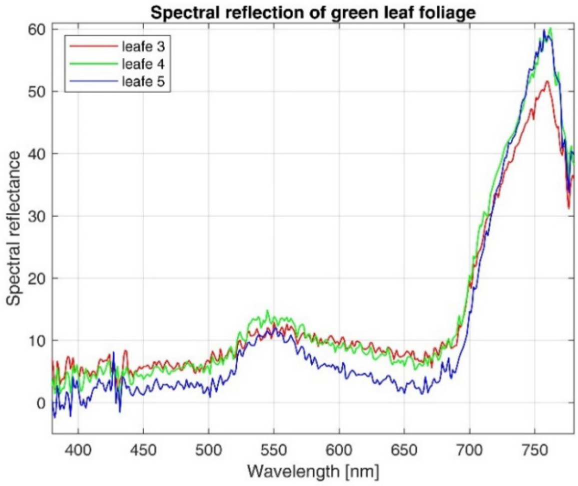
	Summer	**Autumn**	**Winter**
MEDI	385 lx	1626 lx	1440 lx
Photopic	462 lx	1954 lx	1488 lx
Ratio (MEDI/photopic)	0.83	0.83	0.99

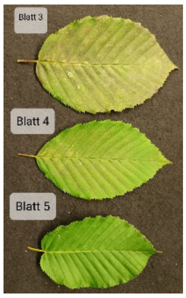
5 Evaluation

Figure 8a compares the reflectance measurements of three green leaf samples collected from the Beech tree during summer. The measurements were conducted using a custom device developed at TUB, which combines a 3D-printed integrating sphere with a Spectraval 1511 spectroradiometer from JETI Technische Instrumente GmbH. The light source used was a LED matrix with a spectrum closely matching daylight (CIE D65) [8].

Leaves contain six different types of chlorophyll, but the most significant impact comes from chlorophyll a and chlorophyll b. These chlorophyll types primarily absorb light in the blue and red regions of the spectrum. Chlorophyll a absorbs wavelengths in the violet and orange ranges, while chlorophyll b is shifted and mainly absorbs light in the blue and yellow parts of the spectrum (Figure 8b). Both types reflect the green part of the spectrum, which is why the summer foliage of trees appears green to the human eye.

As mentioned in Section 4.2, leaves have a natural self-protection mechanism against overheating known as the “red edge”. In this region (680 nm – 1200 nm), multiple reflections occur on the cell walls of the leaves causing a high reflectance curve from 680 -700 nm





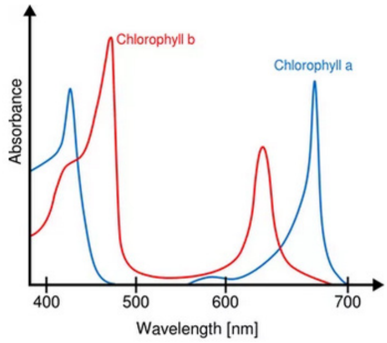


Figure 8a: Measured spectral reflectance of three leaves from the beech tree

Figure 8b: Absorbance of Chlorophyll a and b (https://www.mpsd.mpg.de/42776/2015-04-chlorophyll-rubio)

The measured spectral irradiance in the room closely aligns with the spectral reflectance behaviour of the beech leaves (Figure 8a), particularly during summer (Figure 7). This effect remains consistent regardless of the position in the space or the degree of cloud cover (Figure 4a vs. 4c). In autumn (Figure 7), as the foliage turns yellow and the tree gradually loses its leaves, the spectral influence of chlorophyll decreases, reducing absorption in the blue, orange, and near-infrared ("red edge") regions. By winter (Figure 7), the spectrum between 400 nm and 500 nm elevates and closely matches the normalized CIE D65 spectrum (Figure 6b), highlighting the strong influence of spectral reflectance characteristics of daylight filtered through leaves.

This analysis suggests that tree foliage near windows has a measurable visual impact on occupants within the building. Seasonal variations in foliage should be considered in daylight planning to account for these effects.

6 Summary

The results of this study show that the foliage of deciduous trees, such as beech leaves, significantly modulates the spectral properties of daylight in an indoor space when placed outside windows or glazed facades, acting as a complex fenestration system. The type and amount of chlorophyll in the leaves, along with seasonal changes in foliage, directly influence photometric and spectral characteristics of daylight filtered through trees.

Photometric analysis shows that summer foliage significantly reduces indoor illuminance levels, blocking 97.3% of outdoor daylight illuminance, compared to a 78.3% reduction in winter without leaves. In summer, green foliage along with reducing illuminances also affects the spectral characteristics of daylight by reflecting more in the near-infrared range (>700 nm) while absorbing in short-wave part of the spectrum. This effect is seen not just near the window but all parts of the room including the back of the room and with a cloudy sky condition. In contrast, the spectral characteristics of daylight in winter, filtered through branches and no leaves are less affected. This seasonal variation affects daylight quality, as green foliage appears to lower the Color Rendering Index (CRI) and Correlated Color Temperature (CCT), and reduces the non-image forming potential of daylight compared to winter conditions.

These findings suggest that strategically incorporating deciduous trees in urban areas can improve both the quality and quantity of daylight in indoor environments. Understanding the reflective properties of various leaf species and tree structures can enhance indoor lighting and well-being.

Further research on the spectral reflectance of different tree species, leaves, and branches will support more effective daylight planning using deciduous trees.

7 References

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