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Mapping the Equivalent Vertical Sunshine Duration Curve of Outdoor Space Beside Buildings for Dynamic Landscape Planting Design

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Abstract: Dynamic shading behavior between buildings and other objects has been suggested as one way of changing microclimate and the change in microclimate that would in turn reduce the demand for heating and cooling. Understanding the dynamic shading behavior is an important aspect of the correct consideration of the sunshine in a built environment. Clearly, in order to reach the ideal landscape model for planting design, the light environment for plant growth also has to be taken into consideration. This study of dynamic sunshine distribution takes university buildings as a case to discover and discuss the light comfort zone for plant growth in the area adjacent to the buildings. In addition to simulating a shadow map that displays the duration of shadow at ground level a further number of shadow maps are constructed to represent the shadow patterns and durations at different heights above the ground. These are analyzed to gain an understanding of the vertical distribution of sunshine and its duration. Therefore we developed a novel concept, equivalent vertical sunshine hours curve (EVSH Curve), for different seasons and heights to review the required sunshine conditions for greening around a building. At the same time the behavior of the non-symmetrical light environment was observed on both sides of the portico due to the influence of nearby buildings. A more comprehensive deeper investigation of the light environment will indicate a more appropriate planting design for a greening place in a built environment.

Keywords: Sunshine duration curve; planting design; vertical light environment.

1. Introduction

Sunlight is one of the essential elements in the ecosystem, and it has been proven that the quality, intensity, and duration of light directly impact plant growth. The quality of sunlight refers to the color or wavelength reaching the plant's surface, and output peaks of sunlight on the ground should also be in the visible range. The intensity and duration of sunlight varies significantly under different conditions, such as latitude, season, region, and even the geographic location. In response to the above characteristics of sunlight, plants control their internode length, leaf size, count, and the density of their chloroplasts. Plants also determine the optimum timing for flowering and other physiological processes (Levitt, 1980; Boardman, 1977) from those characteristics of sunlight. Therefore proper and effective usage of sunlight always has been an important consideration in horticulture and landscape architecture [1].

Recent studies of sunlight in the residential environment have been focused on techniques for reducing the intensity of the urban heat island effect and reducing the energy consumption of buildings [2, 3]. Simulation models and experiments have indicated that the use of vegetation could be an effective approach for changing the microclimates of outdoor and indoor environments [4, 5]. Akbari and Taha conducted a large-scale simulation and reported that increasing the vegetation surrounding a city by 30% and the vegetation around houses by 20% would decrease the costs for cooling in the city by 30-100%

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[6]. Small-scale controlled experiments also have demonstrated that trees placed along the wall of a house can reduce cooling costs by 26-47% in a region that has a mild climate [7]. In a region in which the climate is hot and humid, shade trees can provide as much as 80% of the desired cooling effect [8]. Further studies demonstrated that trees planted with different layout in a yard and at different distances from a building could change the indoor environment, e.g., reducing the harvesting of the heat energy in sunlight by the structures, decreasing natural ventilation, and so reducing the use of air-conditioning [9]. As we noted above, the relationship between buildings and trees is an important consideration, and most of the earlier investigations were focused on the beneficial influences of trees on the microclimates of buildings.

Conventionally, greenery was often provided around buildings in spaces where sunlight was often obstructed and so the plants encountered environmental stress for their growth. The lack of sufficient sun exposure slows the rate of photosynthesis and the production of chlorophyll in ground plants. Long-term deprivation of sufficient light exposure will result in unhealthy plants and unfavorable conditions for the differentiation of flower buds [10] and the development of fruit [11] that influence ornamental quality and the greening effect, but few studies have addressed the location and growth condition of trees subject to the shading effect from nearby buildings. Yezioro and Capeluto et al. [12] evaluated the ratio between the insulated area and the total examined area for a period of a year at an urban square with a specific width, length, and height. The recommended insulated and shaded areas of such a design were presented, and the best locations for deciduous plants and evergreen trees were indicated. Wan and Jun [13] performed a case study to optimize the planting design between residential buildings and meet good daylighting requirement. The proposed model helps us to determine which trees to plant between buildings and to realize good daylighting in a built environment. Lin et al. [14] calculated the distribution of sunshine duration around buildings on a university's campus. According to different plant distributions, such as orientation or the distance to the building, the shading impact of nearby buildings on the growth conditions of the trees was demonstrated. The result illustrated the conventional ‘‘symmetric’’ or ‘‘row’’ plant design was usually unable to allow a light environment fit for plant growth. Unlike non-living objects such as statues, street lamps, chairs and ponds, plants grow and alter as time passes. When striving to create a ‘‘comfort zone’’ for human beings, the comfort zones for plants should also be understood and taken into consideration in order to create a mutually beneficial environment for plants and human beings.

In this work, we developed a visual and directly perceivable method, namely the equivalent vertical sunshine hours (EVSH) curve, to demonstrate the sunlight environments at different seasons and heights, and we further analyzed the distribution and duration of sunshine as these are influenced by adjacent buildings. This approach was intended to discover and present the information required to design optimal planting schemes for different seasons and at different ages. If the EVSH curve used for this study can, in fact, be used to predict the growth restriction and condition of the plant and give advice on ex-ante evaluation of planting design, this approach can become a much needed tool for “sunlight prediction first; plant choice second; design last”.

2. Method

The evaluated area of sunshine conditions was the main campus of National United University, Miaoli County, Taiwan (24°N, 120°E). Since the shadow map was highly related to the arrangement of the buildings, partial campus layout including height of the building is illustrated in Fig. 1. The main research area for determining the duration of sunlight that the plants received during different seasons was the greening place in front of the three-story building (building 1), and a detailed map of the investigated area is shown in Fig. 2. There were ten *Juniperuschinensis* planted in front of the building, and the growth performance characteristics of each plant such as, bend direction and shoot tip displacement are illustrated.

2.1 Simulation of a Building's Shadow at Different Elevation

For easy comprehension by designers, we drew shadow graphs at different elevations, i.e., ±0 m, +1 m, +3 m, +5 m, and +10 m by using the Reviet software. The setting of four different elevations above the ground level (±0 m) was based mainly on the circumstances that +1 m is the average shrub height; +3 m and +5 m are the average heights of a small arbor, and +10 m is for a mature arbor. The open space on the north side of buildings was delimited and divided into a 1 m x 1 m grid. We decided to determine the number of hours of sunshine in each grid.

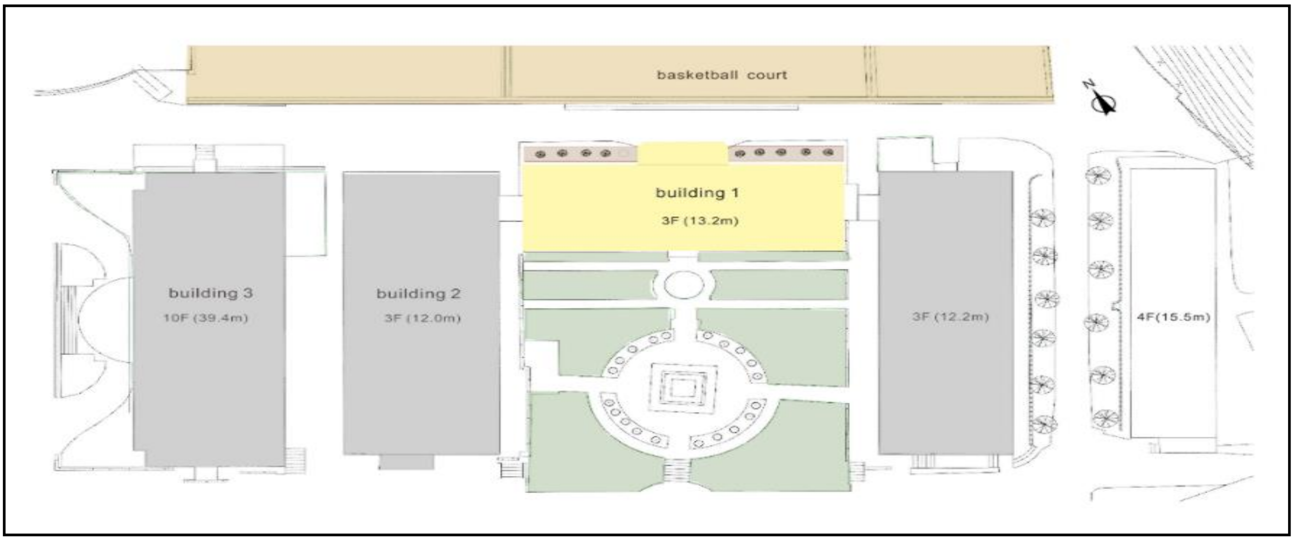


Fig. 1 The partial campus map of the buildings at National UnitedUniversity.

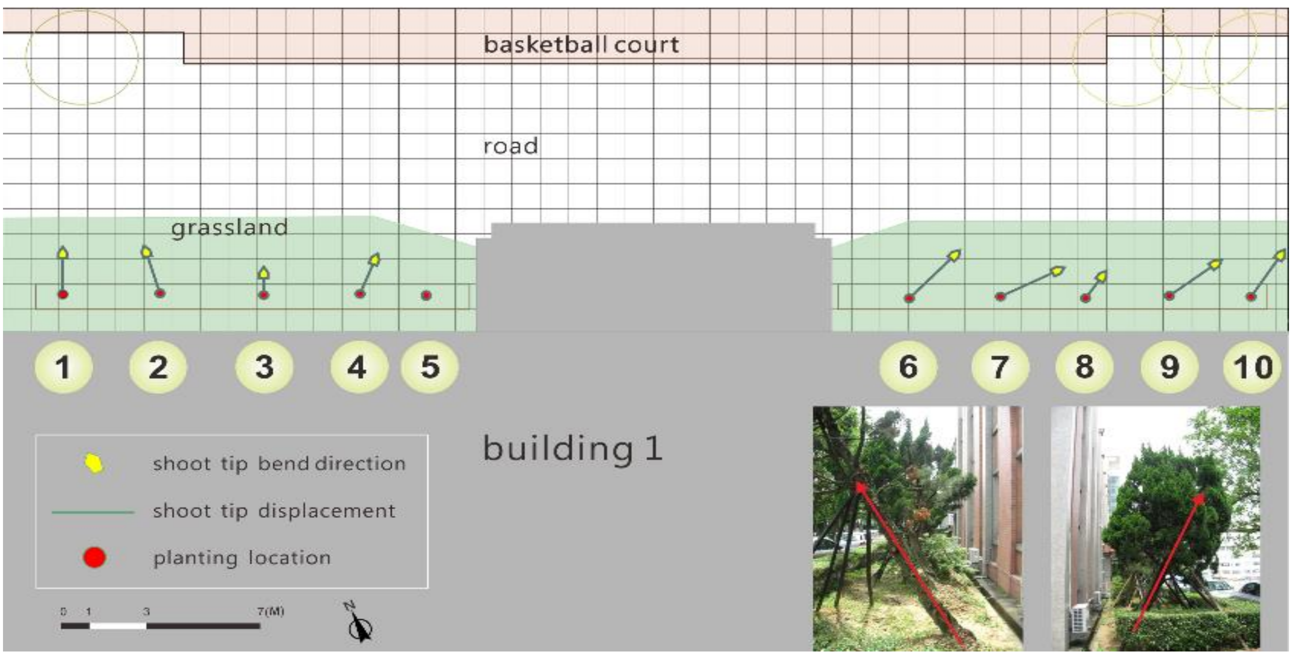


Fig. 2 Planting arrangement in front of the building 1. There are ten *Juniperus chinensis* planted in rows on the north side of the buildings, and because of the non-uniformity of the light environment at the area, phototropism results in severe tilt of the trunks, as shown in pictures.

2.2 Accumulation of Grid Sunshine Hours

Shadow distributions at five elevations were determined every hour from sunrise to sunset at the vernal/autumnal equinoxes, and at the summer and winter solstices respectively, and then the two-dimensional sunshine hour distribution of each equinox or solstice at different height was obtained by calculating the shadow distribution on the grid. The sunshine hour map with different elevations at winter solstices for example is shown in Fig. 3. The two sides of a building's portico are generally key greening places because that is where people enter the building and form their first impression of the building. So we also conducted further analyses of sunshine hour distributions 1.5 m away from the right and left sides of the portico.

2.3 Overlapping and Transforming the Top View Into a Section View

Through use of overlapping sunshine hour distribution with various height from 0 m to 10 m, sunshine hour distribution near two sides of portico were transformed from top view to section view referred as the EVSH curve, as shown in Figs. 4-6. The curves represent the influenced "equivalent" sunshine duration range as modified by the shadow of the buildings

2.4 Ranges of Sunshine for Plant Growth

The average sunshine duration in Miaoli County, Taiwan, at vernal/autumnal equinoxes and the summer and winter solstices are 12, 13.6, and 10.5 hours respectively. In this work, we take three sunshine duration ranges namely 1-4 hr, 4-7 hr, and 7-11hr forsun-shade plant growth under most conditions in winter, vernal/autumn, and summer as points of departure when we discuss optimal locations and arrangement of plants. In turn those findings will be captures into design guidelines.

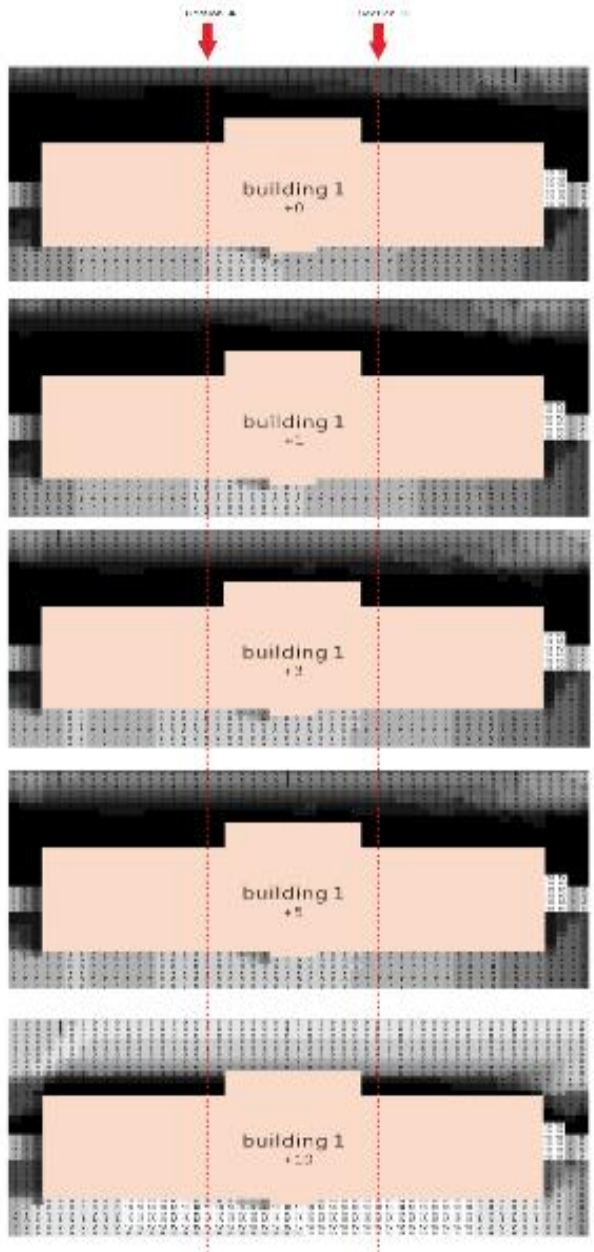


Fig. 3 Sunshine duration maps with different elevation around the building 1. (a) at ground level (b) at an elevation of 1 m (c) elevation of 3 m (d) elevation of 5 m (e) elevation of 10 m. The line on the map is the border between section A and B.

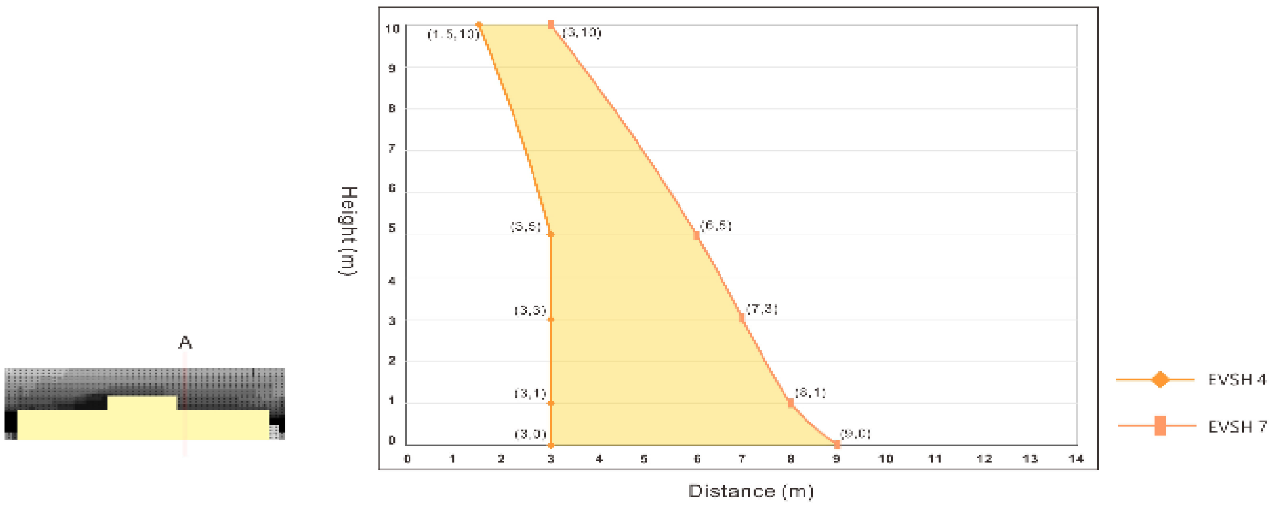
3. Results and Discussion

To analyze the influence of sunshine duration at equinoxes and solstices, the EVSH curves of two sides of the portico are discussed in the following sections.

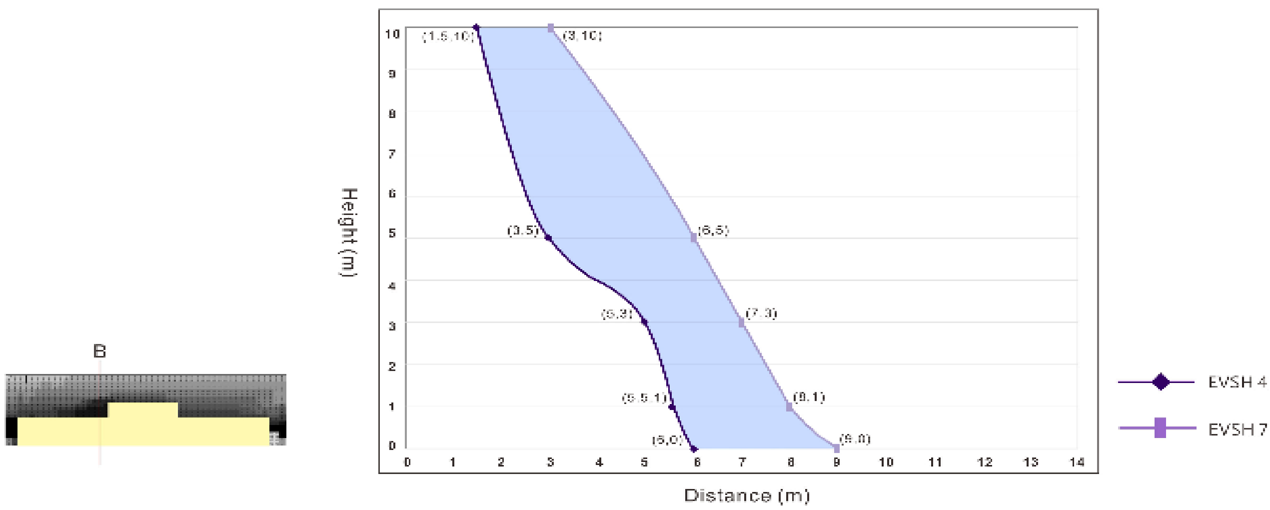
3.1 EVSH Curves of Section A and B at Vernal/ autumnal Equinoxes

As illustrated in the Fig. 4(a), the EVSH-4 curve of section A showed that the point which gets four hours of sunlight is located 3 m away from the building, but the point that also got four hours of sunlight moved inward by 1.5 m at a height of 10 m.

The number of hours sunlight that a curve depicts is given by the number following the capital letters EVSH. In the same manner, if a plant requires seven hours of sunshine at the ground level, it must be shifted 6 m outward, reaching 9 m away from the building. In contrast, the points of EVSH-4 and EVSH-7 at the height of 10 m are 1.5 m and 3 m away from the building, respectively, and their relative distance is 1.5 m, which is much shorter than the relative distance at the ground level. In other words, the height of the plant should be more than 10 m to receive 7 hours of sunshine at the distance of 3 m. The distribution of the EVSH-7 curve of section B is approximately the same as in section A, sketched in the Fig. 4(b). However, when the elevation is less than 5 m, the EVSH-4 is significantly different from the EVSH-4 curve of the section-A.



(a)



(b)

Fig. 4 The EVSH curve at the vernal/autumnal equinoxes. (a) section A and (b) section B. The equivalent vertical sunshine hours were 4 and 7 respectively.

3.2 EVSH Curves of Section A and B at the Summer Solstice

As illustrated in the Fig. 5, the shadow area of the three-story building was narrower than it was at vernal/autumnal equinoxes due to a higher solar elevation angle at the summer solstice. The EVSH-7 curve in section A was revealed in Fig. 5(a) and one can observe that the point to get 7 hours of sunshine on the ground was 2 m away from the building, but at a height of 10 m, the distance is reduced to 1 m. Similarly, the point to get 11 hours of sunshine on the ground was 6 m, whereas, at a height of 10 m, the required distance was only 2 m. Therefore, 2 to 6 m away from building is the region that has 7-11 hours of sunshine on the ground at the summer solstice, and there is a 4 m difference between height at ground and 10m of the EVSH-7 curve. Fig. 5(b) indicated the EVSH curve of section B; the distribution of the EVSH-11 curve is approximately the same on both the east and west sides, but the distribution of EVSH-7 curves on the two sides were different.

3.3 Deduction of "Light Comfort Zone" From EVSH Curves by Comparison of Two Sections of the Overlapping Diagrams

In Fig. 6(a), one can observe the point of the EVSH-1 curve of section A on the ground was 8 m outward from the building. The points of the EVSH-4 curve on the ground and at a height of 10 m were shown to be 13 m and 3.5 m away from the building, respectively. It means that there is 9.5 m difference in the EVSH-4 curve between ground level and at the height of 10 m. In section B as illustrated in the Fig. 6(b), the curve of EVSH-4 is approximately the same as the section A. Due to the influences of the portico and the ten-story building, the distance of EVSH-1 was 1.5 m further away than it was for the section A.

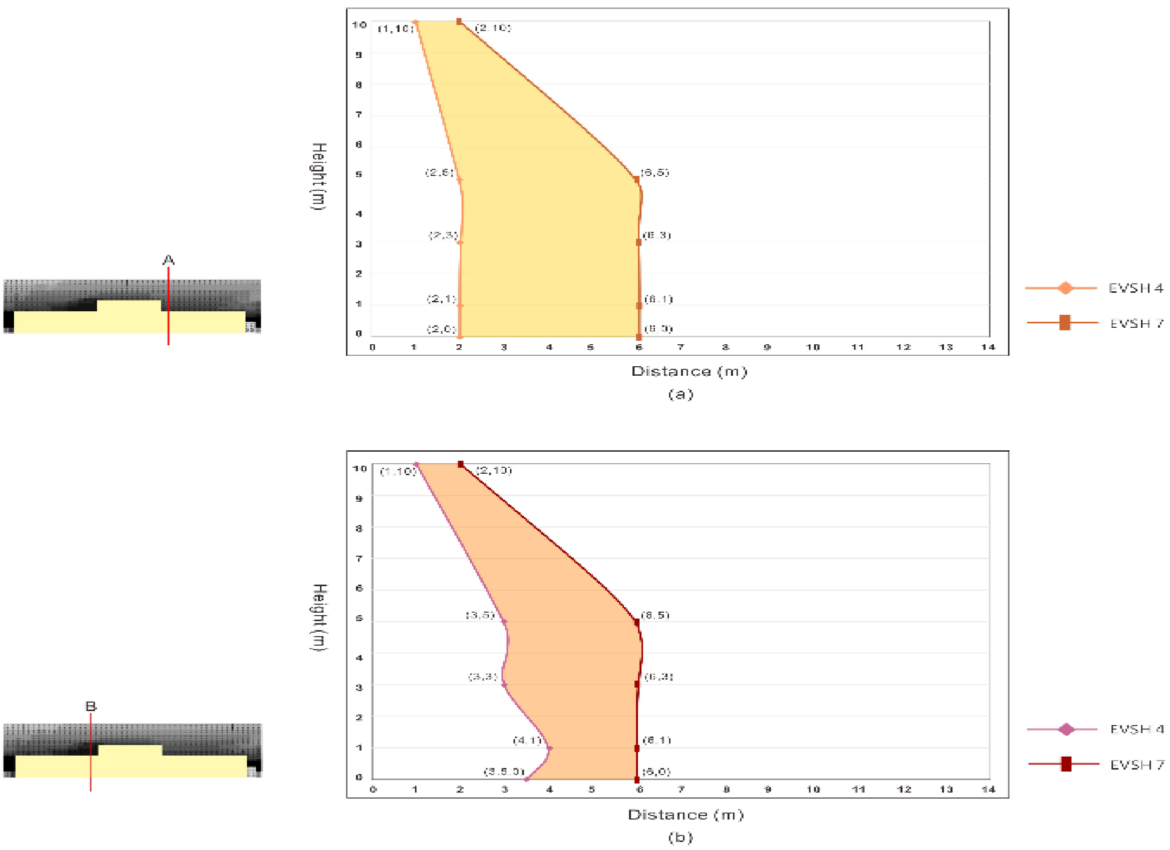


Fig. 5 The EVSH curve at the summer solstice. (a) section A and (b) section B. The equivalent vertical sunshine hours were 7 and 11 respectively.

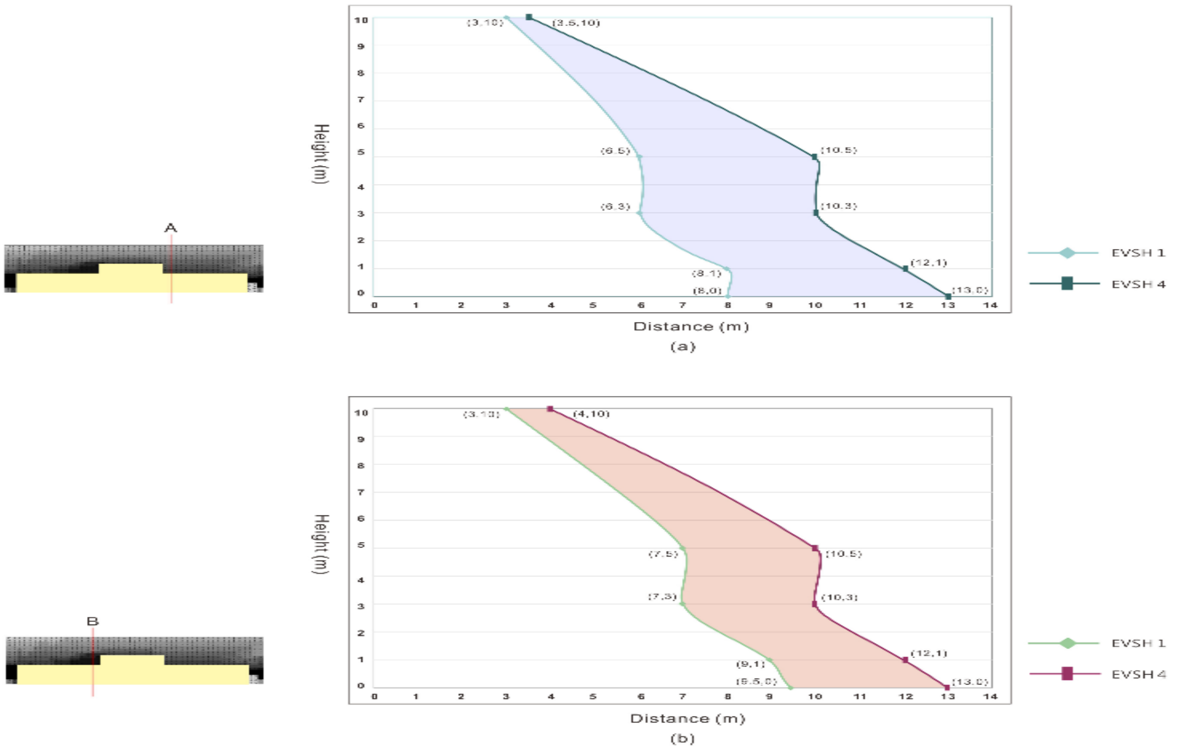


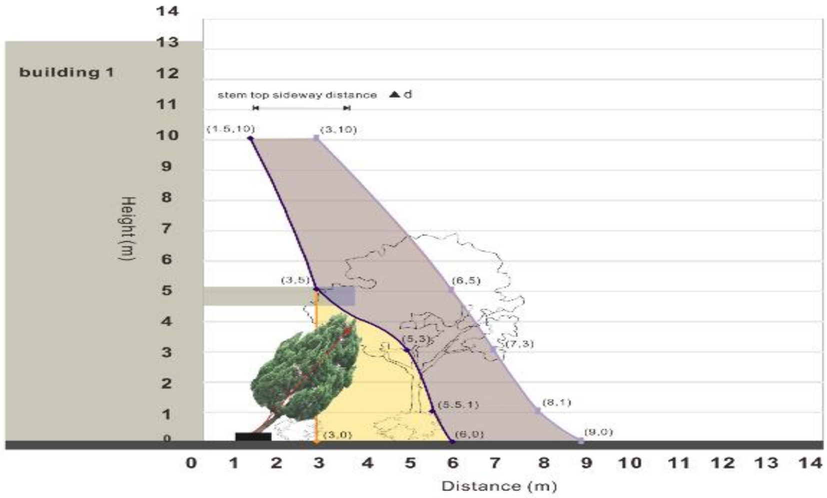
Fig. 6 The EVSH curve at the winter solstice. (a) section A and (b) section B. The equivalent vertical sunshine hours were 1 and 4 respectively.

3.4 Deduction of "light comfort zone" from EVSH curves by comparison of two sections of the overlapping diagrams

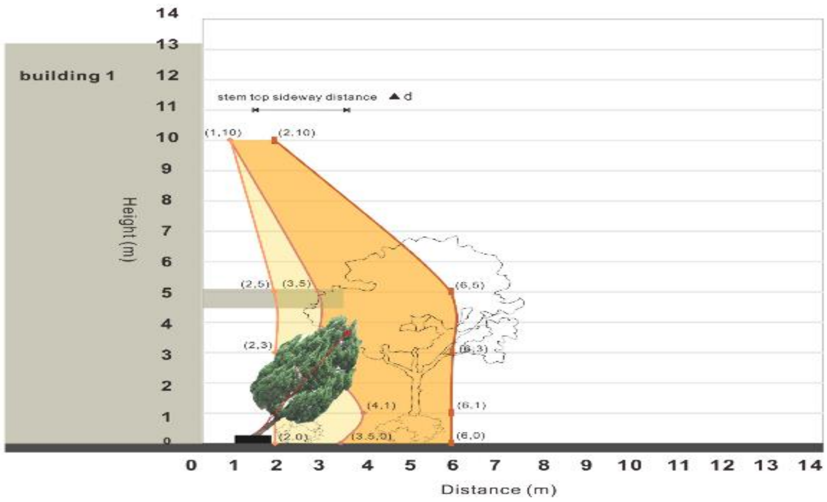
When the sunshine duration maps of the section A and B are overlapped, as shown in Fig. 7, one can easily observe the difference between the two. At vernal/autumnal equinoxes, the distributions are obviously dissimilar at the section A and B of the portico. As we can see in Fig. 7(a), the sunshine hour distribution near the section A of the portico was influenced by the shade effect of the three-story building itself, but it was rarely affected by the portico itself or the ten-story building. The recommended planting location at equinoxes for a popular shrub, with a growth height of less than 1 m, is 3 m away from the building on the section A. However, if one would like to set the plant on the section B of the building, the location of the plant stand should be set at least 6 m away from the building so that the plant has at least the required four hours of sunlight as also can be observed from Fig. 4.

In comparison with the vernal/autumnal equinoxes, at the summer solstice a smaller area was covered by the building's shadow and the variation of the shadow pattern by the portico was less notable at heights less than 5 m, as shown in Fig. 7(b). However, shadow patterns at heights greater than 5 m were different between the section A and B; this was attributable to the extension of the shadow of the ten-story building at the afternoon. Another intriguing point was the elevation of 1 m at the section B of the portico where the more shaded area was observed. It is counterintuitive that less area would be shielded as the height increased. Actually, the real condition can be obtained only by careful consideration of the buildings located farther afield.

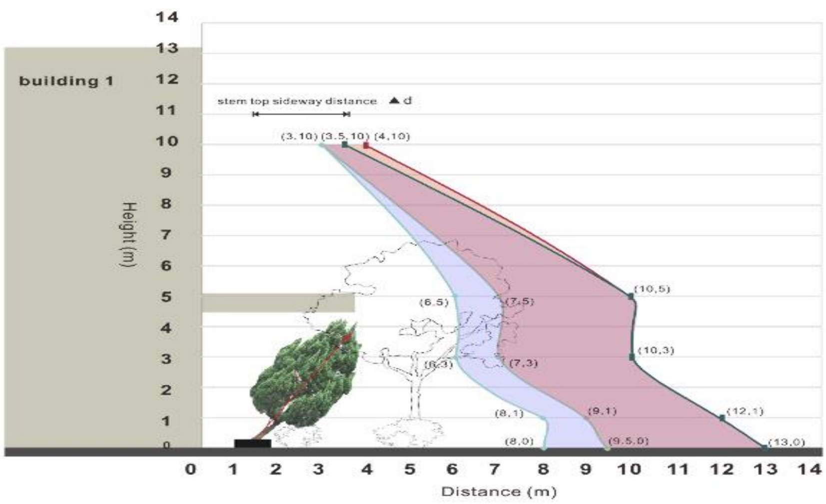
Taiwan is located in a subtropical region, and high temperatures usually persist throughout the summer. It has often been suggested that creating shade by planting trees was a useful approach to change the microclimate of the adjacent buildings. When the proper amount of shade is provided by buildings, it is



(a)



(b)



(c)

Fig. 7 The overlapped EVSH curve of the section A and B at different seasons. (a) at the vernal/autumnal equinoxes (b) at the summer solstice (c) at the winter solstice. Drawing outlines represent the better location for planting a sun-shade tree or a shrub.

advantageous for the plants. As shown in Fig. 7(b), placing plants 6 m away from the building does not allow the building to provide sufficient shade for the shade plants, so it was preferable to locate shade plants within 6 m away from the buildings.

At the winter solstice, the duration of the sunshine on the north side of the building was insufficient when it was originally determined. Taking 4 hours as the expected value, the distance required was at least 13 m away from building, reaching to the basketball court, as shown in Figure 7(c). Due to the low solar elevation angle in winter, most sunlight is blocked by the building, and a great increment of shadow length was observed; therefore, the shadow created by the portico was minor, and the difference of the sunshine hour distribution at the section A and B was not significant. On the other hand, in order to make better use of sunlight and to save heating energy, generally, it was realized that placing deciduous plants alongside a building would not block the natural lighting of the windows in winter.

Through the analysis of the distribution of sunshine duration from vernal to autumn, we can conclude 5 m away the building was the better location for planting a sun-shade tree. Moreover, shrub should be planted 2-3 m and 4-6 m away from the building at the sides A and B respectively to obtain the same sunshine hours. As noted above, this design approach was a not symmetrical layout. If plants are planted without considering the duration distribution of sunshine, the growth conditions and the ornamental quality of the plants could not achieve the desired effect. This approach helps for the rapid creation of unique and imaginative landscape designs, and decreased costs for maintenance.

4. Conclusions

In the northern hemisphere, most areas on the north side of buildings are faced with the problem of insufficient sunlight. However, a green and beautiful entrance scene can be constructed successfully so long as ornamental plants with shade tolerance are placed at proper distances from the building. In this work, we present the EVSH curve as a novel concept to review the required sunshine conditions for greening around a building. The ESVH curve can also be applied in reducing the maintenance cost of the plants in the built environment and for mastering the guidelines of “sustainable landscape design” before the commencing with the construction. In particular involving the concept of the EVSH curve for the layout design of roadside trees, flower beds, and plaza greenery in urban environment, one can determine the relevant conditions in advance as follows: (1) Sun plants or shade plants to be selected (2) The proper planting distances from buildings (3) Plant height and expected growth height (4) Planting seasons and ages of tree.

Three of the findings from simulation and on-site observation are worth summarizing:

4.1 Visualized Quantitative Data Was Beneficial for Landscape Design in Helping to Make Decisions According to Local Conditions

Planting design and arrangement in accordance with local conditions are important. Conventionally, the meteorological data in a contained environment such as a greenhouse was monitored on a regular basis in order to know the optimal region for the trees and flowers. However, due to the city’s varied topography and building patterns, weather conditions may vary from block to block. It is always laborious and costly work to acquire long-term meteorological data in a built environment to determine the optimal species of plants adapted to the different light conditions. The computer simulation techniques involved in making such an extrapolation can be quite effective and accurate. In the study, the visualized sunshine maps reveal that not only shade effect of the three-story building (building 1) but also the shade effect from building 2 and 3 should be taken into consideration; moreover, sunshine hours at different elevations were also displayed for evaluating their growth conditions. As far as the case is concerned, arbor planting in a symmetrical configuration did not coincide with the symmetrical sunshine condition. At the left side of the portico side B, the sunlight distribution resulted in an adverse situation for the growth of grass and shrubs, and one solution for the situation was to cultivate ornamental plants with shade tolerance.

4.2 Vertical Elevation Effect on the Light Environment: Arbor-Shrub-Grass

Generally, the canopy layer of arbor is the main area for photosynthesis, and the direction of plant growth is also modified by the light environment. In this case, the *Juniperuschinensis* lean outward to the EVSH curve; moreover, the sparseness of branches and leaves of *Juniperuschinensis* can be observed in the shaded area, as shown the pictures in Fig. 2. The multi-layer planting approach was a promoted index in the field of green building design. In order to reach the maximum greening effect, the comprehension of the vertical sunshine distribution is an essential task during the design, and the developed EVSH curve could provide an alternative approach to expand the design in scope and depth based on this quantitative analysis in the future.

4.3 Construct a Plant "Light Comfort Zone" to Promote "the Optimal 4-D design"

Since four clearly distinct seasons is the characteristic of the climate of subtropical zones, the impacts of creating shade in sunshine conditions obviously vary with the different seasons. The four dimension (4-D) light environment including space and the seasonal change for plant growth is worthy of detailed analysis. In summer, the overheated period in Taiwan lasts 2-3 months. If one can take the advantage of the shading effect from the buildings, it would be possible to transform limits to positive potentialities for plant growth. To reveal the facts hidden in the ecosystem by observation is one meaning of the "visual ecology" in a built environment [15]. It is a powerful method to construct a mutually beneficially environment between nature and design.

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