Urban Forestry & Urban Greening 29 (2018) 49–57

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Assessment of light adequacy for vertical farming in a tropical city

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ARTICLE INFO

Keywords:
Built environment
Daily light integral
Photosynthetically active radiation
Urban agriculture
Plant physiology
Leafy vegetables

ABSTRACT

The pursuit of urban agriculture as part of a city's green infrastructure is often a challenge, particularly within compact cities, where there is a limited amount of space between buildings for urban farming and gardening. Instead, such high-rise urban developments present often under-utilized spaces on the vertical surfaces of buildings. A key unknown is the adequacy of light for plant growth. Many leafy vegetables that require high amounts of light form a significant proportion of the staple diet in many Asian countries. We report on the assessment of sunlight adequacy for growing leafy vegetables in a compact tropical city, based on the high-rise and high-density residential environment of Singapore. Leaf physiological traits of seven leafy vegetables were assessed and used to estimate plant light requirements. A survey of photosynthetically active radiation (PAR) along exposed corridors showed that the daily light integral (DLI) value ranged from 2 to 35 mol m^{-2} d^{-1} under relatively ideal weather conditions during days with abundant solar insolation, and façades that experienced a minimum of half-day direct insolation matched the light requirements of vegetables within the moderate to very high-light categories. With regard to the building form, PAR increased gradually with height, but remains highly influenced by façade orientation and configuration. Owing to the annual north–south oscillation of the sun's path, reduced annual PAR variability and higher total annual PAR at façades, buildings with an east–west orientation will better support continuous vegetable cultivation, especially for basic building typologies without self-shading configurations. However, excessive PAR and temperatures during mid-day hours may hinder plant growth. By highlighting such patterns in levels of PAR, this study confirms the potential for high-rise and high-density conditions in the tropics to support farming using typically under-utilized vertical spaces of residential buildings.

1. Introduction

The rise of urban agriculture as an important form of green infrastructure has accompanied global efforts to increase the sustainability and resilience of cities in recent years (Lin et al., 2017). Indeed, negative pressures on food supply have led to the practice of urban farming as a possible strategy to improve food security by complementing rural agriculture in supplying food to urban dwellers. This typically includes ground-level farming or gardening in private, rooftop, or community gardens. However, these are often challenging to undertake in compact cities, where there are limited amounts of interstitial green spaces between buildings and competing demands on rooftop spaces for building utilities. Given these constraints, under-utilized vertical spaces along building façades have been explored for the implementation of vertical farming such as conventional low-cost micro-gardening, building-integrated edible landscaping, as well as vertical greenhouse systems (Kalantari et al., 2017).

In spite of the technological feasibility and desirability of vertical farming, one key unknown is adequacy of light for plant growth; in particular, photosynthetically active radiation (PAR) between 400 and 700 nm of the solar spectrum (Ross and Sulev, 2000). Studies have shown that the distribution of instantaneous PAR (measured as photosynthetic photon flux density or PPFD, in μmol m^{-2} s^{-1}) differs significantly from sunshine-hour duration (Mercado et al., 2009; Tan et al., 2015a). Hence, knowledge of PAR conditions in the environment can help us better understand the potential for growing plants that require high amounts of light, such as leafy vegetables (Faust, 2002; He, 2015). The light requirements for ornamental plants, turf grasses, and several plant crops are known (Torres and Lopez, 2010; Warrington and Norton, 1991; Wolff and Coltman, 1990), often expressed as the cumulative daily PAR (mol m^{-2} d^{-1}) over a 24-h photoperiod, or the "Daily Light Integral" (DLI) in production horticulture. However, there

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Abbreviations: N, north-facing façade; *S*, south-facing façade; *EN*, east-facing façade with northward obstruction; *ES*, east-facing façade with southward obstruction; *WN*, west-facing façade with northward obstruction; *WS*, west-facing façade with southward obstruction

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https://doi.org/10.1016/j.ufug.2017.11.004
Received 5 July 2017; Received in revised form 4 November 2017; Accepted 6 November 2017

is little information for the vegetables that form a significant proportion of the staple diet in many Asian countries (Ooraikul et al., 2008).

With a high abundance of sunlight in the tropics, studies have assessed PAR conditions at interstitial building spaces in dense urban environments (Tan et al., 2015a, 2014), and explored the suitability of rooftop spaces for the growth of leafy vegetables (Astee and Kishnani, 2010; He, 2015). However, limited research has investigated the suitability of the light environment along vertical spaces, which are highly affected by building form and spatial factors that influence shading patterns and the availability of direct and diffused incident radiation (Hii et al., 2011; Valladares-Rendón and Lo, 2014). PAR is also subject to both diurnal and annual temporal variations which depend on factors such as time of day, weather, as well as seasonal variability caused by the annual solar cycle. The ability of vertical spaces to support the growth of vegetables is thus an unknown and a possible limitation to urban farming, even under high light conditions in the tropics.

The aim of this study was to evaluate the spatio-temporal characteristics of PAR for growing leafy vegetables at high-rise vertical spaces, using tropical Singapore as a case-study location. Amongst compact cities across the world, Singapore is an example of a city-state that lacks a domestic hinterland for agricultural self-sufficiency through conventional farming. A significant portion of unused vertical space in Singapore includes exposed corridors, balconies, and windows along the building façades at high-density, high-rise public housing residential estates. There are thus opportunities to explore the suitability of PAR conditions along these vertical spaces, and the suitability of such environments for vertical farming. The specific objectives of the study were: (1) Investigate the effect of building form (height, configuration, and façade orientation) on PAR, along exposed accessible corridors of public housing apartment block façades; (2) Estimate the DLI requirements of selected vegetable crops based on leaf physiological traits, and (3) Assess the suitability of such spaces in providing adequate PAR for optimal growth of vegetables.

2. Materials and methods

2.1. Leaf-level gas exchange analysis

Table 1 shows varieties of fast-growing leafy vegetables grown and sold in Singapore and Southeast Asia (Herklots, 1972; Jansen et al., 1993; Kok et al., 1991), which were grown at the National University of Singapore Native Plant Nursery (1°17′43.9“N 103°46′28.4“E) over the course of six weeks from September–October 2015. Local seed varieties from Ban Lee Huat Seed Pte Ltd were used. Black netting was used to reduce excessive radiation to approximately 75% of unshaded conditions. The DLI value within the nursery typically ranged from 5 to 25 mol m^{-2} d^{-1}, with an average of 12–14 mol m^{-2} d^{-1}.

Leaf photosynthetic responses were measured using an open-flow CO_2 gas exchange system (LI 6400, Li-Cor Inc., Lincoln, Nebraska, USA) fitted with the standard leaf chamber, CO_2 injector system and red/blue LED light source (6400–02 B LED). Measurements were made upon the maturation of each crop type, within the edible phase of the growing period. Measurements were taken for the youngest mature leaves of three different individuals per crop type from 0800 − 1700 h. To derive the light response curve, stepwise changes made in PPFD were made in the following order: 250, 100, 50, 25, 250, 500, 750, 1000, 1500, 2000, 2500 μmol m^{-2} s^{-1}. In order to create stable measurement conditions, measurements were made under a block temperature of 28 °C, constant CO_2 level of 360 μmol mol^{-1}, and an air-flow rate adjusted between 300 and 500 μmol s^{-1} to reduce the effect of humidity on measurement error. Leaves were allowed to acclimatise for 2–5 min at each PPFD level, and measurements were logged after readings had stabilized. Using the non-linear regression function in R 3.2.3 (R Core Team, 2015), measurements obtained for each individual were fitted to a non-rectangular hyperbola formula described in Baltzer and Thomas (2007) to derive a modelled light response curve. R^2 larger than 0.97 was achieved for all the fitted light response curves for each individual measured. From the fitted functions, the key variables of the light response curve, namely the light saturation point (LSP) and light compensation point (LRC) were estimated alongside other physiological variables. Duncan's new multiple range test was used to test for significant differences between crops.

Table 1
List of vegetable crops selected for analysis.

Vernacular Name	*Botanical Name*
Bayam (Chinese spinach or red amaranth)	*Amaranthus tricolor* L.
Cai xin (Chinese flowering cabbage)	*Brassica rapa* L. subsp. *chinensis* (L.) Hanelt var. *parachinensis* (L. H. Bailey) Hanelt
Chinese cabbage (Napa cabbage)	*Brassica rapa* L. subsp. *pekinensis* (Lour.) Hanelt
Kailan (Chinese kale)	*Brassica oleracea* L. var. *alboglabra* (L. H. Bailey) Musil
Kang kong (Water spinach/ convolvulus)	*Ipomoea aquatica* Forssk.
Lettuce	*Latuca sativa* L.
Pak choy (Chinese chard)	*Brassica rapa* L. subsp. *chinensis* (L.) Hanelt

Commercial greenhouse production utilizes supplementary lighting to achieve constant PAR levels that match plant's DLI requirements (Torres and Lopez, 2010). Based on this approach, the DLI requirements for each crop were estimated based on the equations:

$$\text{Target DLI} = \text{mean LSP at 70\% of maximum photosynthesis} \times 0.0432$$

$$\text{Maximum DLI} = \text{mean LSP at 85\% of maximum photosynthesis} \times 0.0432$$

where the target DLI value is the level of cumulative PAR over a 12-h photoperiod required for daily growth. It was calculated based on the LSP at 70% of maximum photosynthesis, as there were insufficient differences between crop LSP values at lower percentages. The maximum DLI value is the maximum level of cumulative PAR over a 12-h photoperiod for daily growth. It was calculated based on the LSP at 85% of maximum photosynthesis, as higher percentages resulted in unreasonably high PFFD values (i.e., 3000–7000 μmol m^{-2} s^{-1}). The value 0.0432 represents the conversion factor for PAR (μmol m^{-2} s^{-1}) to DLI value (mol m^{-2} d^{-1}) over a 12-h photoperiod.

These equations assume an ideal, controlled environment for factors such as temperature and humidity, that the crops grow optimally at constant PAR levels throughout a 12-h photoperiod, and that fluctuations in the PFFD are minor and do not exceed levels that negatively affect the crops. Unlike woody plants, leafy vegetables are relatively small, less morphologically complex, and do not invest significant amounts of photosynthates for structural growth and the formation of woody tissues (Chapin et al., 1990). Also, increased light requirements with plant age owing to self-shading and phenology is less pronounced in vegetable crops, because of their relatively short edible growth phase and life span (Gerrish, 1990; Thomas and Wien, 1997). Thus, it was assumed that the leaf-level LSP is a reasonable estimate of the whole-plant light saturation point (Baltzer and Thomas, 2007).

2.2. PAR measurement and analysis

This study examines the effect of building form (i.e. height, configuration, and façade orientation) on PAR. Amongst the diverse public housing building typologies in Singapore, basic configurations such as Linear, Point Block and L-shape block arrangements built before the 1990s generally provide more predictable conditions, because of minimal self-shading building geometry and more spacious, exposed corridors suitable for micro-gardening. Apartment blocks 861, 861A, and 859 along Tampines Avenue 5 (1°21′17.5“N 103°56′15.5“E) with