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A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Estimation of Canopy Light Interception of Lettuce (*Lactuca sativa* L.) Grown under Reflective Surroundings and Artificial Lights with Different Blue and Red Compositions in Plant Factory

식물공장 내에서 주변 반사재질 및 서로 다른 적·청 조합의 인공광에서 자란 상추의 수광량 추정

BY

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AUGUST, 2013

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SEOUL NATIONAL UNIVERSITY

Estimation of Canopy Light Interception of Lettuce (*Lactuca sativa* L.) Grown under Reflective Surroundings and Artificial Lights with Different Blue and Red Compositions in Plant Factory

UNDER THE DIRECTION OF DR. JUNG EEK SON
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY

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Estimation of Canopy Light Interception of Lettuce (*Lactuca sativa* L.) Grown under Reflective Surroundings and Artificial Lights with Different Blue and Red Compositions in Plant Factory

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ABSTRACT

It is one of the most important topics among researches related to crop growth model to construct an accurate method for the estimation of crop light interception. The light environment is highly modified in recent horticultural facilities by the abundant use of artificial lights and reflective materials. Due to the difficulties in quantifying the effect of various light environmental factors, outstanding progresses have not been made in the development of models to estimate crop light interception available for the facilities. The aims of this study are to construct a model for the estimation, which reflects the critical light environmental traits of the facilities (Chapter I), and to verify the reliability and applicability to the existing crop growth model (Chapter II). The light environment of a plant factory was analyzed and a new model was constructed based on the result in the Chapter I. The model estimations for lettuce light interception were compared to actual crop

light interceptions, which were measured and calculated using artificial lettuce and modified Nicolet model, and applied to original Nicolet model to investigate the effect on the entire crop growth model at Chapter II. As a result, ambient light environment, such as ground reflectance and the proportion of diffuse light, was shown to have significant influences on overall crop light interception. And, it was possible for the new model to estimate the immediate and accumulative crop light interception with a maximum RRMSE of 11% and to complement original Nicolet model for the accuracy of estimation. This ultimately indicates that it is required to change a conventional paradigm of light environmental control in the plant factory or growth chamber which manages the light environment with a single factor of initial light intensity. In addition, it suggests a simple methodology available for recent horticultural facilities to quantify the effect of changes in the light quality on crop light interception with a single factor of 'b/a ratio', and the ideotype canopy.

Additional key words: lettuce, light interception, plant factory, light quality, light distribution, crop model, extinction coefficient, ground reflection, diffuse light, ideotype canopy, b/a ratio

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INTRODUCTION

The crop growth model plays a critical role in planning and managing the production for many recent horticultural facilities, which adopt various light manipulation techniques, such as artificial lights and optical materials, to optimize the productivity (Heuvelink et al., 2006; Marcelis et al., 2002; Hemming, 2008). The light quality and distribution highly affect crop light interception, and consequent growth (Elings et al., 2012; Hogewoning et al., 2010c). The quality of light is involved in the plant morphogenesis, and different spectra have different influences on the morphology with which the light distribution affects crop light interception interdependently (Goudriaan, 1988). Because of the complexity and difficulties in quantifying the effect of light quality and distribution on the light interception, many of the traits were excluded in previous crop modeling researches despite the potential risk of resultant estimation error (Hogewoning, 2010a).

Except for the effect on photosynthetic efficiency, botanical researches on light quality have mainly focused on qualitative analysis. (Kim et al., 2004; Ohashi-Kaneko et al., 2007; Shimizu et al., 2011; Stutte and Edney, 2009) This caused mutually conflicting results and explanation among researches due to the dependence of subjective interpretation, and as a result, the applicability of those has been fairly limited. On the other hand, quantitative studies have normally adopted mathematical models, constructed on the basis of solar radiation, to suggest objective interpretation and to forecast crop growth. However, the majority

of those focused on particular cases or partially applied overall effects of light quality and distribution on crop biology. (Cavazzoni et al., 2002; Trouborst et al., 2010; Paradiso et al., 2011) In addition, although light profile inside recent horticultural facilities essentially differs from traditional cultivation site, many of the unique light environmental traits have been excluded.

Given close relation between light quality and plant morphology, the effects of light quality and distribution on crop light interception are simultaneous and dynamic (Goudriaan, 1988; Papadopoulos and Pararajasingham, 1997). Therefore, it is required to consider and apply both effects in a comprehensive and dynamic manner. This study is aimed at constructing a reliable methodology to estimate crop light interception and its effect on the growth, which reflects inherent light environmental features of the latest horticultural systems.

LITERATURE REVIEW

The effect of light quality on the plant growth

The light quality affects the plant growth through changes in the efficiency of net carbon assimilation and of light interception of the canopy. (Hogewoning *et al*, 2010a) Blue light was reported to promote the development of sun-type leaves, the higher accumulation of leaf mass per unit leaf area (LMA), and thereby the increase of photosynthetic rate (Poorter *et al*., 2009; Hogewoning *et al*, 2010b). Such a phenomenon was commonly observed for rice, wheat and cucumber (Matsuda *et al*., 2004; Goins *et al*., 1997; Hogewoning *et al*., 2010b).

On the other hand, blue light was shown to inhibit the expansion of leaf area in an experiment with lettuce, which could negatively affect the growth (Johkan *et al*., 2010; Brazaityte *et al*., 2006). Ohashi-Kaneto *et al*. (2007) observed a higher accumulation of biomass in lettuce grown under monochromic red light alone than under a mixture of blue and red light, for which the inhibition of leaf expansion and consequent light interception by blue light mainly accounted. Contrarily, in another experiment with lettuce, the lower dry weight was observed under monochromic red light, and the unfavourable canopy form for light interception induced by the light treatment was presumed to be the main reason (Stutte and Edney, 2009).

Although the importance of light quality in the determination of crop light interception and consequent growth was repeatedly emphasized as stated, the extent of light spectral effect on the light interception is still in question due to the

absence of effective method for the measurement. As a result, the applicability and consistency of results from related studies were fairly limited.

Previous modeling researches to estimate crop light interception

Various models were developed to explain and calculate the effect of external and internal factors of the plant canopy on the light interception based on natural solar radiation. Most of quantitative researches on crop light interception have underlain modified Lamber-Beer equation (Monsi and Saeki, 1953).

$$I_{int} = 1 - \exp(-K_{crop} \cdot LAI) \tag{1}$$

where K_{crop} is the light extinction coefficient of crop canopy, and LAI is leaf area index ($m^2 \cdot m^{-2}$).

Goudriaan and Van Laar (1994) suggested equations to estimate crop light interception according to changes in the ambient light environment and leaf optical properties, such as proportion of diffuse light, ground reflectance and leaf scattering coefficient [eqns (2)-(14)].

$$\sigma_{leaf} = \tau_{leaf} + \rho_{leaf} \tag{2}$$

$$K_{crop} = K_{bl}\sqrt{1 - \sigma_{leaf}} \tag{3}$$

$$\rho_{c,horiz} = \frac{1 - \sqrt{1 - \sigma_{leaf}}}{1 + \sqrt{1 - \sigma_{leaf}}} \tag{4}$$

$$\rho_c = \frac{2 \cdot K_{bl}}{K_{bl} + K_{bl,diff}} \cdot \rho_{c,horiz} \tag{5}$$

where τ_{leaf}, leaf transmittance; ρ_{leaf}, leaf reflectance; σ_{leaf}, leaf scattering coefficient; K_{bl}, the extinction coefficient of black leaf; $K_{bl,diff}$, K_{bl} for diffuse light; ρ_c, reflectance of crop canopy; $\rho_{c,horiz}$, ρ_c with horizontal leaf distribution.

And, in order to quantify the effect of ground reflection, light balance inside a cultivation site was divided into and expressed as four radiation fluxes, i.e. upward ($\varphi \uparrow$) and downward flux ($\varphi \downarrow$), and before (φ_1) and after ground reflection (φ_2) [eqns (6)-(11)].

$$\varphi \downarrow_L = \varphi \downarrow_{1,L} + \varphi \downarrow_{2,L} \text{ and } \varphi \uparrow_L = \varphi \uparrow_{1,L} + \varphi \uparrow_{2,L} \tag{6}$$

$$\varphi \downarrow_{1,L} = \frac{\varphi \downarrow_0}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(-K \cdot L) \tag{7}$$

$$\varphi \downarrow_{2,L} = \frac{\varphi \downarrow_0 \cdot \eta \cdot \exp(-2K \cdot LAI)}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(K \cdot L) \tag{8}$$

$$\varphi \uparrow_{1,L} = \frac{\varphi \downarrow_0 \cdot \rho_c}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(-K \cdot L) \tag{9}$$

$$\varphi \uparrow_{2,L} = \frac{\varphi \downarrow_0 \cdot \eta \cdot \exp(-2K \cdot LAI)/\rho_c}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(K \cdot L) \tag{10}$$

$$\eta = \frac{\rho_c - \rho_s}{\rho_s - 1/\rho_s} \tag{11}$$

where $\varphi \downarrow_0$, initial downward flux; ρ_s, reflectance of soil or ground; L, partial LAI from the considered level upward ($m^2 \cdot m^{-2}$).

Three major zones approach was used to calculate the effect of diffuse light on the light interception [eqns (12) and (13)].

$$\varphi \downarrow_{diff} = \varphi \downarrow_{0,diff} \{w_{15} \cdot \exp(-K_{15} \cdot L) + w_{45} \cdot \exp(-K_{45} \cdot L) + w_{75} \cdot \exp(-K_{75} \cdot L)\} \quad (12)$$

$$K_{diff} = -\ln(\varphi \downarrow / \varphi \downarrow_0)/L \quad (13)$$

where K_{diff} is the light extinction coefficient for diffuse light, and $K_{15,45,75}$ is the extinction coefficient at the elevation angle of 15, 45 and 75°, respectively.

Campbell (1986) constructed ellipsoidal leaf distribution model to apply morphological traits of individual crops to the extinction coefficients, while Goudriaan and Van Laar (1994) calculated the coefficient mostly assuming that crop canopies are commonly circular. Campbell's model assumed the crop canopy to be ellipsoidal and calculated the extinction coefficient with the ratio of vertical radius to horizontal radius (hereafter, b/a ratio).

The fact that various models were already developed and verified on the basis of natural sunlight indicates that it is possible to construct a methodology to estimate crop light interception under highly modified light environment, as in the plant factory, by modifying and integrating these models. However, it is necessarily required to verify the reliability and accuracy of the integrated version which consists of models developed by mutually independent studies.

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CHAPTER I

A model for canopy light interception of lettuce as affected by light quality and reflectance in a plant factory

ABSTRACT

- *Background and Aims* The light environment of the crop cultivation site is a critical factor in the determination of crop light interception and consequent growth. Due to the increased use of artificial light sources and reflective materials, recent horticultural facilities have different light environments, in terms of light quality and distribution, from traditional facilities, which depend mostly on natural sunlight. Both light quality and distribution affect crop light interception in an interdependent and simultaneous manner. This complex interaction and the difficulty of quantification have hindered the progress of research in estimating canopy light interception in the horticultural facilities. Our research is aimed at constructing a methodology to estimate and explain the effect of light quality and distribution on crop light interception in plant factories and other horticultural systems with similar light profiles.

- *Model* A new mathematical model was developed based on experiments with lettuce grown under different light qualities in a plant factory. Changes in the light conditions and crop morphology were quantitatively applied to the

new model, on the basis of existing models with or without partial modification.

- *Key results* The simulation results indicate that canopy light interception can significantly vary with reflectance of the surroundings or proportion of the diffuse light as well as the light quality. They also show that the highly reflective surroundings complement unfavourable canopy form for light interception.

- *Conclusions* It is inappropriate to manage the light environment simply based on the initial light intensity, which is general for experiments in plant factories or growth chambers, and it is essential to consider the effects of other light environmental factors comprehensively and simultaneously to understand the overall picture.

Key words: lettuce, light interception, plant factory, light quality, light distribution, crop model, extinction coefficient, ground reflection, diffuse light

INTRODUCTION

Artificial light sources have widely been adopted in various horticultural facilities including greenhouses because of the contribution to year-round production and product quality (Heuvelink *et al*., 2006; Marcelis *et al*., 2002). However, the spectral composition of the artificial light source is significantly different from that of natural sunlight, and different light spectra have different influences on plant biology (Fujiwara and Yano, 2011). Additionally, covering, mulching, and structural materials facilitate the reflection and diffusion of incident light inside the facilities, which change the light distribution inside cultivation sites and, as a result, crop light interception and growth (Boderson *et al*., 2007; Sarlikioti *et al*., 2011). Therefore, it is essential to understand and quantify the effects of light quality and distribution on crop light interception in order to interpret and forecast the growth in these facilities.

Hogewoning *et al*. (2010b) suggested that light quality could be the most decisive factor in the determination of crop light interception and growth through experiments with cucumber plants and artificial lights. From experiments with lettuce, it was reported that the average dry weight was higher for crops grown under a mixture of blue and red light than under monochromic red light, due to the unfavourable form of the canopy for light interception induced by the single red light (Stutte and Edney, 2009). In contrast, another study observed a higher accumulation of biomass in lettuce under red light alone, which was presumably caused by the inhibition of leaf expansion under the blue light (Ohashi-Kaneto *et*

al., 2007). While the importance of light quality and its effect on light interception has been emphasised repeatedly as stated above, the consistency between results and the applicability of studies have been fairly limited as many of them focus on specific cases or qualitative analysis.

Most quantitative studies on plant light interception are based on mathematical models constructed under the natural sunlight base. For example, Monsi and Saeki (1953) suggested a model for the estimation of light interception by modifying Lambert-Beer's law, Campbell (1986) constructed one for the calculation of the extinction coefficient considering canopy shapes, and Goudriaan and Van Laar (1994) suggested equations to apply the effects of diffuse light and ground reflection on it. Although various studies have attempted to estimate the light interception inside recent horticultural facilities by adopting these established models, the majority were focused on certain cases or partial application of the overall effect of the change in light quality and distribution (Cavazzoni *et al*., 2002; Trouborst *et al*., 2010; Paradiso *et al*., 2011). Additionally, many critical factors, such as the complex interaction between light quality and distribution and the inherent characters of locally fixed artificial light compared to natural sunlight, were excluded.

Under locally fixed light sources, the intensity of light directly incident on the canopy increases as the plants grow, since it is proportional to the square of the distance between the light source and objective (Jacob and Dranoff, 1970). On the contrary, the intensity of light incident on the canopy after wall or ground

reflection decreases as time passes due to the expansion of the wall and ground area covered by the leaves. Due to this, the distribution of light inside these recent horticultural facilities changes continuously as the plant grows, and the extent and direction are closely interrelated with the quality of the light which is involved in plant morphogenesis. Therefore, in estimating the light interception, it is essential to apply the effects of both light quality and distribution on the physiology of the plant comprehensively and dynamically; partial application of these can distort the results. In this study, we analysed the light profile and crop growth in a plant factory, which is among one of the highest users of artificial light and reflective surroundings among the latest horticultural facilities, in order to construct a model reflecting the critical light environmental features.

MODEL DESCRIPTION

Main structures

The light interception of the crop canopy (I_{int}) with leaf area index (LAI) of n can be calculated by subtracting the emitted fraction outside the canopy ($\varphi \uparrow_0$) and the absorbed or transmitted fraction by the ground ($(1-\rho_s)\cdot\varphi\downarrow_n$ or $\varphi\downarrow_n - \varphi\uparrow_n$) from the initial incident light ($\varphi\downarrow_0$) [Fig. I-1, eqn (1)]. Light interceptions from direct and diffuse fractions of initial downward flux were calculated separately due to the different extinction coefficients [eqn (2)]. Once emitted outside the canopy, the fraction was assumed to be extinguished.

$$I_{int} = \varphi\downarrow_0 - \varphi\uparrow_0 - (1-\rho_s)\cdot\varphi\downarrow_n \text{ or } \varphi\downarrow_0 - \varphi\uparrow_0 - (\varphi\downarrow_n - \varphi\uparrow_n) \quad (1)$$

$$I_{int,total} = I_{int,dir} + I_{int,diff} \quad (2)$$

Each upward flux ($\varphi\uparrow$) and downward flux ($\varphi\downarrow$), consisting of the total light balance in the cultivation site, was divided into the fraction before ($\varphi\uparrow_1, \varphi\downarrow_1$) and after ground reflection ($\varphi\uparrow_2, \varphi\downarrow_2$) and calculated individually by the equations suggested by Goudriaan and Van Laar (1994) [eqns (3), (4), (5), (6), (7), and (8)].

$$\varphi\downarrow_L = \varphi\downarrow_{1,L} + \varphi\downarrow_{2,L} \text{ and } \varphi\uparrow_L = \varphi\uparrow_{1,L} + \varphi\uparrow_{2,L} \quad (3)$$

$$\varphi\downarrow_{1,L} = \frac{\varphi\downarrow_0}{1+\eta\cdot\exp(-2K\cdot LAI)}\cdot\exp(-K\cdot L) \quad (4)$$

$$\varphi \downarrow_{2,L} = \frac{\varphi \downarrow_0 \cdot \eta \cdot \exp(-2K \cdot LAI)}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(K \cdot L) \tag{5}$$

$$\varphi \uparrow_{1,L} = \frac{\varphi \downarrow_0 \cdot \rho_c}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(-K \cdot L) \tag{6}$$

$$\varphi \uparrow_{2,L} = \frac{\varphi \downarrow_0 \cdot \eta \cdot \exp(-2K \cdot LAI)/\rho_c}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(K \cdot L) \tag{7}$$

$$\eta = \frac{\rho_c - \rho_s}{\rho_s - 1/\rho_s} \tag{8}$$

The equations are based on natural sunlight conditions and assume the same extinction coefficient for both primary incident light from the light source and secondary incident light from the ground reflection. However, while the sun continuously rotates along the celestial sphere during the day and has a variety of incidence angles, fixed artificial light sources have a constant incidence angle of direct light that can significantly vary with the properties of the ground material once reflected by the ground. Specifically, the incidence pattern of reflected light is closely dependent on the light-scattering (haze) factor of the ground material. Consequently, it is necessary to consider using a different extinction coefficient (K_{diff}) for the fraction reflected by ground when the haze factor is high [eqns (5b) and (7b)].

$$\varphi \downarrow_{2,L} = \frac{\varphi \downarrow_0 \cdot \eta \cdot \exp(-K \cdot LAI)}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp\{-K_{diff} \cdot (LAI - L)\} \tag{5b}$$

$$\varphi \uparrow_{2,L} = \frac{\varphi \downarrow_0 \cdot \eta \cdot \exp(-K \cdot LAI)/\rho_c}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp\{-K_{diff} \cdot (LAI - L)\} \tag{7b}$$

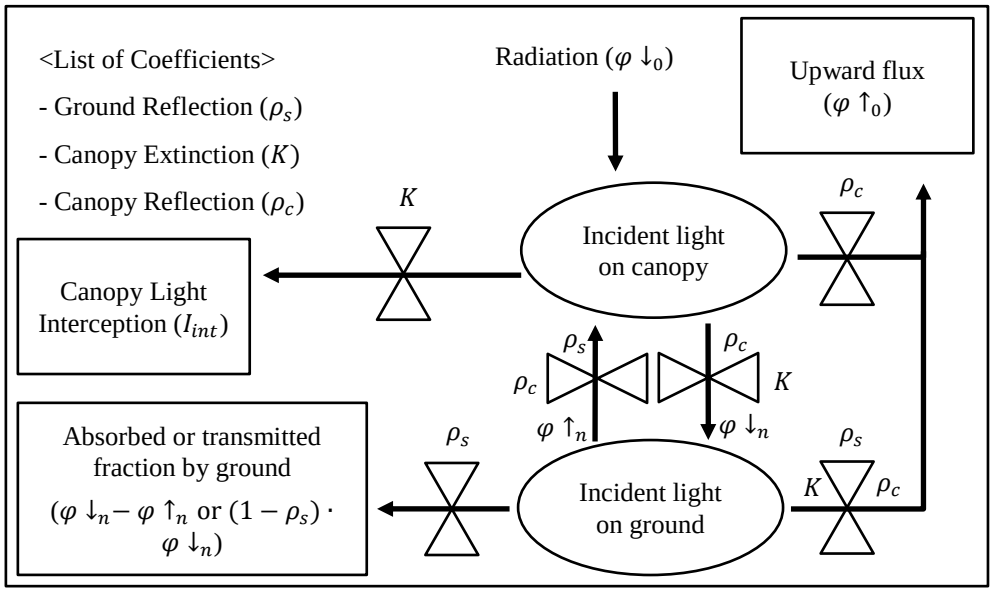

Figure I-1. Conceptual diagram of light balance in the cultivation site.

Estimation of the extinction, reflection, and scattering coefficients

The ellipsoidal model assumes the shape of an individual crop to be a prolate or an oblate spheroid, depending on the distribution of the leaf angle within the canopy (Campbell 1986). According to the model, the extinction coefficient can be calculated by the ratio of the horizontal radius (a) to the vertical radius (b) (hereafter, the 'b/a ratio'). In this study, Campbell's model was used for the estimation of the extinction coefficient of crops grown under different light quality for the quantitative application of the morphological differences [eqns (9), (10), (11), and (12)].

$$K_{bl} = \frac{(x^2 + 1/\tan^2 \phi)^{1/2}}{x + (1/2\epsilon_1 x)\ln[(1+\epsilon_1)/(1-\epsilon_1)]} \quad (if\, x \geq 1) \tag{9}$$

$$K_{bl} = \frac{(x^2 + 1/\tan^2 \emptyset)^{1/2}}{x + (\sin^{-1}\epsilon_2)/\epsilon_2} \quad (if\, x \geq 1) \tag{10}$$

$$\epsilon_1 = (1 - a^2/b^2)^{1/2} \text{ and } \epsilon_2 = (1 - b^2/a^2)^{1/2} \tag{11}$$

$$x = b/a \tag{12}$$

Extinction coefficients for diffuse light from wall and ground reflections, or from the diffusion of the downward and upward flux, were calculated using the three major zone approach [eqns (17) and (18)], and the optical parameters of the crop canopy were calculated with those of leaves [eqns (13), (14), (15), and (16)]. For all the calculations, equations suggested by Goudriaan and Van Laar (1994) were used.

$$\sigma_{leaf} = \tau_{leaf} + \rho_{leaf} \tag{13}$$

$$K_{crop} = K_{bl}\sqrt{1 - \sigma_{leaf}} \tag{14}$$

$$\rho_{c,horiz} = \frac{1 - \sqrt{1 - \sigma_{leaf}}}{1 + \sqrt{1 - \sigma_{leaf}}} \tag{15}$$

$$\rho_c = \frac{2 \cdot K_{bl}}{K_{bl} + K_{bl,diff}} \cdot \rho_{c,horiz} \tag{16}$$

$$\varphi \downarrow_{diff} = \varphi \downarrow_{0,diff} \{w_{15} \cdot \exp(-K_{15} \cdot L) + w_{45} \cdot \exp(-K_{45} \cdot L) + w_{75} \cdot \exp(-K_{75} \cdot L)\} \tag{17}$$

$$K_{diff} = -\ln(\varphi \downarrow / \varphi \downarrow_0)/L \tag{18}$$

Compensation of light intensity according to the vertical growth of the crop canopy

A quadric equation was used to estimate the relative light intensity against height, by which the intensity of incident light at time t ($\varphi \downarrow_{0,t}$) was compensated for longitudinal growth by time [eqns (19) and (20)].

$$\varphi \downarrow_{0,t} = \varphi \downarrow_{0,0} \cdot v \tag{19}$$

$$v = z_1 h^2 + z_2 h + z_3 \tag{20}$$

However, because the outermost section of the plant canopy, or the interface between the incident light and the crop, is not flat, there is a gap in the light

intensity between the apex of the plant and the average height of whole canopy. If it is assumed to be ellipsoidal, only the upper hemisphere would participate in light interception. From the viewpoint of geometry, the average height of all the points on the surface of the upper hemisphere can be explained as the height of a cylinder with the same volume and area of base [Fig. I-2, eqn (21)]. In this regard, it is possible to calculate the average height (h_m) with eqn (22), by which the new model estimates the coefficient to compensate light intensity for the vertical growth of the crop (v, hereafter 'vertical compensation factor') at each time point [eqn (20)].

$$a_m = 2/3 \cdot a \ \ (\because V = 2/3 \cdot b^2 \cdot a \cdot \pi = b^2 \cdot a_m \cdot \pi) \tag{21}$$

$$h_m = a_m + a = 5/3 \cdot a = 5/6 \cdot h \ \ (\because h = 2 \cdot a) \tag{22}$$

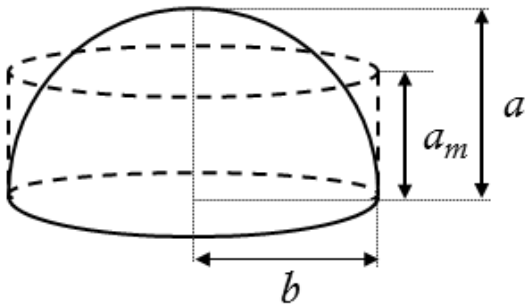

Figure I-2. Schematic description of the average height.

Experimental data for the parameter calculation

In order to obtain data for the parameter calculation, lettuce plants were grown in a vertical hydroponic plant factory (DFT) on 3 levels at Seoul National University, Korea. Seedlings were transplanted and grown under LED lamps with an initial light intensity of 166±3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (PAR) for 3 weeks. The temperature was maintained at 22 ± 1 °C during the day and 18 ± 1 °C during the night, and the light period (day) was 18 hours. EC 1.2 $dS \cdot m^{-1}$ of Yamazaki nutrient solution was applied. All treatment groups were divided into five groups by the red and blue light composition, namely 10:0, 9:1, 8:2, 7:3, and 5:5 (hereafter 'R10:B0', 'R9:B1', 'R8:B2', 'R7:B3', and 'R5:B5', respectively). The peak wavelengths of the light sources were 465 and 625 nm, respectively. In all, twelve plants were raised for each treatment group, and four were sampled to obtain base data for the parameter calculation.

The b/a ratios for the extinction coefficients were calculated by averaging the observed data during the experiment because the extinction coefficients were assumed to remain constant (Rawson *et al*., 1984; Tsubo *et al*., 2005; Takai *et al*., 2006). The horizontal radius of the canopy (b) was calculated using the area of the ground covered by the plant canopy, which was assumed to be circular and measured by image analysis software (ImageJ 1.45s, http://imagej.nih.gov/ij) with the image photographed in a perpendicular direction. ($A_{crop} = b^2 \cdot \pi$). The vertical radius was measured as half the length of the crop height. The leaf transmittance for scattering coefficient was measured with a photometer (LI-250A Light Meter,

Li-Cor, Lincoln, NE, USA) under growth light condition for each treatment group, where 3 leaves per plant were sampled and placed right above the sensor, avoiding the midrib.

For the calculation of accumulative light interception, the changes in average plant height and leaf area over time were estimated using the non-linear regression approach with the experimental data (Fig. I-5, Table I-1). Although the actual growth pattern of leaf area against time (t, day) showed an exponential curve, the highest R-square values were observed when it was fitted with the cubic equation [Fig. I-5A, eqn (23)]. However, in the case of the plant height, the highest R-square values were observed for either the cubic or sigmoid function among the treatment groups. As a result, cubic functions were used for the estimation of the leaf area and either cubic or sigmoid functions were used for plant height considering the R-square value [Fig. I-5B, eqn (24)].

$$LA = p \cdot t + q \cdot t^2 + r \cdot t^3 + y_0 \tag{23}$$

$$h\ (2a) = p \cdot t + q \cdot t^2 + r \cdot t^3 + y_0\ or\ y_0 + p/(1 + \exp(-(t - q)/r)) \tag{24}$$

For experimental cultivation and measurement of initial light intensity, each side of the cultivation sites was surrounded with stainless steel sheets, except for the entrance, which was covered with aluminium foil where the surface of the ground was covered with white acryl panels (Fig. I-3). Firstly, ground reflection was blocked with black acryl panels to calculate the ratio of the initial downward

flux to the initial light intensity (75%). Then, after elimination of the wall and ground reflectance with black covering materials and removal of the aluminium foil, the ratio of the wall reflection (ρ_w=0.1) was calculated. The fraction of direct light was calculated by subtracting the fraction of the wall reflection from the total downward flux as defined by eqn (26). Under the same conditions, light intensity was measured at 3 designated points in a cultivation site, increasing the height 7 times, to calculate relative intensity by height (Fig. I-4). Ground reflectance (ρ_s) was not obtained from this experiment because the body of the quantum sensor is made of black plastic, which could distort the data by absorbing part of reflected fraction of light from the ground (Fig. I-3).

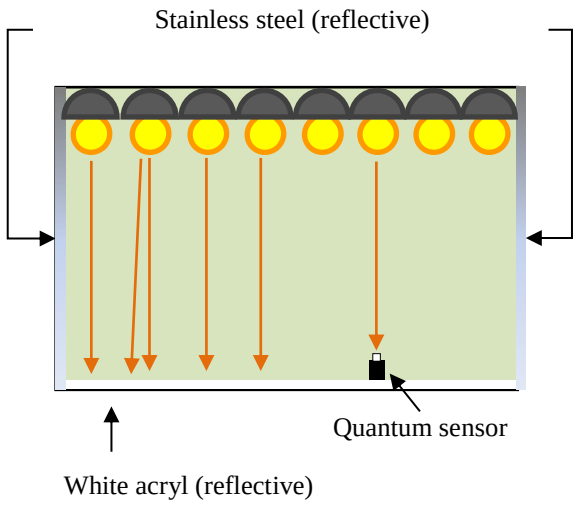

Figure I-3. Schematic description of the experimental cultivation site, a condition for measurement of initial light intensity.

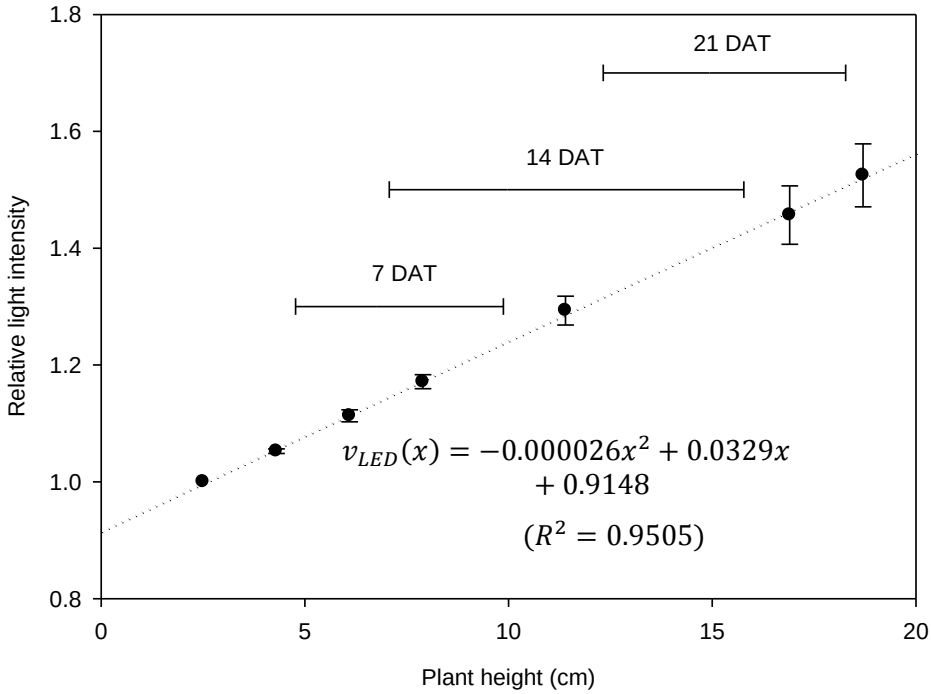

Figure I-4. Change of light intensity by height in the experimental cultivation site. The dotted line and equation indicate the regression model to estimate the relative increment of the light intensity by the longitudinal growth of plants [eqn (20)]. Vertical bar, mean SE (n=3). The horizontal bars represent the ranges of measured crop heights at each time point.

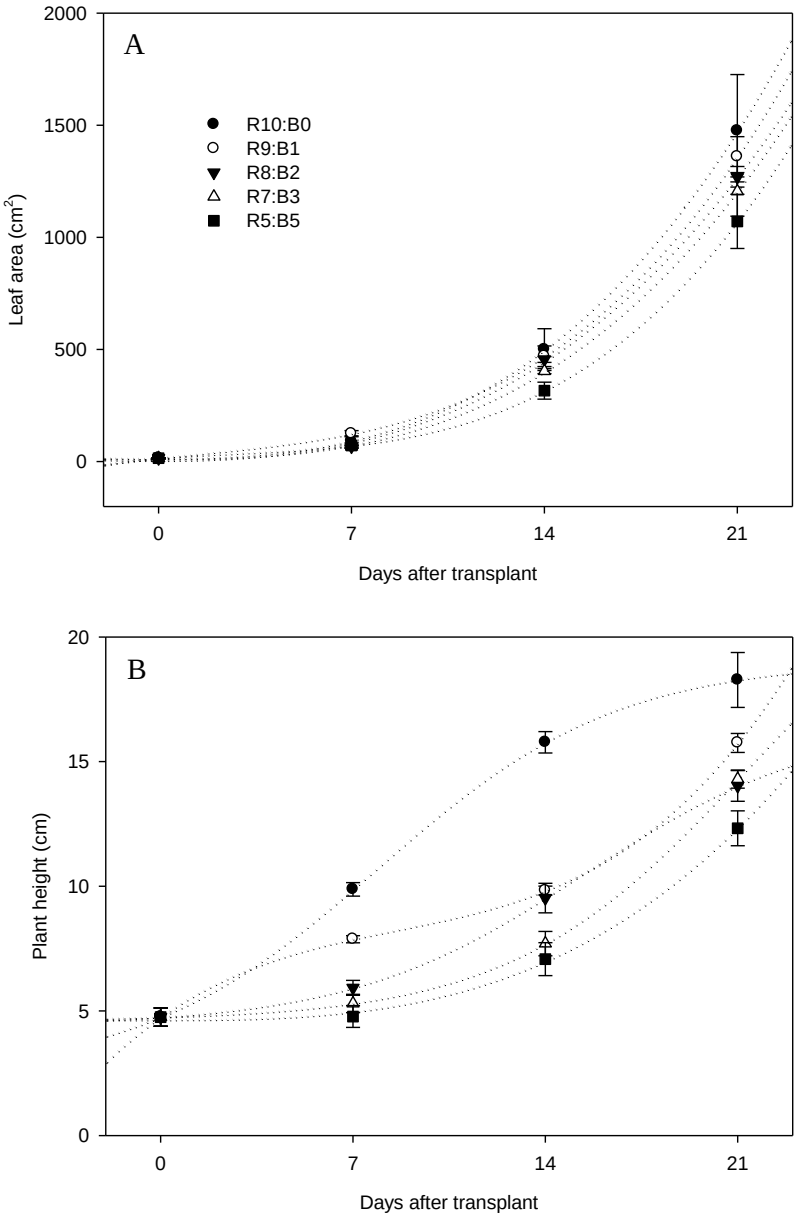

Figure I-5. Transitional aspects of the leaf area (A) and plant height (B) over time. The dotted line indicates the regression model [eqns (23) and (24)]. Vertical bar, mean SE (n=4).

Table I-1. Coefficients and R-square values for the leaf area and height estimation model. The leaf area fitting with the cubic function and height fitting with the cubic (R9:B1, R5:B5) and sigmoidal functions [eqns (23) and (24)]. Curve fitting and the calculation of R-square were based on the mean values of leaf area and crop height.

	Coef.	R10:B0	R9:B1	R8:B2	R7:B3	R5:B5
Leaf area	y_0	13.7032	14.9725	4.2947	11.2174	14.9725
	p	2.5E-10	13.4232	1.8E-08	3.8E-10	9.9636
	q	0.7918	-0.7322	1.0340	0.5400	-1.3629
	r	0.1201	0.1496	0.0874	0.1033	0.1563
	R^2	1.0000	1.0000	0.9995	0.9999	1.0000
Crop height	y_0	2.4482	4.7500	4.4248	4.6117	4.6395
	p	16.5996	0.7756	12.2167	20.1371	3.7E-12
	q	7.9151	-0.0645	15.4280	21.3240	0.0009
	r	4.3336	0.0025	4.2864	4.2869	0.0008
	R^2	1.0000	1.0000	1.0000	1.0000	0.9986

Major assumptions and calculation methods

The leaf reflectance for mixed spectra was assumed to be the weighted average of reflectance for each peak spectrum as shown in eqn (25). The reflectance of each wavelength was obtained from previous studies [Phan *et al*. (1979) and Pacumbaba and Beyl (2011)], and the weighted value for each treatment was determined by the proportion of blue and red light on the basis of PPFD.

$$\rho_{leaf,\ Rn:Bn} = \rho_{leaf,\ 465} \times w_{Rn} + \rho_{leaf,\ 625} \times w_{Bn} \tag{25}$$

$$\varphi \downarrow_{0,dir} = (1 - \rho_w) \times \varphi \downarrow_{0,total} \quad (\therefore \varphi \downarrow_{0,diff} = \rho_w \times \varphi \downarrow_{0,total}) \tag{26}$$

The incidence angle of direct light was assumed to be 0° for the calculation of the extinction coefficient. It was assumed that the ratio of diffuse light from the reflection of the wall (ρ_w) remained constant [eqn (26)] and that the diffuse light from the wall reflection was uniformly distributed in all directions toward the canopy [eqn (17), $w_{15}, w_{45}, w_{75} = 1/3$]. The reflectance of white plastic film ($\rho_s = 0.58$) suggested by Stanghellini and de Jong (1995) was used as the ground reflectance in this study. The model was simulated under two different regimes for the application of the extinction coefficient. Firstly, it was assumed that the ground had no light-scattering effects and the pattern of light incidence remained unchanged after ground reflection; consequently, eqns (5) and (7) were used (hereafter 'single K method'). Secondly, the light incidence was assumed to be

highly scattered after ground reflection and thus eqns (5b) and (7b) were applied (hereafter 'dual K method'). Both simulation results were compared to examine the effect of light-scattering by the ground material on canopy light interception. For the dual K method, the same extinction coefficient for diffuse light (K_{diff}) was adopted as that in the case of wall reflection. The growth of leaf area and height was assumed to be independent of the light distribution for the model simulation under modified light conditions (Fig. I-8).

In this study, parameter estimations and statistics processes were performed using the Sigmaplot (Ver. 10.0, Systat Software Inc., CA, USA), and model simulation was performed with Berkeley Madonna (Ver. 8.3.18, Berkeley Madonna Inc., CA, USA).

Table I-2. Notation.

Symbol	Description	Unit
a	Vertical radius of canopy	cm
b	Horizontal radius of canopy	cm
h	Height of canopy	cm
I_{int}	Intercepted light per unit ground area	μmol (PAR) m^{-2} s^{-1}
K	Extinction coefficient	
L	Partial LAI from the considered level upward	m^2 (leaf) m^{-2} (ground)
LA	Leaf area	cm^2
LAI	Leaf area index	m^2 (leaf) m^{-2} (ground)
p, q, r	Coefficients of regression model for crop growth	
t	Time	day
v	Vertical compensation factor	
w	Weighted value	
x	b/a ratio	
z	Coefficient of regression model for relative light intensity	
η	Intermediate variable	
ρ	Reflection coefficient or factor	
σ	Scattering coefficient	
τ	Transmission factor	
$\varphi\downarrow$	Downward flux of photons	μmol (PAR) m^{-2} s^{-1}
$\varphi\downarrow_n$	$\varphi\downarrow$ after n layers	μmol (PAR) m^{-2} s^{-1}

$\varphi\downarrow_{1,n}$	$\varphi\downarrow_n$ before reflected by ground	μmol (PAR) m^{-2} s^{-1}
$\varphi\downarrow_{2,n}$	$\varphi\downarrow_n$ after reflected by ground	μmol (PAR) m^{-2} s^{-1}
$\varphi\uparrow$	Upward flux of photons	μmol (PAR) m^{-2} s^{-1}
$\varphi\uparrow_n$	$\varphi\uparrow$ after n layers	μmol (PAR) m^{-2} s^{-1}
$\varphi\uparrow_{1,n}$	$\varphi\uparrow_n$ before reflected by ground	μmol (PAR) m^{-2} s^{-1}
$\varphi\uparrow_{2,n}$	$\varphi\uparrow_n$ after reflected by ground	μmol (PAR) m^{-2} s^{-1}
ϕ	Elevation angle of direct light	degree
ϵ	Intermediate variable	

Subscripts

bl	Black leaf
c	Canopy
$crop$	Crop
dir	Direct light
$diff$	Diffuse light
m	Mean value
s	Soil or ground
$total$	Total
w	Wall

SIMULATIONS

Simulation results under the light condition of actual crop cultivation

A higher efficiency of light absorption and interception was observed in treatment groups with the higher ratio of blue light, which, however, did not directly correspond with more light interception. Blue light was shown to promote growth of the canopy in a horizontal direction relative to the vertical direction so the b/a ratio increased as the blue ratio increased (Fig. I-6). The extinction coefficient followed the same pattern, whereas the scattering coefficient did not, meaning that under the incidence angle of 0° the efficiency of light interception and absorption increased with the percentage of blue light (Table I-3). Nevertheless, the result of model simulation indicated that it was not clear whether both of the parameters made meaningful contributions to canopy light interception. Rather, R10:B0 and R9:B1 had the greatest value of light interception despite the lowest value of the two coefficients (Fig. I-7).

Regardless of the K application method (dual or single), the immediate light interception (ILI) was the highest for R10:B0 from around 13 days after transplant (DAT), exceeding that of R9:B1, and a notable fluctuation in the rank between treatments was observed around 7 DAT (Fig. I-7A). Overall, the transitional aspect of accumulative light interception (ALI) followed an expo-linear pattern, which is a typical form of biomass accumulation for plants (Fig. I-7B). As the end point approached, the slope of the curve gradually decreased for the ILI. In particular, the

gap between R5:B5 and the others also gradually decreased, suggesting relatively lower reduction of the slope. Compared to the dual K method, the application of the single K method caused 4-8% lower ALI at the end. The largest gap (8%) between both K methods was observed for R10:B0, which is shown as the change of the slope in the ALI curve (Fig. I-7B1, B2). No significant difference was found in the rank or transitional trend between the two K application methods, and the gap of the ILI declined up to 0.05-0.3% at the end (Fig. I-7A1, A2).

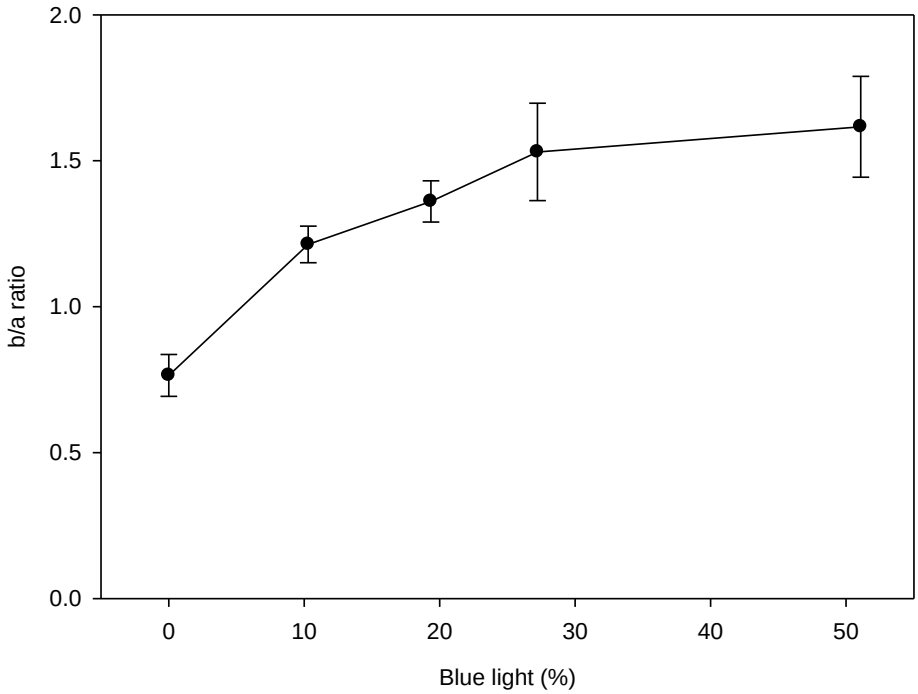

Figure I-6. Change of the ratio of the horizontal radius to the vertical radius (b/a ratio) of the canopy against the percentage of blue light. The mean values are averages of all the observations from the entire experimental period.

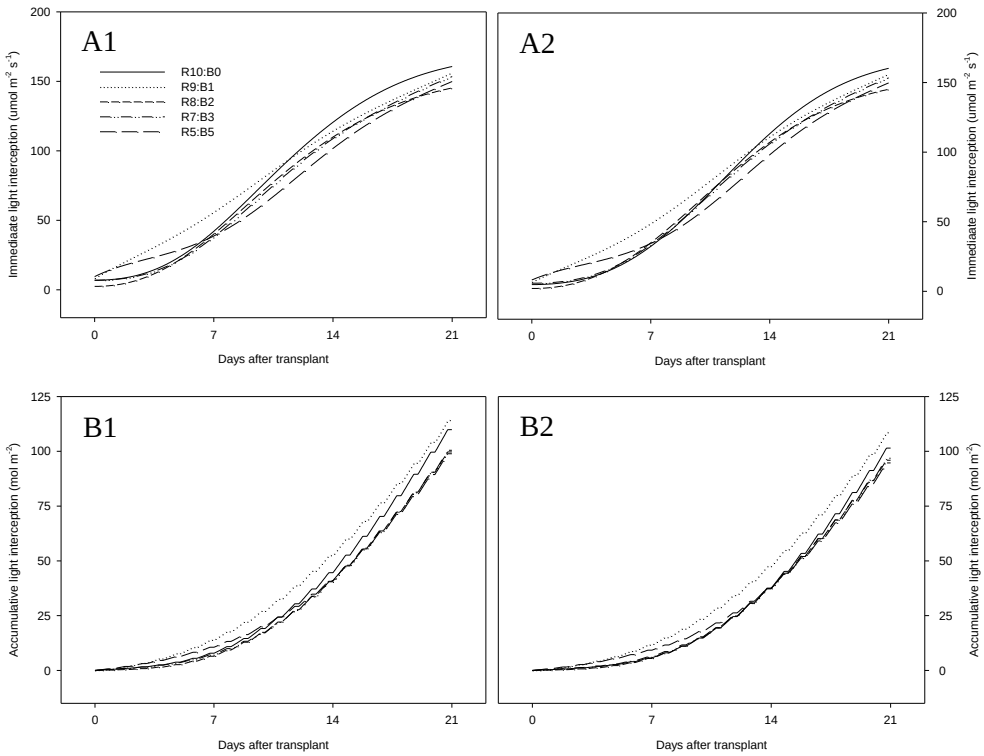

Figure I-7. Immediate (A) and accumulative light interception (B) of the plant canopy grown under different light qualities, estimated by both the dual K (1) and single K (2) methods over time.

Table I-3. Estimation results of the parameters: b/a ratio, scattering and extinction coefficients for black leaf and crop. Blue ratios were used for the calculation of scattering coefficients as weight values. Extinction coefficients were calculated with average b/a ratios.

	R10:B0	R9:B1	R8:B2	R7:B3	R5:B5
Blue ratio (%)	0	10.29	19.35	27.22	51.08
σ_{leaf}	0.2122	0.1801	0.1734	0.1600	0.1413
K_{bl}	0.4129	0.5649	0.6033	0.6418	0.6594
K_{crop}	0.3665	0.5115	0.5485	0.5883	0.6111

Effect of light environmental changes on crop light interception

The modification of light environmental conditions gave rise to the change in canopy light interception and the extent varied with the applied light quality. The initial light environment was modified to examine and compare the effect of light environmental changes on the ALIs. Firstly, it was assumed that black plastic mulching or dark coloured substrate without mulching was applied on the ground instead of white plastic as in the initial experimental condition. Consequently, the ground reflectance (ρ_s) changed to 0.048, which is the reflectance of black plastic film suggested by Siwek *et al*. (2007), and the relative change in the simulated ALI was calculated. All other conditions remained constant. As a result, the ALI decreased by 17-22% for the dual K method and 13-16% for the single K method at the end, indicating that the light-scattering factor had an accelerative influence on the effect of ground reflection (Fig. I-8A1, A2). Under both K methods, the largest reductions were observed for R10:B0 and R5:B5 as the end approached. In particular, that of R5:B5 was less fluctuant compared to the other groups. The relative change of ALI was shown to decrease over time, suggesting a decreasing effect of ground reflectance on it. Similarly, the relative ILI was less than 5% for all treatment groups at the end regardless of the K application method (data not shown). The most sensitive change in the ALI was displayed for R10:B0 against the change of ground reflectance under the dual K application.

For the next modification, a cultivation site was assumed to have the same initial light intensity as our experimental condition at ground level (166±3 μmol·m-

$^{2}\cdot s^{-1}$, PAR) but different ground material (black plastic) and light distribution, in order to investigate the combined effect. The ground reflectance declined to 0.048 as in the first modification case, and the intensity of the light source, or the amount of direct light, was modified accordingly (about 27% increase). The possible distortion of light intensity by absorption from the black body of the quantum sensor was excluded in the calculation. The patterns of curves were fairly similar to the case of single modification in the ground reflectance (Fig. I-8A, 8B). However, in contrast, the relative ALI mostly displayed positive values as the end approached under this regime, even though only negative changes were observed before 17 and 15 DAT under the dual and single K methods, respectively (Fig. I-8B1, 2). The extent of positive change was higher for R8:B2 and R7:B3 and lower for R10:B0 and R5:B5.

Finally, the use of a diffuse filter was assumed, and the ratio of diffuse light fraction to total downward flux was modified from 0.1 to 0.8 under the same initial light intensity at ground level. The change in the ALI was more significant for the early stage, and the largest change was observed for R10:B0 (Fig. I-8C). Relative ALIs under the singe K method displayed 50-62% higher values than under the dual K method.

Although the fluctuation of the relative ALI against overall changes in the ground reflectance and diffuse ratio was the greatest for R10:B0, the extinction coefficient for diffuse light was the lowest (Fig. I-8A, 8C, 9A). Instead, the coefficient was higher for the treatment groups with the higher blue light ratio and

that for direct light (Table I-3, Fig. I-9A). But the ratio of light incident on the ground ($\varphi \downarrow_{n,total}$) to total downward flux ($\varphi \downarrow_{0,total}$) was higher for R10:B0 and R5:B5, for which the ALIs displayed a higher reduction under the decreased ground reflectance (Fig. I-9B, 8A). No difference between two K application methods was found for both parameters shown in Fig. I-9.

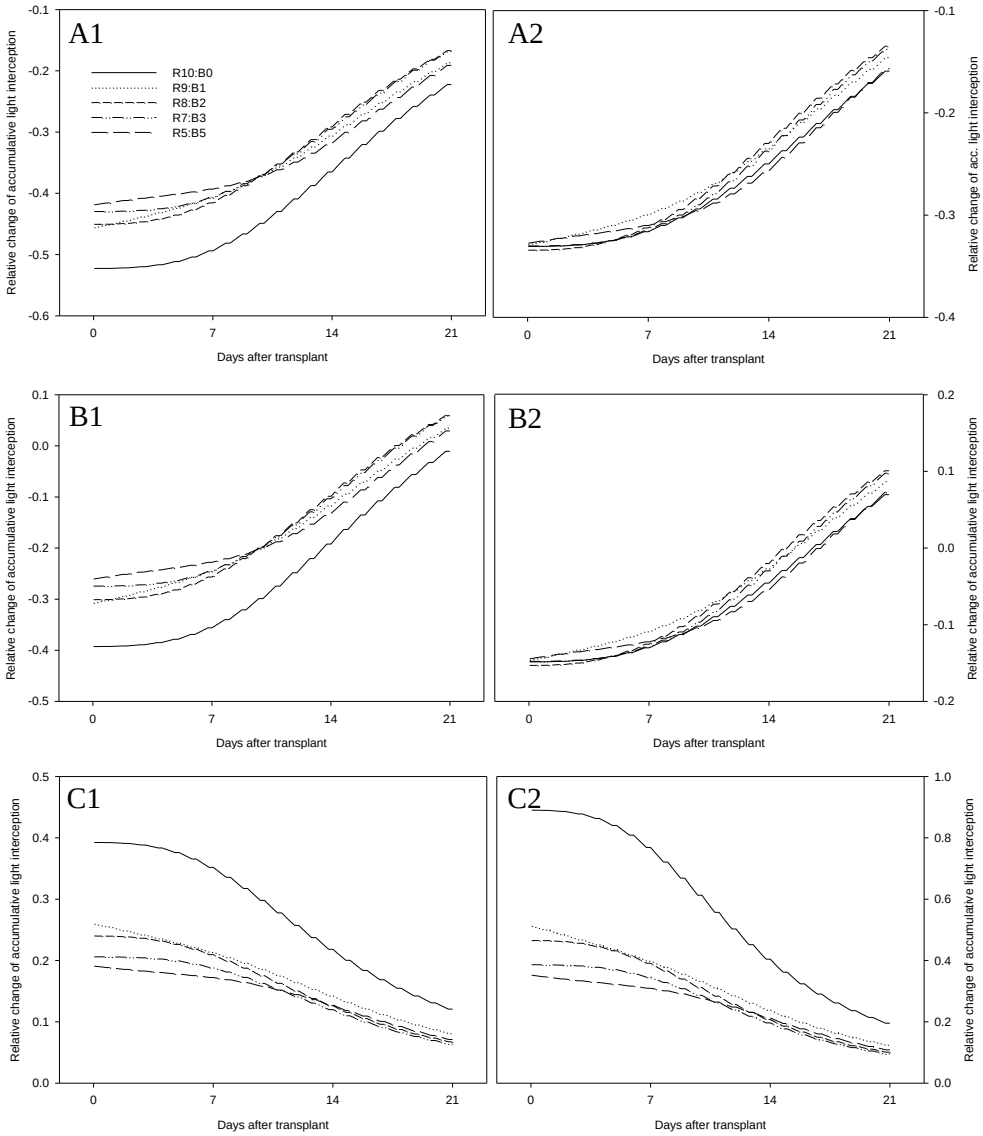

Figure I-8. Relative change of the accumulative light interception, or relative ALI, against the change of ground material from white to black (A), of ground material from white to black under the same light intensity with increased amount of direct light (B), and of the diffused fraction of downward flux from 10 to 80% (C) by the dual K (1) and single K (2) methods.

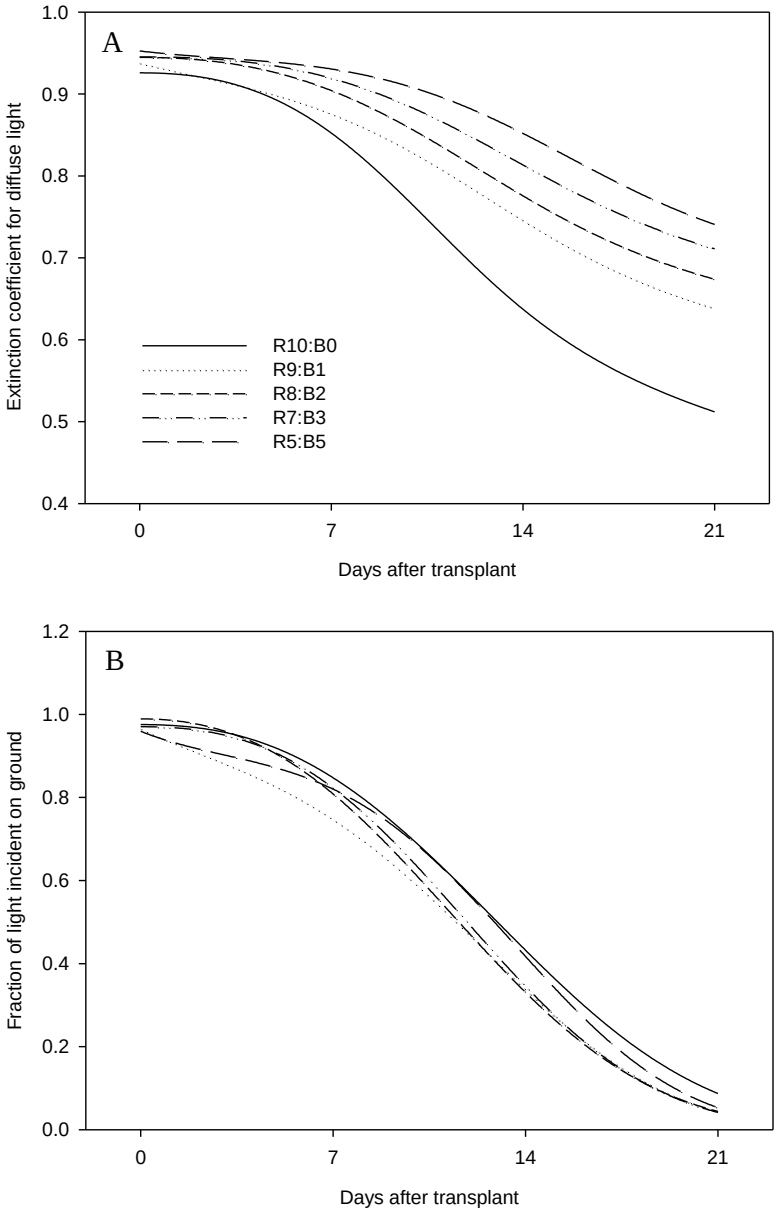

Figure I-9. Change of the extinction coefficient for diffuse light (A) and the fraction of light incident on the ground (B) over time.

DISCUSSION

Features and implications of the new model

The main features of the new model can be summarised in the following three points: (1) the quantitative application of crop morphological changes driven by the modification of light quality through the b/a ratio, (2) the compensation of light intensity for the longitudinal growth of the canopy, and (3) the application of the light-scattering effect from the ground by adopting dual extinction coefficients. Different light qualities resulted in different canopy forms for light interception, and, as a result, different extinction coefficients, namely efficiency of light interception per unit leaf area, even under the same environmental conditions (Fig. I-5, 6, Table I-3). However, the higher efficiency could not guarantee higher light interception, which suggests that various factors were involved in the determination of light interception during this experiment (Fig. I-7). For example, the ILI and ALI were the first or second highest for R10:B0 despite having the lowest extinction coefficients, which was presumably accounted for by multiple factors, such as rapid growth of the height and leaf area, higher sensitivity to ground reflection, and diffuse light (Fig. I-5, 8A, 8C). In this context, the effects of plant morphogenetic and light environmental factors are simultaneous and complexly interrelated. The new model complements the previous models in that it considers and includes those factors in a comprehensive and simultaneous manner.

Crop light interception also varied with light distribution even under the same

light quality and environmental conditions. Specifically, our simulation result suggests it was affected more in the early stages of growth by the changes in the reflection and light-scattering factor of the surrounding materials, than in the later stages (Fig. I-8A, C). In other words, changes in light distribution have more influence on young plants for biomass accumulation, due to the tight connection between production and light interception (Pinho *et al.*, 2012). Therefore, it is more likely to find a larger variation in the actual ILI and ALI between treatments than in the simulated result, considering that plant growth was assumed to be independent of light distribution in this study. In this regard, it is important to clarify and control the factors associated with the distribution of direct and diffuse light; otherwise the result could be misinterpreted. For experiments with crops grown under monochromic red light treatment, more careful analysis is considered to be necessary because of the higher sensitivity to ambient light environment (Fig. I-8).

In most cases, artificial light sources are locally fixed, and the intensity of light incident on the plant is closely linked to the distance between the plant and the light source. According to the common notion, the form for light interception is important only when it comes to an open canopy, which is clearly true for cultivation under natural sunlight (Hogewoning, 2010a). However, in horticultural facilities highly dependent on artificial lights, crop light interception can be significantly affected by the growth pattern of height as well as the level of canopy closure. In particular, in facilities with relatively narrow vertical spaces, such as

plant factories or growth chambers, the light intensity can be more fluctuant according to the height and properties of the light source; thus it is necessary to evaluate their effects on crop light interception and growth. However, as far as we know, such a change has not been applied into studies or models for the estimation of plant growth or light interception even in plant factories or growth chambers. Additionally, in the previous studies comparing crop growth under different light qualities, one single factor of initial light intensity was generally used in the control of the light environment (Kim *et al.*, 2004; Ohashi-Kaneko *et al.*, 2007; Shimizu *et al.*, 2011; Stutte and Edney, 2009). Presumably, differences in the light environment except for the initial light intensity were partially or mainly attributed to the reason why the studies carried out in plant factories or growth chambers suggested conflicting results and interpretations.

The new model enables a dynamic estimation of crop light interception based on changes in light quality, distribution, and intensity by growth. The simulation result suggests that it is necessary to consider the optical properties of the light sources and surrounding materials for the comparison, analysis, and interpretation of experimental results, especially for facilities highly dependent on artificial lights.

Effect of reflection and light-scattering from surrounding areas

The effect of ground reflection on crop light interception gradually decreased over time, and the extent varied with light quality applied (Fig. I-8A). Higher

sensitivity was observed for R10:B0 and R5:B5 for which the fractions of light incident on the ground were also relatively higher (Fig. I-9B). However, the extinction coefficient for diffuse light, a parameter representing the efficiency of light interception for the fraction reflected from ground, was higher for the groups with a higher blue light ratio, displaying its unclear association with light interception (Table I-3, Fig. I-9A). The above results explain that the reflective ground material complements unfavourable canopy form for light interception by supporting the re-entry of light that primarily reached the ground rather than the canopy. This is also supported by another result under increased direct light that indicated the higher increase in the ALI for R8:B2 and R7:B3, of which fractions of light incident on the ground belonged to the lower ranks (Fig. I-8B, 9B). For R5:B5, the fact that the ALI was highly affected by the ground reflection despite the highest extinction coefficient is considered to account for the low expansion of the leaf area and resultant canopy coverage.

Similarly, the diffuse fraction of the total downward flux was shown to complement the unfavourable canopy form, even though the result was somewhat different in that the relative change of the ALI was higher for R9:B1 than R5:B5 (Fig. I-8A, C). However, despite its relevance to diffuse light, the increase in the light-scattering factor of the ground weakened the effect of the diffused downward flux, while it strengthened the effect of the ground reflection (Fig. I-8C1, 2). Presumably, the scattering and reflection from the ground also enhanced the uniformity of light distribution and consequently offset the effect of the additional

diffuse light among the downward flux. Moreover, in a real situation, diffuse filters or glass are not absolutely transparent and accordingly block part of the light incidence according to the transmittance. This implies that prudent and quantitative analysis is required for the commercial application of these materials in cropping facilities such as plant factories, where this new model can possibly make a contribution.

Generally, rapid expansion of leaf area in the early growth stage is known to promote light interception of crops and thereby overall growth, which can be induced by the application of the higher temperature or far-red light (Li and Kubota 2009, Seginer *et al.*, 1991). Despite this usefulness, such an environmental control cannot be simply applied to commercial horticulture because it requires high energy consumption or expensive equipment. However, according to our study, crop light interception can also be improved by the use of materials with high efficiency of reflection and light-scattering, which can provide a more economic and realistic alternative.

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CHAPTER II

Verification of a canopy light interception model in a plant factory with artificial lettuce and the Nicolet model

ABSTRACT

- *Background and Aims* The crop growth model plays a critical role in commercial horticultural systems for planning and operating. In recently constructed horticultural facilities, the light quality and distribution are strongly affected by the use of artificial lights and reflective surroundings, which can significantly affect crop light interception and consequent growth. However, the effects of the light environmental changes have not been fairly considered in models despite the potential risks related to model accuracy. This study was designed to verify the reliability of an estimation model for crop light interception in a plant factory and to investigate its applicability for a full growth model.

- *Methods* For the verification, the model estimations were compared with the actual light interception, which was measured using artificial lettuce with photodiodes and was calculated by the Nicolet model that was calibrated with the experimental results from lettuce cultivation under different light qualities in a plant factory.

- *Key results* The new model estimated crop light interception within 11% of

the relative root mean square error (RRMSE), and it complementarily improved the accuracy of a full growth model.

- *Conclusions* Our results suggest a possibility for the quantitative application of the light spectral effect on crop light interception with a single parameter, the 'b/a ratio', and a simplified method for the determination of ideal canopy form or canopy ideotype.

Key words: diffuse light, canopy ideotype, light interception, light quality, reflection, plant factory

INTRODUCTION

The crop growth model is a useful means to forecast and characterise crop growth under various environmental changes (Gent and Seginer, 2012). In particular, the model plays a critical role in commercial farming systems for production planning and management. Current horticultural crops tend to be cultivated in technically advanced facilities and, consequently, are exposed to different light environments than field culture. The gap is mainly caused by the abundant use of artificial light sources and materials for mulching, covering, and structuring, which can highly modify light quality and distribution in the facilities (Siwek *et al*., 2007; Hemming, 2008; Sarlikioti *et al*., 2011a). Although this light environmental change can have significant influences on crop growth, many of the effects are normally excluded from growth models.

Light quality determines crop growth by affecting the efficiency of carbon assimilation and light interception (Hogewoning, 2010a). There have been various qualitative and quantitative studies on the change of crop photosynthesis according to light quality, and higher efficiency has been observed for crops grown under higher percentages of blue light in experiments with rice, wheat, and cucumber (Matsuda *et al*., 2004; Goins *et al*., 1997; Hogewoning *et al*., 2010b). Similar to strong light, such phenomenon has been reported to account for blue light promoting the development of thicker leaves or leaves with a larger leaf mass per area (LMA) because LMA is closely related to photosynthetic efficiency (Broderson *et al*., 2007; Poorter *et al*., 2009; Hogewoning *et al*., 2010b). In

addition, lettuce seedlings grown under monochromic blue light or a mixture of blue and red lights have higher accumulations of photosynthetic pigments, including chlorophylls and carotenoids, which may contribute to the assimilation efficiency compared to monochromic red light (Johkan *et al*., 2010).

Although additional blue light increases the rate of photosynthesis, it has been shown to decrease total leaf area at the same time. In another experiment with high pressure sodium (HPS) and light emitting diode (LED) lamps, plants under light treatment with blue spectra have lower leaf areas (Brazaityte *et al*., 2006). Because rapid leaf expansion in the early stage promotes light interception, blue light can negatively affect overall crop growth while increasing photosynthetic efficiency (Seginer *et al*., 1991; Ohashi-Kaneto *et al*., 2007). Therefore, quantitative studies of light interception and photosynthesis are required to understand and forecast the overall effect of a certain spectrum on crop growth. Hogewoning *et al*. (2010c) suggested that light quality can affect the entire crop growth by modifying light interception more than photosynthesis. Because light quality is involved in crop morphogenesis, such as leaf area, canopy width, canopy length, and leaf angle distribution, modification of light quality induces changes of the key parameters that determine crop light interception, namely the extinction coefficient and leaf area index (Pierik *et al*., 2004; Dougher and Bugbee 2001; Monsi and Saeki 2005). In addition to crop morphology, light quality has also been reported to affect the efficiency of light interception by the change of optical properties (reflectance and transmittance) of the leaves (Paradiso *et al*., 2011).

Even though the shape of the crop canopy is one of the most critical determinants of light interception, it is closely interrelated with light distribution, for example, diffuse light fraction and incident light angle of cultivation sites (Goudriaan, 1988; Papadopoulos and Pararajasingham, 1997). In this regard, functions of light quality are closely interrelated with light distribution due to the close connection with crop morphology, thereby increasing the complexity and difficulty of estimating crop light interception in current horticultural facilities. Individual models to evaluate the effects of light distribution and crop morphological traits on light interception have been suggested on the basis of natural sunlight conditions (Goudriaan and Van Laar, 1994; Campbell, 1986) suggesting that it is possible to develop a new estimation model and to suggest the theoretical foundation by the integration and modification of previous models. However, it is necessary to ensure the accuracy and relevance of the integrated version of models constructed by mutually independent studies.

Adoption of supplemental lighting and light manipulation technology has gradually increased in recent horticultural facilities. Consequently, it is necessary to develop a reliable and suitable model to make accurate estimations for crop light interception reflecting the effect of the complex light profile. Thus, this study was designed to suggest an effective methodology and to verify its reliability.

MATERIALS AND METHODS

Plants, growth conditions and measurements

Lettuce plants (*Lactuca sativa* L.) were grown as previously described in Chapter I. Five different red and blue light compositions with an initial light intensity of 166±3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (PAR) at ground level were applied to each treatment group as follows: 10:0, 9:1, 8:2, 7:3, and 5:5 referred to as R10B0, R9B1, R8B2, R7B3, and R5B5, respectively. Net photosynthesis was measured with two sample plants for each treatment group before every destructive investigation using a portable measuring device (LI-6400, LI-COR, Lincoln, NE, USA). An open chamber was applied to make observations under the same light condition as the cultivation sites. Dark respiration was measured by eliminating light incidence, and gross photosynthesis was calculated by adding the respiration to the net photosynthesis (Hogewoning 2010a, b). Gross photosynthesis at the growth light intensity (166 $\mu mol \cdot m^{-2} \cdot s^{-1}$) was calculated under the assumption that the quantum yield was constant under the light limited phase because of difficulties in precise control of light intensity with the open chamber. For the calculation of LMA, total dry weight was divided by the total leaf area. The total nitrogen content in lettuce leaves was measured by the Kjeldahl method.

Model description and simulation

The new model was designed to calculate the amount of crop light

interception by subtracting the upward flux outside of the crop canopy and the absorbed fraction by the ground from total light incidence on unit ground area [eqn (1)]. It was assumed that the fraction of light that was once reflected from the canopy or passed through it after initial ground reflection was eliminated. Light interceptions for direct and diffuse fractions were separately calculated due to the different extinction coefficients [eqn (2)]. Each light flux was calculated by the equations suggested by Goudriaan and Van Laar (1994). To apply the light scattering effect of the ground material, a different extinction coefficient was adopted for the fraction of direct light reflected from the ground [referred to as the 'dual K method'; eqns (3b) and (4b)], and the estimation result was compared to that of the original equation with a single extinction coefficient [referred to as the 'single K method'; eqns (3a) and (4a)].

$$I_{int} = \varphi\downarrow_0 - \varphi\uparrow_0 - (1-\rho_s)\cdot\varphi\downarrow_L \text{ or } \varphi\downarrow_0 - \varphi\uparrow_0 - (\varphi\downarrow_L - \varphi\uparrow_L) \tag{1}$$

$$I_{int,\ total} = I_{int,\ dir} + I_{int,\ diff} \tag{2}$$

$$\varphi\downarrow_{2,L} = \frac{\varphi\downarrow_0 \cdot \eta \cdot \exp(-K\cdot LAI)}{1+\eta\cdot\exp(-2K\cdot LAI)} \cdot \exp\{-K\cdot(LAI-L)\} \tag{3a}$$

$$\varphi\uparrow_{2,L} = \frac{\varphi\downarrow_0 \cdot \eta \cdot \exp(-K\cdot LAI)/\rho_c}{1+\eta\cdot\exp(-2K\cdot LAI)} \cdot \exp\{-K\cdot(LAI-L)\} \tag{4a}$$

$$\varphi\downarrow_{2,L} = \frac{\varphi\downarrow_0 \cdot \eta \cdot \exp(-K\cdot LAI)}{1+\eta\cdot\exp(-2K\cdot LAI)} \cdot \exp\{-K_{diff}\cdot(LAI-L)\} \tag{3b}$$

$$\varphi\uparrow_{2,L} = \frac{\varphi\downarrow_0 \cdot \eta \cdot \exp(-K\cdot LAI)/\rho_c}{1+\eta\cdot\exp(-2K\cdot LAI)} \cdot \exp\{-K_{diff}\cdot(LAI-L)\} \tag{4b}$$

The extinction coefficient for direct light was estimated by the ellipsoidal inclination angle distribution model of Campbell (1986) to reflect the differences in crop morphology under different light qualities (Appendix B). The horizontal radius of the canopy was calculated with photographic images taken perpendicular to the ground under the assumption that the area was circular, and the vertical radius (a) was directly measured as half the length of the canopy height. The image analysis was performed with specialised software (ImageJ 1.45s; http://imagej.nih.gov/ij). The incidence angle of all the direct light was assumed to be 0°.

Models suggested by Goudriaan and Van Laar (1994) were used to calculate the parameters related to diffuse light and optical properties of the canopy (Appendix C). All diffuse light was assumed to be evenly distributed in all directions toward the canopy [eqn (5); $w_{15}, w_{45}, w_{75} = 1/3$]. The leaf reflectance was estimated by the weighted average method with the reflectance data from previous studies for 2 peak wavelengths (465 and 625 nm) of blue and red LEDs used in the present study (Phan *et al*., 1979; Pacumbaba and Beyl, 2011) [eqn (6)].

$$\varphi \downarrow_{diff} = \varphi \downarrow_{0,diff} \{w_{15} \cdot \exp(-K_{15} \cdot L) + w_{45} \cdot \exp(-K_{45} \cdot L) + w_{75} \cdot \exp(-K_{75} \cdot L)\} \quad (5)$$

$$\rho_{leaf,\ RnBn} = \rho_{leaf,\ 465} \times w_{Rn} + \rho_{leaf,\ 625} \times w_{Bn} \quad (※\ w_{Rn} = 1 - w_{Bn}) \quad (6)$$

The light intensity at each time point was compensated for the relative change by the vertical crop growth with a factor (referred to as ‘vertical compensation

factor'; v) calculated by a quadratic regression because the intensity is proportional to the square of the distance from the light source (Jacob and Dranoff, 1970) [eqns (6) and (7)]. For the formulation of a regression model, the relative changes of light intensity were measured on 3 designated points in the centre of the cultivation site at 7 different heights. Because the outermost section of the canopy was not flat, the vertical compensation factor (v) was computed with the average crop height rather than the real crop height. Under the assumption that the crop canopy is ellipsoidal, the average height was defined as the sum of the height of the cylinder (with the same base area and volume as the upper hemisphere) and the height of the remaining hemisphere [eqns (8) and (9)].

$$\varphi \downarrow_{0,t} = \varphi \downarrow_{0,0} \cdot v \tag{6}$$

$$v = z_1 h^2 + z_2 h + z_3 \tag{7}$$

$$a_m = 2/3 \cdot a \quad (\because V = 2/3 \cdot b^2 \cdot a \cdot \pi = b^2 \cdot a_m \cdot \pi) \tag{8}$$

$$h_m = a_m + a = 5/3 \cdot a = 5/6 \cdot h \quad (\because h = 2 \cdot a) \tag{9}$$

The fraction of diffuse light from the reflection of the wall (ρ_w) was assumed to be constant [eqn (10)]. The value and measurement method of the wall reflectance were the same as in Chapter I ($\rho_w = 0.1$). The ground reflectance ($\rho_s = 0.580$) was taken from the reflectance of white plastic (Stanghellini and de Jong, 1995). The extinction coefficients for diffuse light were assumed to be the same for the fraction from the ground and wall. Detailed explanations about the

new model are included in Chapter I and the Appendix, including equations to estimate the crop height and LAI, which were used to calculate the accumulative light interception.

$$\varphi \downarrow_{0,dir} = (1 - \rho_w) \times \varphi \downarrow_{0,total} \quad (\therefore \varphi \downarrow_{0,diff} = \rho_w \times \varphi \downarrow_{0,total}) \qquad (10)$$

Design and utilisation of artificial lettuce

Artificial lettuce was designed to obtain the actual amount of light intercepted by the crop by imitating real lettuce (Fig. 1). The transmittance of artificial lettuce leaves made of synthetic resin was adjusted with spray paint to set the error range less than ±1% point. A length of wire was placed through the midrib of each leaf to fix the form of the canopy. In total, 6 prototypes were made for R10B0 and R9B1 at 3 different stages, namely 7, 14 and 21 days after transplant (DAT), and the final products had an error range of ±5% in the canopy height and width. Photodiodes (OHP-3ML, Oscar Electronics, Seoul, Korea) were attached to the adaxial and abaxial surfaces of each leaf. The number of diodes was determined according to the leaf size with a maximum of 9 on one side. All the diodes in one artificial lettuce were connected in parallel, and the voltage value of generated electricity was measured and stored by a data logger (CR-23x, Campbell Scientific Inc., UT, USA) for 2 minutes per observation. For direct comparison with the calculation result of the Nicolet model, the light interceptions of the artificial lettuces were measured at 4 different points alternatively among positions of the final harvests on

the cultivation site in which real crops were grown. The light interception PPFD values were calculated by a linear regression model formulated with measurements from the photodiodes and a photometer (LI-250A Light Meter, LI-COR, Lincoln, NE, USA) at the same 5 points on the cultivation site. The observed values were adjusted considering differences in the leaf area and initial canopy reflection between the artificial and real lettuce. Eqn (12b) was used to estimate the extinction coefficients for individual artificial lettuces, and the light interceptions were recalculated with the extinction coefficients and actual leaf areas (Monsi and Saeki, 2005) because the leaf area afforded for the artificial lettuce was limited as the leaves were significantly thicker than the real ones. For the final correction, reflected fractions of incident light from the outermost leaf layer were calculated by eqn (11) and subtracted from observed values in which those were inseparably included.

$$\varphi \uparrow_{1,L} = \frac{\varphi \downarrow_0 \cdot \rho_c}{1 + \eta \cdot \exp(-2K \cdot LAI)} \cdot \exp(-K \cdot L) \tag{11}$$

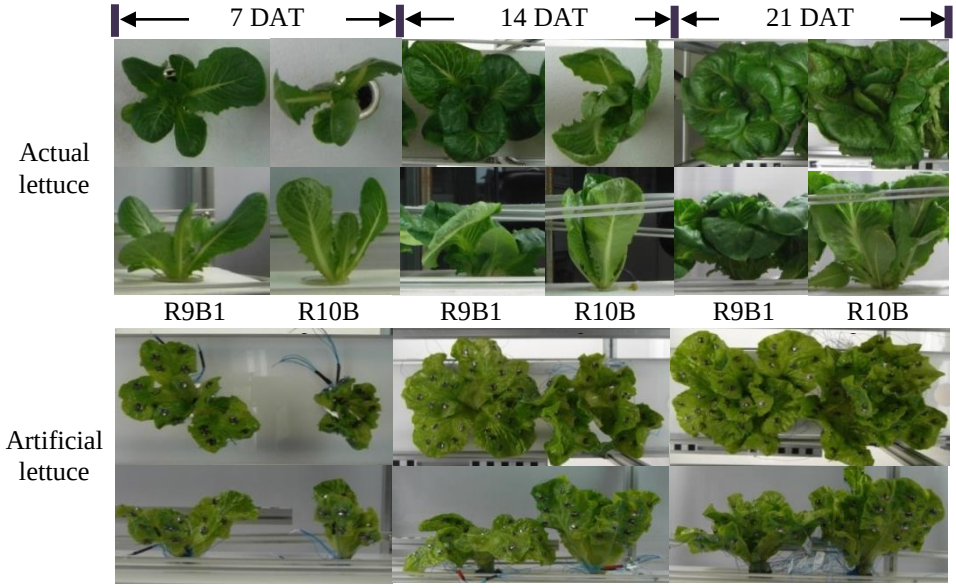

Figure II-1. Pictures of actual (above) and artificial (below) lettuce at 7 (left), 14 (middle) and 21 (right) days after transplant (DAT). Black dots on the leaves of artificial lettuces are photodiodes.

Calculation of canopy light interception with the modified Nicolet model

The Nicolet model developed by Seginer *et al*. (1998, 2003) can dynamically forecast the growth of lettuce in a greenhouse. Because the reliability and usefulness have been verified by various studies, the Nicolet model was used to calculate the actual crop light interception in the present study (Ioslovich *et al*., 2002; Linker *et al*., 2004; Linker and Johnson-Rutzke, 2005; Mathieu *et al*., 2006; Ioslovich, 2009). Eight parameters were chosen to be calibrated among the sixteen parameters of the Nicolet model due to the reasons stated in Table 1. Six of the parameters were mathematically estimated with the 'curve fit' module of Berkeley Madonna (Ver. 8.3.18, Berkeley Madonna Inc., CA, USA) modelling software, and the other two parameters (ε and λ) were directly calculated with experimental data. The λ parameter was computed according to Seginer (2003), and the ε parameter was substituted with the average quantum yield of absorbed photon. The total nitrate content required to calculate the λ parameter was measured with a nitrate test kit (Kit No.: 1.09713.0001, Merck KGaA, Darmstadt, Germany) where the reagent was prepared according to the recipe of Hunt and Seymour (1985). Values of the eight uncalibrated parameters were taken from Seginer (2003).

Unlike the general definition, the extinction coefficient of the original Nicolet model includes the conversion factor between structural carbon (M_{Cs}) and leaf area index (LAI) [eqn (12a)]. Thus, the original equation was modified as eqn (12b) following the general concept to exclude the effect of changes in LMA and to clarify the effect of changes in the canopy form for light interception. Additionally,

the vertical compensation factor (v) and average height (h_m) were also applied in the Nicolet simulation to compensate light intensity dynamically because the original Nicolet model has no means to reflect the fluctuation of light intensity against height [eqns (6), (7), (8) and (9)]. The initial light intensities of both the Nicolet model and our new model were measured at positions of the final harvests for direct comparison of the results. The same equations were used to estimate the growth of LAI and crop height as in the new model.

$$f\{M_{Cs}\} = 1 - \exp(-K_{ON} \cdot M_{Cs}) \tag{12a}$$

$$f\{LAI\} = 1 - \exp(-K_{MN} \cdot LAI) \tag{12b}$$

The initial canopy reflection, which is also inseparably included for the original Nicolet model, was computed by eqn (11) and deduced from the initial light intensity at each time point. To eliminate the effect of an estimation error from the modified Nicolet model, the calculated immediate light interception (ILI) and accumulative light interception (ALI) were corrected on the basis of dry weight. All the corrections were based on the assumption that variation in the ALI causes change of both the dry weight and ILI at the same rate and direction (Pinho *et al.*, 2012).

Table II-1. List of Nicolet parameters and the estimation methods (Seginer, 2003).

Parameter	Description	Estimation methods
T_r	Reference temperature	Assumed to be species-specific trait of lettuce and taken from Seginer (2003)
β_c	Osmotic potential of vacuolar carbon	
β_n	Osmotic potential of vacuolar nitrogen	
Π	Osmotic potential in vacuole	
b_g	Growth inhibition border	Insensitive to dry weight and taken from Seginer (2003)
r	Nitrogen to carbon ratio in structure	
s_g	Growth inhibition slope	
s_p	Photosynthesis inhibition slope	
ε	Photosynthetic efficiency	Calculated with data from the experiment
λ	Volume of water associated to structural carbon	
b_p	Photosynthesis inhibition border	Mathematically estimated
K	Light extinction coefficient	
k	Maintenance respiration rate	
θ	Growth respiration as fraction of growth	
ν	Ratio of growth resp. to maintenance resp.	
σ	Leaf conductance to CO_2	

Verification of model error

The estimations from the new model were compared with the measurements from the artificial lettuce and calculation results from the modified Nicolet model. The size of error was evaluated with the root mean square error (RMSE) and relative RMSE (RRMSE). The model simulation and calibration of six Nicolet parameters were performed with Berkeley Madonna software, and the statistic processes were performed using Sigmaplot (Ver. 10.0, Systat Software Inc., CA, USA).

RESULTS

Plant growth

With a few exceptions, the overall crop average weights decreased under the higher ratio of blue light, and the average rates of photosynthesis increased with the ratio (Figs. 2 and 3A). Most significantly, the average fresh and dry weights were the highest for R10B0 at the end of the experiment despite the lowest rate of photosynthesis. The average leaf mass and total N content per leaf area also increased with the increase of blue light (Fig. 3B). The coefficient of variation (CV) values among treatments were 0.037 and 0.107 for the dry and fresh weight, respectively, which indicated that the water contents were affected by blue light.

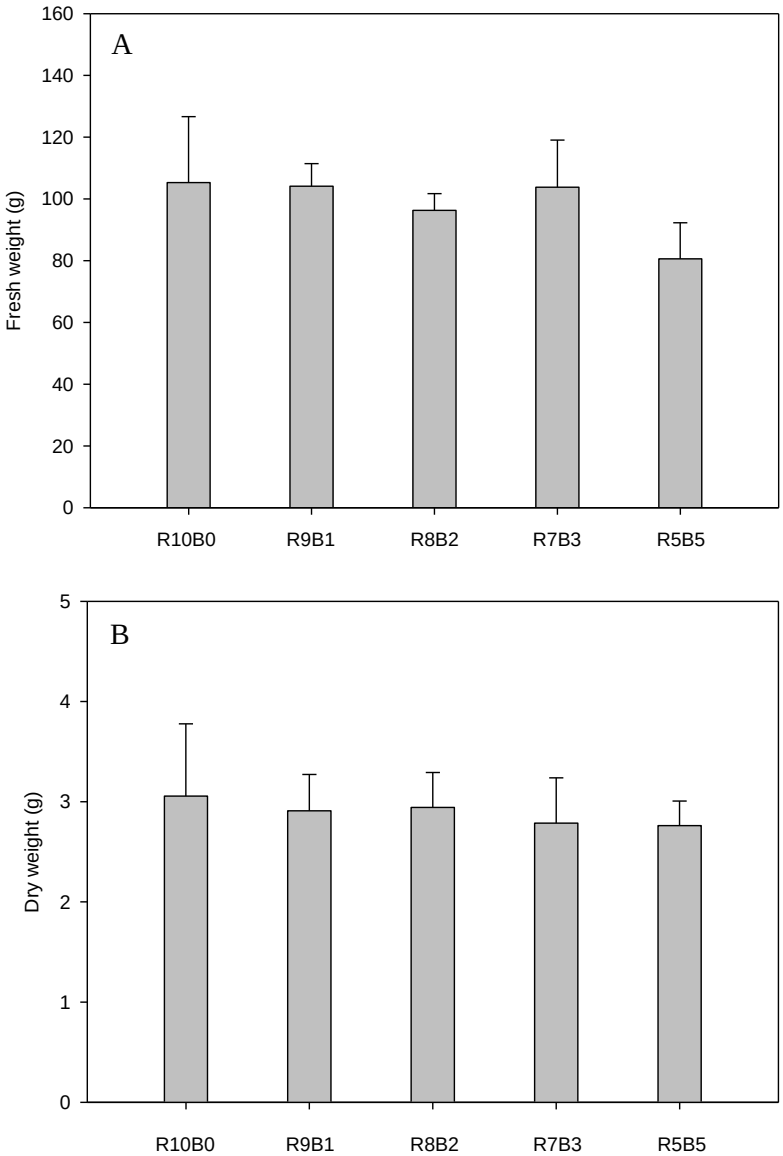

Figure II-2. Fresh (A) and dry weight (B) of each treatment group at 21 DAT. Error bars indicate SE. (n=4)

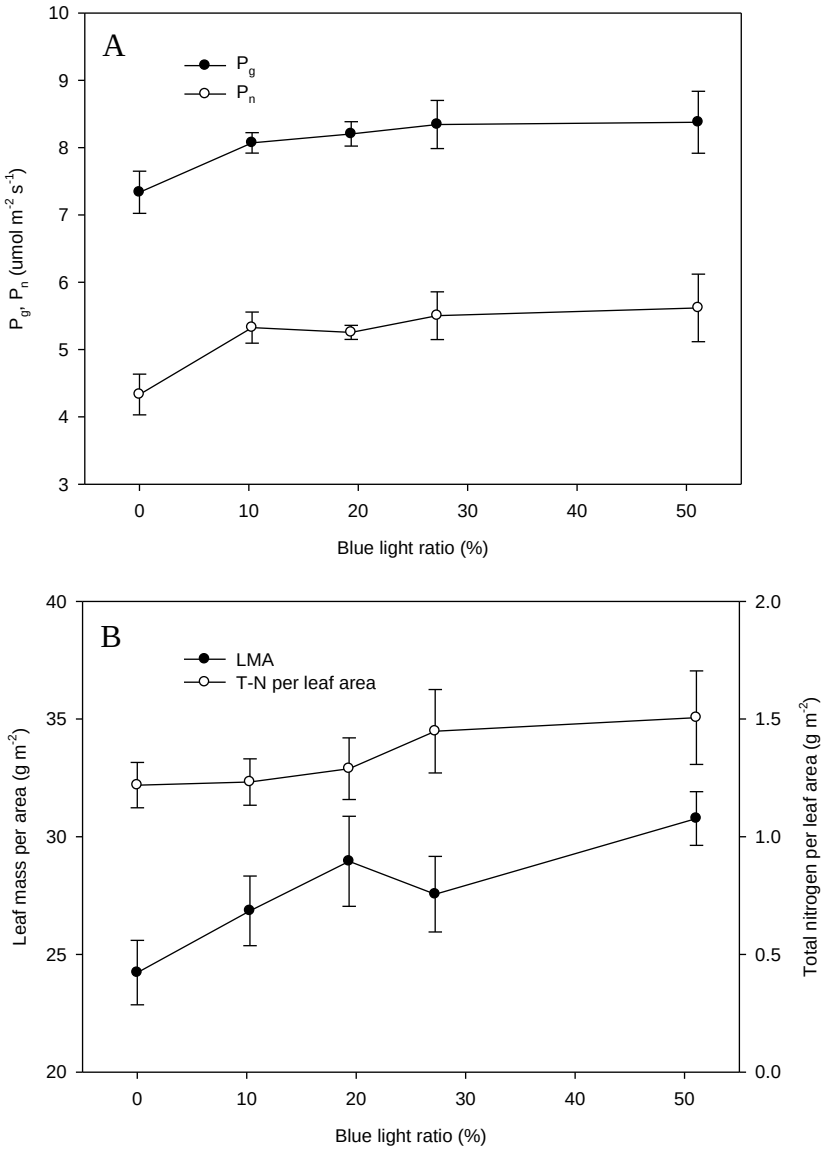

Figure II-3. Gross and net photosynthesis under the growth light condition with an intensity of 166 μmol·m^{-2}·s^{-1} (A) as well as leaf mass (LMA) and total nitrogen per unit leaf area (B) against the percentage of blue light.

Calibration of the modified Nicolet model

The calibrated parameter values had consistent up or down trends toward the increase in the ratio of blue light, except for the ε parameter, which is described as 'photosynthetic efficiency' or 'light efficiency coefficient' (Table 2). However, the ε parameter also indicated a consistent increase with the ratio of blue light when it was calculated under incidence base and not absorption base (data not shown). In contrast, the λ parameter, which was directly calculated, decreased with the percentage of blue light suggesting a decrease in the content of water per unit fresh weight. Among treatment groups, the λ value was exceptionally higher for R7B3 ($\lambda = 0.00245$). Because the λ for R7B3 negatively affected the accuracy of the model estimation and caused deviation from the other parameters on a consistent basis, it was solely obtained by mathematical estimation. The rates of maintenance (k) and growth respiration (θ) increased with the proportion of blue light. The ratio of growth respiration to maintenance respiration (ν) followed the opposite pattern. Higher stomatal conductance (σ) values were observed for the groups with higher blue light values. The parameter involved in the inhibition of photosynthesis (b_p) decreased with the ratio of blue light suggesting a decrease in the sustainability of photosynthesis under high accumulation of photosynthates. The extinction coefficients of the modified Nicolet model (K_{MN}) increased with the percentage of blue light in a decreasing manner similar to those of the new model for direct light ($K_{crop,dir}$) (Tables 2 and 4).

After calibration and curve fitting, the calculated RMSE and RRMSE of the

modified Nicolet model were 0.0631 and 0.1196, respectively. The largest deviation between the observation and estimation was displayed for the leftmost dot group in Fig. 4F, which indicated that the estimation error for the observations at 7 DAT was relatively higher than those at the other time points.

Table II-2 Estimation result of Nicolet parameters.

Parameter	R10B0	R9B1	R8B2	R7B3	R5B5
b_p	0.9013	0.8601	0.8421	0.8310	0.8100
K_{MN}	0.5439	0.7181	0.7792	0.8251	0.8569
k	0.8E-07	1.0E-07	1.3E-07	1.5E-07	1.8E-07
ε	0.0561	0.0593	0.0598	0.0598	0.0588
θ	0.0007	0.0011	0.0013	0.0014	0.0016
λ	0.0019	0.0017	0.0014	0.0013	0.0012
ν	24.2413	17.2778	15.3196	13.2683	11.5767
σ	0.1615	0.2388	0.2702	0.3094	0.3199

Table II-3. The extinction coefficient for direct light ($K_{crop,dir}$), scattering coefficient (σ_{leaf}) and coefficients of vertical compensation factor [z_1, z_2, z_3; eqn (7)] for the new light interception model. All the parameters were taken from Chapter I.

Parameter	R10B0	R9B1	R8B2	R7B3	R5B5
$K_{crop,dir}$	0.3665	0.5115	0.5485	0.5883	0.6111
σ_{leaf}	0.2122	0.1801	0.1734	0.1600	0.1413
z_1			-0.000026		
z_2			0.0329		
z_3			0.9148		

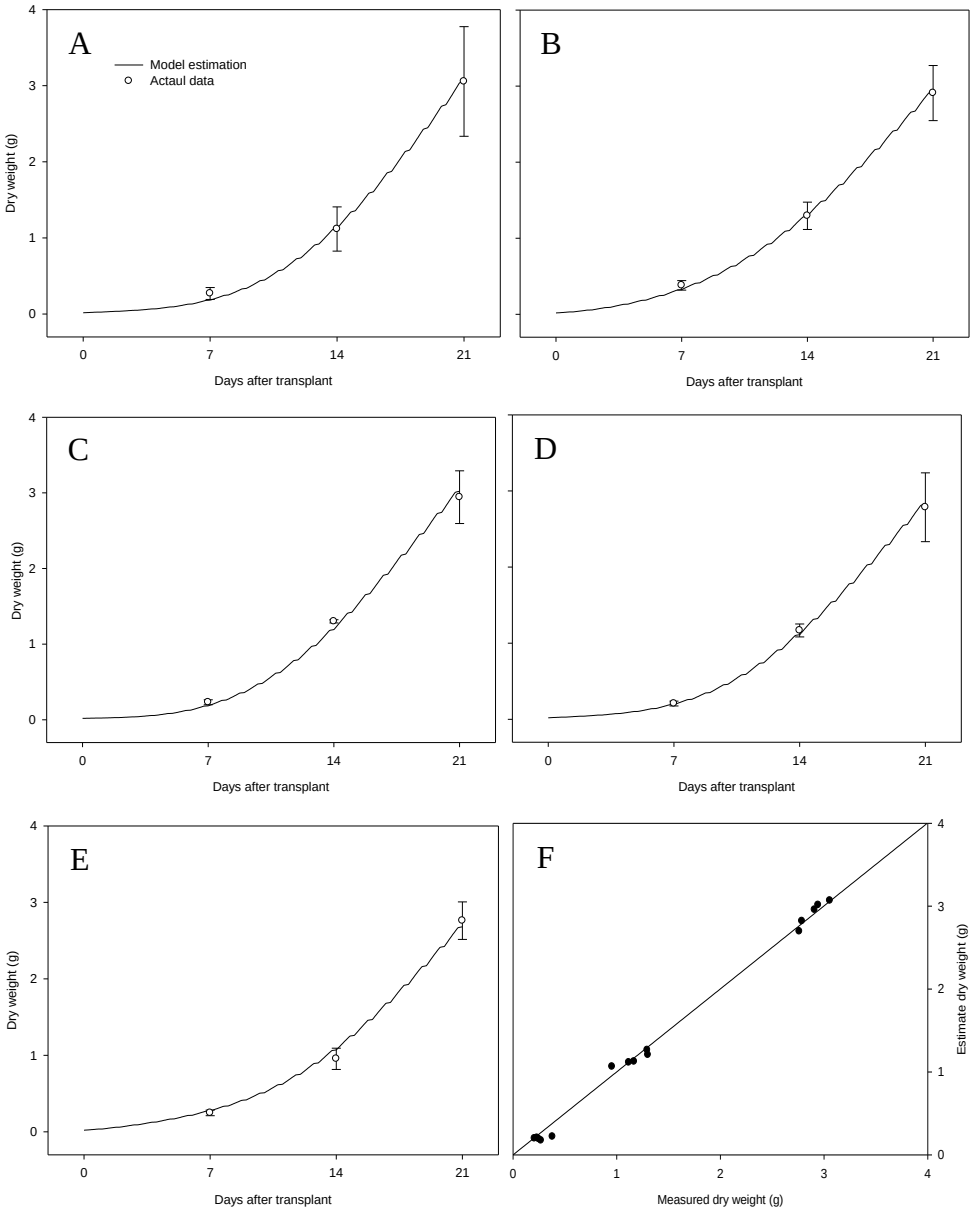

Figure II-4. Curve fitting result of the modified Nicolet model for each treatment group (A, R10B0; B, R9B1; C, R8B2; D, R7B3; and E, R5B5) and comparison of estimated and measured dry weight (F). The regressive equation is as follows: $Y = 1.0007 \cdot x$ ($R^2 = 0.9969$).

Model verification

In terms of RMSE and RRMSE, the single K method displayed lower errors for overall estimations, except for ILI from artificial lettuce (Table 3). Moreover, the application of the new model with the single K method to the Nicolet model decreased the RMSE and RRMSE for the dry weight estimations. Regardless of the K application method, the Nicolet model complemented with the new model indicated a lower RRMSE than the original Nicolet model. The ILI gap between the artificial lettuce and modified Nicolet model was exceptionally higher for R10B0 at 14 DAT (Figs. 5A and 5B). When the RMSE was calculated with the ILIs from artificial lettuce, it was approximately 2 times higher for the single K method than the dual K method (data now shown). The gap of estimation between the dual and single K methods was most noticeable for R10B0 (Fig. 5). Among the regression models for the comparison of the actual and estimated values, the gaps of the slopes between the dual and single K methods were smaller for ILI than ALI (Fig. 6).

Despite the highest ALI, the average dry weight was smaller for R9B1 than R10B0 and R8B2 (Figs. 2B and 5). Differences in the light use efficiency (LUE) over time were observed among R9B1, R10B0 and R8B2 (Fig. 7A). The overall values of LUE were relatively stable for R10B0, and the overall values of LUE for R9B1 and R8B2 fluctuated in the shape of waves. During the entire experimental period, the most drastic changes in LUE were observed for R9B1 where the values were lower and more volatile than R8B2. The photosynthesis inhibition factor of

the Nicolet model (h_p) had similar transitional aspects to LUE, except that it was always the highest for R10B0 (Fig. 7B).

Table II-4. The slopes and R-square values of the regression models in Fig. 7 as well as root mean square error (RMSE) and relative RMSE (RRMSE) calculated by 2 different K application methods for the immediate lighter interception (ILI), accumulative light interception (ALI), and dry weight. Errors of the original Nicolet model were used to investigate the complementary effect of the new model in estimating dry weight.

Error Base	Method	Slope	R^2	RMSE	RRMSE
ILI (Nicolet)	Dual K	1.0124	0.9808	6.8595	0.1260
	Single K	0.9932	0.9860	6.0523	0.1043
ILI (Art. lettuce)	Dual K	0.9753	0.9900	5.7266	0.0892
	Single K	0.9499	0.9829	9.2705	0.0953
ALI (Nicolet)	Dual K	1.0925	0.9940	6.7141	0.1866
	Single K	1.0301	0.9972	2.8767	0.1113
Dry weight	Org. Nicolet	1.0012	0.9960	0.0711	0.1625
	Dual K	1.0620	0.9932	0.1459	0.1528
	Single K	0.9986	0.9969	0.0605	0.1040

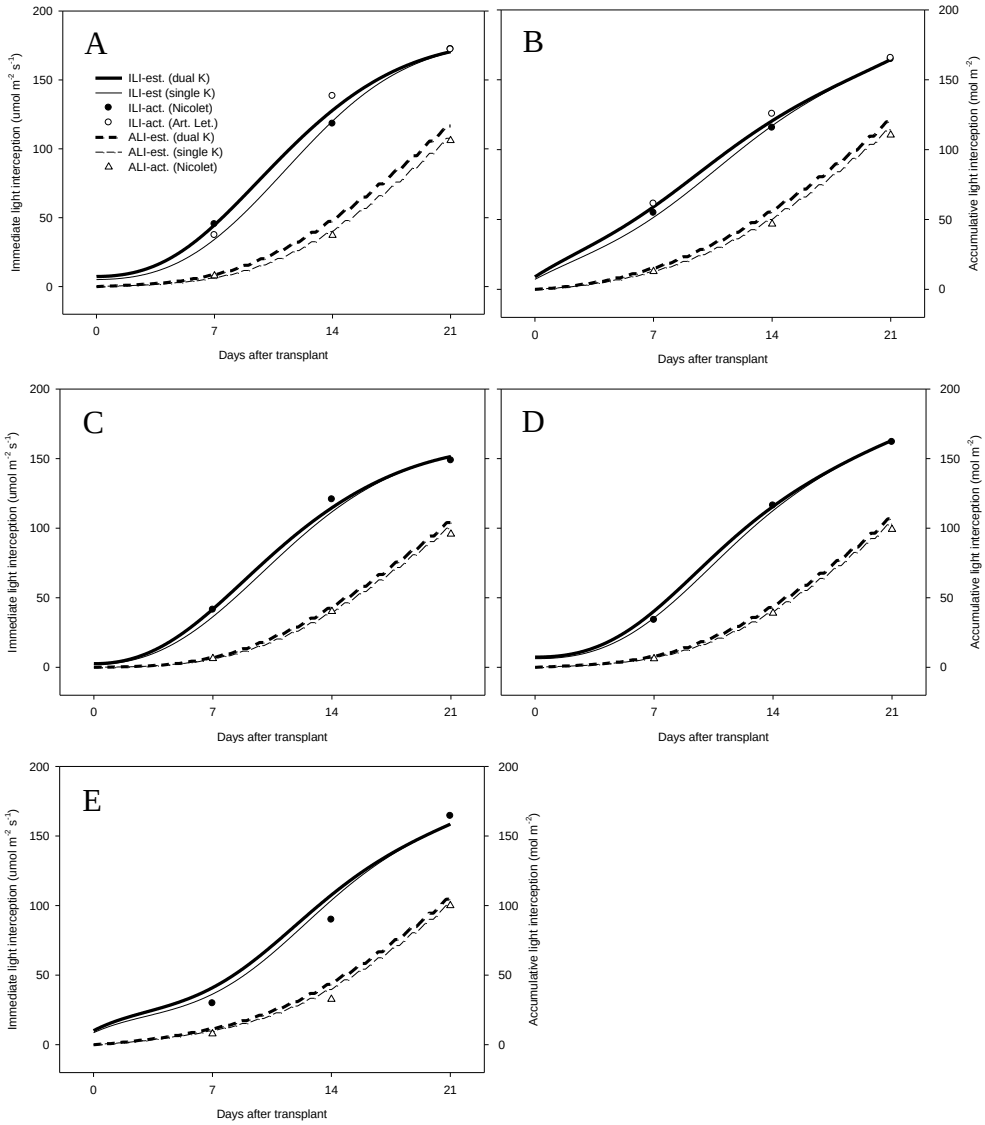

Figure II-5. Comparison of the estimation from the new model and the actual ILI (solid line) and ALI (dotted line) from the artificial lettuce and modified Nicolet model (A, R10B0; B, R9B1; C, R8B2; D, R7B3; and E, R5B5). Thick and thin lines represent estimations from the dual K and single K methods, respectively.

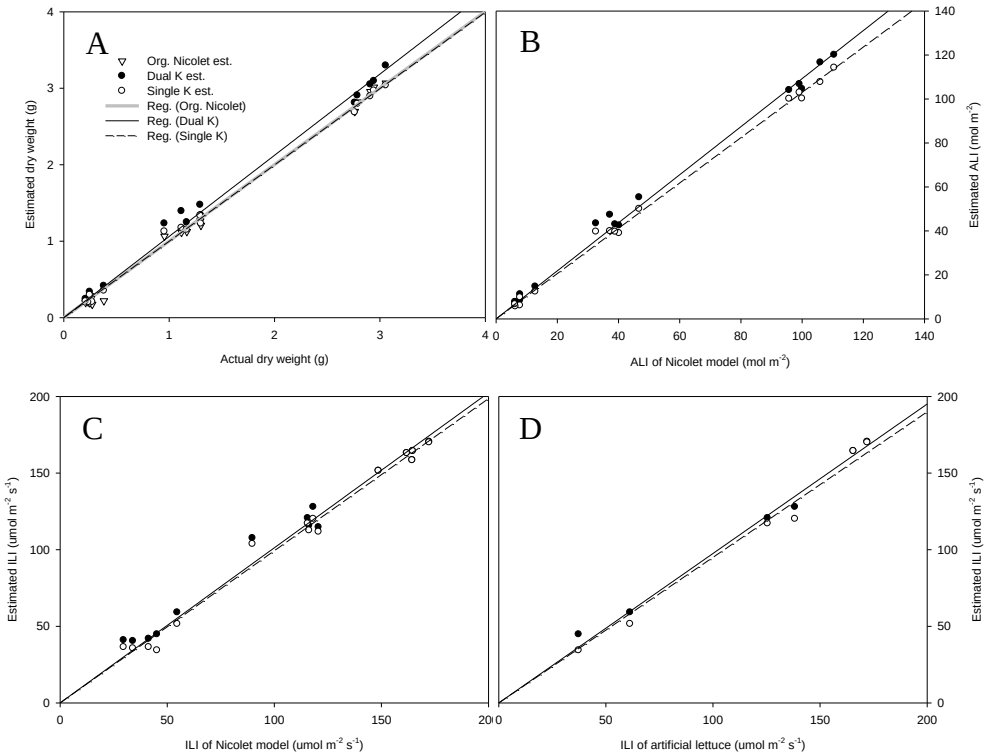

Figure II-6. Comparison of estimated and measured values for dry weight (A), ALI (B) and ILI from the modified Nicolet model (C) and artificial lettuce (D). Solid and dotted lines represent the regression model for estimations from the dual K (●) and single K (○) methods, respectively, except for the red solid line representing that from the original Nicolet model (▽). The slopes and R-square values are shown in Table II-4.

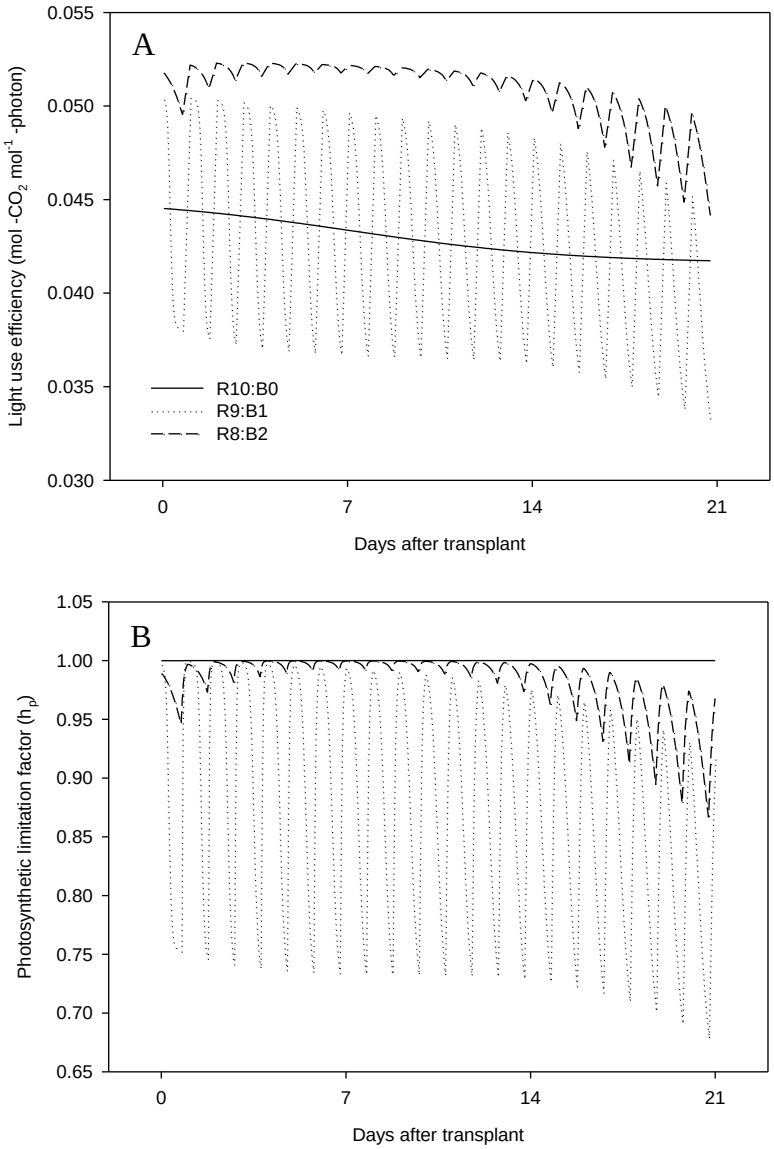

Figure II-7. Change of the light use efficiency (photosynthetic carbon fixation per photon on crop level) (A) and limiting factor of photosynthesis in the Nicolet model (h_p) (B) for R10B0, R9B1 and R8B2.

DISCUSSION

Effect of light quality on plant physiology and related model parameters

The highest ALI was observed for R9B1, and the highest extinction coefficient and photosynthetic rate were observed for R5B5 (Figs. 3A and 5; Tables 2 and 4). Regardless of the above 2 parameters, however, accumulation of biomass was the highest for R10B0 at the end (Fig. 2B). Such a complicated result implied that the light quality was complexly involved in the crop growth. According to the calibration result, incremental blue light increased the proportion of maintenance respiration to growth respiration as well as the volume of both respirations (Table 2). Because crop respiration is proportional to the light intercepting area of the canopy in the Nicolet model, differences in those parameters represent differences in the respiration traits of unit leaf area (Seginer, 2003). Blue light has been reported to contribute to the higher accumulation of leaf mass, chlorophyll, and nitrogen per leaf area (Hogewoning *et al.*, 2010; Poorter *et al.*, 2009). Consequently, the amount of respiration for production and maintenance of unit leaf area is expected to increase with the ratio of blue light, which is also supported by the fact that the reduction of nitrate in plants requires a high quantity of energy consumption (Taiz and Zeiger, 2010). In this regard, the fact that the average dry weight at the end was lower for R9B1 than R10B0 despite the higher ALI can be attributed to the higher respiration of crops under the treatment. Nevertheless, such an interpretation is still incomplete because higher average dry weight was found for R8B2 than R9B1 at the end despite having the higher

respiration parameter values. Moreover, the ALI from the Nicolet model was 15% higher for R9B1 than R8B2 at 21 DAT (data not shown). Therefore, another physiological aspect besides respiration is required to be considered for the exact understanding.

According to Gent and Seginer (2012), light intensity is involved in the determination of the required reserve of non-structural carbon in plants. Stronger light causes a higher minimum reserve level and, thus, may have a negative influence on the capacity of photosynthate storage in leaves. The photosynthesis inhibition border (b_p) decreased with the percentage of blue light, which suggested that the inhibition would appear at a lower level of photosynthate accumulation. (Table 2) The higher ratio of blue light should have the same influence on the parameter as the stronger light as previously suggested (Hogewoning *et al*., 2010b). The simulation result displayed a more fluctuant LUE for R9B1 and R8B2 than for R10B0 (Fig. 6A). The photosynthetic limitation factor (h_p) is a function that includes b_p as one of the coefficients, and it indicates the current ratio of photosynthesis to the potential. When h_p is 1, there is no inhibition, and photosynthesis is the same as the potential or maximum in the crop. A lower value of h_p for R9B1 implied that even though the accumulation of photosynthates was relatively faster under the treatment for the higher ALI, it exceeded the storage capacity resulting in inhibition of photosynthesis (Fig. 6B). In contrast, the maximum efficiency was the lowest for R10B0, but the photosynthetic inhibition was also the lowest for R10B0, which presumably accounted for the higher

biomass accumulation. As compared to R8B2, the LUE and h_p under the R9B1 treatment displayed steeper decreases and lower maximum values during the entire experimental period, which was considered to be the main reason for the lower dry weight.

The above results suggest that the light quality affected the crop growth through various channels, such as the storage capacity of leaves, light interception and quantum use efficiency. Moreover, these results also suggest that the transitional aspects of the calibrated Nicolet parameters according to the ratio of blue light were consistent with the results of previous studies.

Interpretation of results and implications

Overall, the new model with the single K application exhibited a lower estimation error than the new model with the dual K application, which indicated that the pattern of light incident on canopy after ground reflection was more similar to that of the initial direct downward flux, rather than uniform distribution (Table 3). Nevertheless, the single K-adopted model showed the higher error for ILI calculated from artificial lettuce. However, there was a marked gap between ILIs from the modified Nicolet model and artificial lettuce for R10B0 at 21 DAT. The gap of ILIs between the K application methods was also the highest for R10B0, which suggested that crop light interception under this treatment was more sensitive to related conditions than under the other treatments. Thus, the artificial

lettuce for R10B0 involved more risks of distortion of the light interception during the processes of production and measurement. In addition, part of the model error may have been induced by the scattering coefficients (σ_{leaf}) and extinction coefficients for diffuse light (K_{diff}), which were estimated with data from previous studies and discretionary assumptions and not from actual measurements.

Even when a plant canopy is completely closed and has accumulated massive leaf layers, it is unable to capture all of the incident photons due to the inherent reflectance (Goudriaan and Laar, 1994). Accordingly, the potential amount of light interception is limited to the fraction of light penetrable to canopy, i.e., the remainder of incident light after subtracting the initially reflected fraction. Before the adjustments, the ILIs from both the artificial lettuce and modified Nicolet model exceeded the potential amount as the end approached (data not shown). Moreover, all the ILI and ALI data obtained from the Nicolet model required correction of the estimation error. Although the ratio of incremental light to weight for lettuce has been reported to be approximately 1, there is still controversy surrounding if both ILI and ALI are absolutely proportional to the dry weight in common (Pinho *et al*., 2012).

Despite the limited suitability of parameters and reference standards for ILI and ALI as stated, an encouraging result for the new model was that the total RRMSEs for ILI, ALI and dry weight were not higher than 11% and that the application complemented the original Nicolet model for the accuracy of estimation under the single K method (Table 3). The fact that the new model

contributed to the reduction of the RMSE and RRMSE at the same time and that the relative reduction of RRMSE was much more than that of RMSE suggested that it enhanced the accuracy of estimation for the entire growth period. Because RMSE is affected more by higher values, the models with low RMSE but high RRMSE tend to generate larger estimation errors for crops in the early or middle growth stage even though the error decreases over time due to the low RMSE. In this regard, the new model can be more useful for crops that require relatively long growth periods. However, it is necessary to use more reliable standards for the actual light interception and parameters for the purpose of further studies with higher precision and applicability.

Beyond the reasonable performance of the new model, this study also provided novel insights for the quantification of relation between the light quality and plant growth. At first, our results suggested that the b/a ratio (ratio of horizontal radius to vertical radius of canopy) can be the key to understand and forecast changes in the efficiency of crop light interception. The light spectral effect on the light interception is attributed to transformation of the plant canopy (Hogewoning *et al*., 2010c). The quantitative application of light spectral effect on the light interception has been limited due to the difficulties in quantifying the effects of morphological change. However, the b/a ratio is expected to be the feasible solution available for a variety of crops as well as for lettuce because it comprehensively embraces morphological traits of plants, such as leaf angle, relative growth of stem, relative growth of petiole, and leaf folding, in an

undetailed but general manner. Therefore, the use of the b/a ratio should contribute to a more objective interpretation of the effect of light quality on plant growth and to improvement of the predictability.

In addition, the new model suggested a methodology for the quantification and simplification of the ideal canopy form or canopy ideotype for light interception. There have been various studies on canopy ideotype in which complicated and elaborate approaches are required for the analysis and integration of diverse data associated with morphological traits (Peng *et al*., 2008, Sarlikioti *et al*., 2011b). Being less accurate but more efficient, the ideotype can be obtained by optimisation of the new model considering the light environment and pattern of plant growth. More specifically, the ideotype can be defined as the target b/a ratio of a particular crop under a certain light condition that needs to be achieved by various technical means, including light spectral treatments, for higher productivity.

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CONCLUSIONS

This new model dynamically outlines the light profile of the latest horticultural facilities and crop light interception more similar to real circumstances by the quantitative application of crop morphology and of the optical properties of both the light source and surrounding material than the previous models based on natural sunlight. The simulation result indicates that light interception varies with the quality and distribution of light inside the facility, which emphasises the need to change the paradigm of the conventional method, which manages the light environment with a single factor of initial light intensity. Moreover, it also suggests that the higher reflection and light-scattering from surrounding materials complements the unfavourable form of the canopy for light interception and the effect is stronger in the early stage of growth, proposing more economic and less energy consuming methodology for the improvement of productivity.

In regards to model accuracy, the new model with single K application displayed the lower estimation error than with dual K and enhanced the accuracy of an established growth model to which it was transplanted. In terms of crop modeling, this result suggests a possibility to quantify the effect of light quality on crop light interception simply through a single parameter, b/a ratio. At the same time, in terms of cultivation technique, the new model suggests a simplified methodology for the determination of ideal canopy form in a quantitative manner.

ABSTRACT IN KOREAN

작물 생육 모델과 관련된 연구 중 작물의 수광량을 정확히 추정하기 위한 모델의 구축은 가장 중요한 연구 주제 중 하나이다. 최신 원예 시설 내의 광환경은 다수의 인공광원 및 반사재질의 사용으로 자연상태와 비교하여 상당히 변형된 양상을 보인다. 다양한 광환경 요소들의 영향에 대한 정량화의 어려움으로, 이러한 시설 내 작물의 수광량을 예측하기 위한 모델의 개발은 현재 미진한 상태이다. 본 연구의 목적은 이러한 시설들의 주요 특성을 반영하는 모델을 개발하고 (Chapter I), 그 적합성 및 응용가능성을 증명 (Chapter II)하는데 있다. 이를 위해 Chapter I 에서는 식물공장 내 광환경을 분석한 후 이를 근거로 새로운 모델을 구축하였으며, Chapter II 에서는 변형된 Nicolet 모델 및 모형상추를 사용하여 측정 · 계산된 실제의 작물수광량과 본 모델의 추정결과를 비교하였다. 또한 새로운 수광량의 추정 모델의 측정결과가 Nicolet 모델에 적용되어 전체 생육모델의 정확성에 미치는 영향을 조사하였다. 결과적으로 지면반사율 및 산란광 비중과 같은 주변의 광환경이 전체 작물 수광량에 현저한 영향을 주는 것으로 나타났다. 새로운 모델은 RRMSE 를 기준으로 11%의 오차범위 내에서 시점별 및 누적수광량을 추정해낼 수 있었으며, 기존 Nicolet 모델을 보완하여 전체 생육모델의 추정 정확성 또한 높이는 것으로 나타났다. 본 연구의 결과는 단순히 초기 입사광도만을 기준으로 식물공장 또는 생육챔버의 광환경을 관리하는 기존의 관행에 변화가

필요함을 보여주고 있으며, 새로운 모델이 단일 파라미터인 'b/a ratio'를 통해 작물수광량에 대한 광질의 영향 및 이상적 캐노피 형태를 정량화할 수 있는 방법론을 제시하고 있음을 나타낸다.