Estimation of the light interception of a cultivated tomato crop canopy under different furrow distances in a greenhouse using the ray tracing

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Abstract

We constructed 3D models of the greenhouse (168 m²) and tomato plants (plant height: 150 cm). The point cloud data of tomato plants was acquired by a 3D scanner and converted to the 3D model, which was constructed using polygons. The canopy 3D model was installed in the greenhouse 3D model. In addition, the date, time, latitude, longitude, global solar radiation, and optical properties of objects, such as plants and covering material, were used as input values to estimate the amount of solar radiation received by canopy models using the ray tracing. The amount of solar radiation received by the canopy models at different layers under different furrow distances (60–160 cm) was calculated every 1 h. The lower layer and the middle layer of tomato plants were saturated with solar radiation at furrow distances of 120 cm and 100 cm, respectively. However, the radiation received by the upper layer of tomato plants did not change across the range (60–160 cm) of investigated furrow distances. This investigation has provided a visual demonstration of the relationship between the arrangement of cultivated fruit and vegetable plants, such as tomato, in the greenhouse and the amount of solar radiation received.

Key words: Canopy, Light environment, Optical simulation, Solanum lycopersicum, 3D model

1. Introduction

When cultivating tall fruit vegetable plants, such as tomato, the amount of solar radiation received by the plant canopies varies depending on the seasonal and daily changes in the solar altitude, which in turn affects the yield. There have been several previous investigations into the relationship between plant density and yield. When tomato plants were cultivated with different spacings (23, 30, 38, 45, 53, and 60 cm) in Ontario, Canada, the fruit set rate was not affected by plant spacing except under 23 cm spacing in fall; on the other hand, it declined steeply in spring with decreasing plant spacing (Papadopoulos and Ormrod., 1990). In addition, Amundson et al. (2012) demonstrated that tomato plants grown at a spacing of 70 cm had significantly higher fruit yields per plant than when grown at 30 cm plant spacing, but that yield per area decreased with wider plant spacings in Tennessee, USA. Cebula (1995) reported that the highest total yield of sweet pepper was obtained from plants pruned to one shoot, and grown at 8 plants m⁻² in Cracow, Poland.

However, it is difficult to apply the results obtained in some conditions because of the variations in location and season, and the amount of solar radiation received by the canopies varies depending on the solar altitude. An optical simulation to estimate the light environment inside the plant canopy can offer a viable solution to address this problem.

Recently, it has become possible to estimate the light environment in a greenhouse environment using optical simulation. Buck-Sorlin et al. (2011) used a Monte-Carlo light model with functional-structural plant modeling (FSPM) of the cut-rose to compute the local light climate for leaf photosynthesis. Sarlikioti et al. (2011) revealed that the internodes and shape of leaves of tomato plants affects the light environment in a canopy, whereby those with long internodes and thin leaves were shown to be suitable for winter cultivation when the reduction of light was large at the lower levels of the canopy in winter. de Visser et al. (2014) reported that the combination of a ray tracer and a tomato 3D model could compute the optimal lighting of leaves by the quantification of light fluxes by rendering the lighting patterns. Higashide (2009) used optical simulations to demonstrate that the light attenuation in the plant canopy in a sloped greenhouse built on sloping land was significantly less than that in a conventional greenhouse. Li et al. (2018) simulated the interactions between light and heterogeneous 3D forest scenes using Monte Carlo path tracing with the 3D structure of the forest constructed with a LiDAR. Perez et al. (2018) indicated that significant differences in light interception efficiencies in different palm progenies were observed, using five 3D architectural models, constructed with a LiDAR and ray tracing. The importance of plant architectural components, such as internode length and leaf shape for light absorption and photosynthesis, were investigated using a virtual plant (Sarlikioti et al., 2011). Hosoi et al. (2011) constructed a 3D model of a tomato canopy using a portable high-resolution scanning LiDAR and indicated that a mean absolute percent error of estimated leaf area from the polygons was 4.6%. Zhang et al. (2018) described that the 3D imaging technique has the potential for remotely monitoring plant growth.

As described above, the optical simulation can estimate the light interception of plants under different canopy structures and cultivation environments. Additionally, the plant 3D models can...
reflect the plant growth and plant morphology. Generally, crops are cultivated using furrows; and the leaf area and structural changes depend on the growth stage (Sameshima, 1995). Jiang et al. (2017) reported that the periodic alteration of the plant density for tomato using the movable bench was effective to improve the light environment of lower canopies. Therefore, the furrow distance is important when considering the light environment around the canopy. Optical simulation was suitable for identifying the light distribution inside plant canopies with different furrow conditions, as it can be utilized with variable factors, such as greenhouse structures, plant species, location, and season. However, when investigating the relationship between the furrow distance and light interception of fruit vegetables, the use of optical simulation has not been reported.

In this study, we estimated the light interception of a cultivated tomato crop canopy under different furrow distances using the ray tracing method. This will enable us to visualize the relationships between the plant arrangement and the amount of solar radiation received by the plants.

2. Materials and Methods

2.1 Test plants and greenhouse

Tomato plants (Solanum lycopersicum L., ‘Reika’, SAKATA SEED Co., Ltd.), 3 weeks after sowing, were transplanted on rockwool cubes (DELTA6.5G, Grodan Inc.) on March 21, 2019. The rockwool cubes were installed on rockwool slabs (2075 A2W, Grodan Inc.) in an experimental greenhouse (168 m²). Plants were arranged in a zigzag pattern and at a distance of 33 cm between plants. Twelve plants were transplanted in a cultivation bench with a furrow distance of 120 cm (Fig. 1). Polyolefin film (transmittance: ~70%) was used as the covering material of the greenhouse. The greenhouse was equipped with a roof and side-wall ventilators. The air temperature and vapor pressure deficit in the greenhouse during the cultivation period (March 21–May 23, 2019) were as follows.

- The average air temperatures of the light period (6:00–18:00) and dark period (18:00–6:00) were 24.4°C and 16.7°C, respectively.
- The vapor pressure deficits of the light period and dark period were 1.2 kPa and 0.3 kPa, respectively.

2.2 Construction of the 3D model of the tomato canopy

Point cloud data was acquired by scanning a tomato canopy of six plants at 63 days after transplanting (DAT) using a 3D scanner (DPI-8X, OPT Inc.). The PrimeSense Carmine sensor 1.08 (Apple Inc.) was installed onto the 3D scanner. The measuring range was from 0.6 to 4.0 m (spatial x/y resolution at 2 m was 3.4 mm; depth resolution at 2 m was 12 mm). When the measured distance was 1.0, 2.0, and 3.3 m, the accuracy of the 3D scanner was 2, 6, and 10 mm, respectively. When the point cloud data was acquired, the measured distance between the 3D scanner and tomato canopy ranged from 0.6 to 1.0 m. The 3D scanner orbited the canopy for scanning after sunset. About 20 million point clouds were acquired. The point cloud data was converted to the polygon data using OPT Cloud Survey (OPT Inc.) to construct the 3D model of the tomato canopy. Houdini 17 (Side Effect Inc.) trimmed unnecessary polygons and reduced the polygons of the canopy 3D models. Overall, the canopy 3D model was composed of 200 thousand polygons. We reported that the regression model between the measured individual leaf area and the estimated leaf area by calculating the polygon areas, showed a linear and good estimation (R² = 0.99, Mean absolute error (MAE) = 34.0 cm²) (Ohashi et al., in press). The above MAE was calculated using the data of Ohashi et al. (in press). The canopy 3D model was installed in the greenhouse 3D model, and 12 plants were positioned on the cultivation bench using SketchUp 2017 (Trimble Inc.). (Fig. 2). The greenhouse 3D model was constructed using SketchUp 2017 based on the blueprint of the greenhouse. The furrow distance was virtually altered to range from 60 to 160 cm (Fig. 3). The same canopy 3D model was used regardless
2.3 Estimation of the light environment

The light environment was estimated using optical simulation software (Radiance 5.2, Berkeley Lab) that is mainly used in the architectural field. Using sunlight as the light source, Radiance can simulate the light distribution, considering optical properties such as reflectance and transmittance by ray tracing. Maamari et al. (2005) reported that it is possible to estimate the light environment by Radiance with high accuracy, except for the indirect lightning test with reflectance values of 0.8 and above. Takada et al. (2008) indicated that Radiance could simulate solar altitude.

The date, time, latitude, longitude, and global solar radiation at the greenhouse location (Matsudo, Chiba, Japan) were used as the input values to estimate the photosynthetic photon flux density (PPFD) in the greenhouse. The transmittance (400–700 nm) of the covering material of the roof and south and north sides was 70%, and the diffuse light in all transmitted light was set at 20%. The transmittance of the covering material of the east and west sides was set at 50%. The set values of transmittance for the covering materials were decided by considering the aging and degradation of the polyolefin films. Reflectance and transmittance (400–700 nm) of tomato leaves were measured using a spectrophotometer (V-750, Jasco Inc.) fitted with an integrating sphere unit (ISV-922, Jasco Inc.), and were determined to be 8% and 3%, respectively. The ratios of diffuse reflection in all reflected light and diffuse transmission in all transmitted light from tomato leaves, were both set at 70%. The above ratios were based on the values measured using a self-made integrating sphere. The annual date which characteristically has the highest solar altitude, June 21, was chosen as the target day for the estimation of the light environment to estimate the effect of furrow distance and diffuse solar radiation on the solar radiation received. The global solar radiation used as the input value and the solar altitude are shown in Fig. 5. The ratio of diffuse solar radiation to the global solar radiation was set at 10% or 90%. Normally, global solar radiation is smaller under a high ratio of diffuse solar radiation; however, the same input value of global solar radiation was used under different weather conditions in this study. When converting irradiance (W m⁻²) into PPFD (µmol m⁻² s⁻¹) in the simulation, the ratio of the photosynthetically active radiation in the solar radiation was assumed 45% (Jacovides et al., 2003) and the conversion factor of 4.57 from irradiance (400–700 nm) to PPFD (McCree, 1972) were used.

The PPFD was estimated at the center of gravity of each polygon of the 3D canopy model. The estimated PPFDs per plant was calculated by integrating the canopy PPFDs. Six plants were used to simulate the tomato canopy, as shown in Fig. 1. These plants included one edge plant that was located on the north side and was less affected by direct solar radiation. The tomato canopy was divided into three layers, the lower (0–50 cm), middle (50–100 cm), and upper layers (>100 cm). The leaf areas of the lower, middle, and upper layers were 1909, 2997, and 574 cm², respectively (Fig. 4). The hourly and daily (6:00–19:00) integrated PPFDs per plant were estimated for each layer. The daily integrated PPFD per cultivation area was also estimated.
We had already checked the accuracy of the above simulation model by measuring the PPFDs of the lower, middle, and upper layers inside the real canopy from November 27 to November 30, 2018. The MAE of the estimated daily integrated PPFD was 0.7 mol m$^{-2}$ day$^{-1}$ and the above value was calculated using the data of Ohashi et al. (in press).

3. Results and Discussion

The daily integrated PPFDs per plant (on June 21) under different furrow distances (60–160 cm) are shown in Fig. 6. The relationship trend between furrow distance and the daily integrated PPFD per plant was almost the same when the ratio of diffuse solar radiation to the global solar radiation was set at 10% or 90%. In the lower canopy layer, the daily integrated PPFD per plant increased and became saturated as the furrow distance increased up to 120 cm. In the middle layer, the daily integrated PPFD per plant was saturated at 100 cm. In the top layer, the daily integrated PPFD per plant was not influenced by the furrow distance between 60 and 160 cm. Therefore, the daily integrated PPFD per plant was saturated at 120 cm or at longer furrow distance between 60 and 160 cm. The hourly integrated PPFD per plant at the lower layer from 60 to 160 cm furrow distances, regardless of the ratio of diffuse solar radiation.

The largest daily integrated PPFD among the layers was observed in the middle layer, followed by the lower and upper layers (in this order). The upper layer easily received solar radiation; however, the leaf area of the tomato plant at the upper layer was found to be smaller than those of the lower and middle layers (Fig. 4). Therefore, the daily integrated PPFDs per plant of the lower and middle layers were larger than that of the upper layer.

A comparison of the daily integrated PPFD per plant between the 10% and 90% ratios of diffuse solar radiation revealed that the PPFD was larger at 10%. The solar radiation came from all directions in the greenhouse when the ratio of the diffuse solar radiation was large. In addition, the ratio of solar radiation coming from the side of the greenhouse increased as the ratio of diffuse solar radiation increased. It is noteworthy that the side film transmittance of the greenhouse used in the present study was lower than the top film transmittance. Therefore, the daily integrated PPFD per plant was larger when the ratio of diffuse solar radiation was 10%.

The hourly integrated PPFD per plant under different furrow distances (60–160 cm) and the ratios of diffuse solar radiation are shown in Figs. 7 and 8. When the ratio of diffuse solar radiation was set at 10%, the hourly integrated PPFD per plant fluctuated in that day because it was influenced by the greenhouse structure (Fig. 7). Hayashi and Suzuki (1996) indicated that the greenhouse structure easily affected the direct solar radiation in the greenhouse. In addition, high light intensity under direct solar radiation usually induces photosynthetic saturation and decreases light use efficiency, because the photosynthetic rate of a single leaf has a nonlinear response to the light flux density (Li and Yang, 2015). On the other hand, the tendency of hourly integrated PPFD per plant was similar to the global solar radiation (Fig. 5) value used as the input value when the ratio of diffuse solar radiation was set at 90% (Fig. 8). Ohishi (2016) indicated that the tendency of diffuse solar radiation in the greenhouse was similar to the global solar radiation, because the effect of the greenhouse structure on the diffuse solar radiation was small. When the ratio of diffuse solar radiation was large, the solar radiation entered from all directions of the greenhouse. Therefore, the hourly integrated PPFD per plant under the high ratio of diffuse solar radiation was not influenced by the greenhouse structure. Hence, the equalization of the light environment in the canopy can be expected if a covering material that increases scattered light is used in climatic conditions that involve an abundance of direct solar radiation.

**Fig. 5.** The virtual global solar radiation outside the greenhouse and the solar altitude on June 21. Global solar radiation was used as an input value for the optical simulation. The global solar radiation consists of diffuse and direct solar radiation. The solar altitude represents that of Matsudo, Chiba, Japan.

**Fig. 6.** Effect of furrow distance on the daily integrated photosynthetic photon flux density (PPFD) per tomato plant (June 21). The daily integrated PPFD (6:00–18:00) was simulated by Radiance (Berkeley lab) under diffuse solar radiation levels of 10% and 90% of the global solar radiation. Tomato plants were 63 DAT. Plant height was ~150 cm.
Furthermore, Li et al. (2014) reported that the deeper penetration of diffuse light played a positive role in tomato photosynthesis enhancement at a high LAI, when a diffuse covering material was used. Hemming et al. (2008) indicated that diffuse light converted from direct solar radiation by diffuse material had a positive effect on cucumber production in the summer because of the deeper light penetration into the canopy, and the increased photosynthesis capacity. It will be important to use our simulation method to evaluate the performance of covering materials, to find the best material when considering plant species, greenhouse structure, and season.

The daily integrated PPFDs per cultivation area (on June 21), with the different furrow distances (60–160 cm), are shown in Fig. 9. The tendencies of the daily integrated PPFDs per cultivation area, with the different furrow distances, were the same between the different ratios of diffuse solar radiation. In the middle and upper layers, the daily integrated PPFD per cultivation area became larger as the furrow distance became narrower. Contrarily, in the lower layer, the integrated PPFD per cultivation area tended to decrease at furrow distances of < 80 cm. Across the entire canopy, the narrower furrow distances were found to increase the light interception per cultivation area. However, tomato plants are often confronted with light insufficiency for leaf photosynthesis, plant growth, and fruit development in the lower canopy (Jiang et al., 2017). Therefore, in the future, we need to consider canopy photosynthesis when selecting furrow distance, to increase the productivity in the greenhouse.

Hence, if canopy 3D models are constructed using real canopies during cultivation, we can determine the furrow distance to increase light interception per plant or cultivation area.
4. Conclusions

The simulation developed in this study enabled the estimation of the hourly and daily integrated PPFD of the tomato canopy under different furrow distances using the tomato canopy 3D model with ray tracing. This methodology also enabled the estimation of the integrated PPFD of each layer of plants. The amount of solar radiation received by the lower and middle layers of the tomato plant canopy was saturated when the furrow distances were 120 and 100 cm, respectively. The radiation received by the upper layer of tomato plants did not change between treatments with 60–160 cm furrow distances. In the middle and upper layers, the daily integrated PPFD per cultivation area became larger as the furrow distances narrowed. In the lower layer, the integrated PPFD per cultivation area tended to decrease at the furrow distance of < 80 cm. The present study could estimate the light interception per plant and cultivation area under different furrow distances at each layer in the greenhouse. Therefore, if canopy 3D models are constructed using real canopies during cultivation, we will be able to determine the furrow distance to increase light interception per plant or cultivation area.

References

Amundson S, Dayton DE, Kopsell DA, Hitch W, Moore A, Sams CE, 2012: Optimizing plant density and production systems to maximize yield of greenhouse-grown “Trust” tomatoes. HortTechnology 22, 44–48. doi.org/10.21273/HORTTECH.22.1.14

Buck-Sorlin G, De Visser PHB, Henke M, Sarlikioti V, Van Der Heijden GWAM, Marcelis LFM, Vos J, 2011: Towards a functional structural plant model of cut-rose: Simulation of light environment, light absorption, photosynthesis and interference with the plant structure. Annals of Botany 108, 1121–1134. doi.org/10.1093/aob/mcr190

Cebula S, 1995: Optimization of plant and shoot spacing in greenhouse production of sweet pepper. Acta Horticulturae 412, 321–329. doi.org/10.17660/ActaHortic.1995.412.37

de Visser PHB, Gerhard H, Buck-Sorlin GH, van der Heijden GWAM, 2014: Optimizing illumination in the greenhouse using a 3D model of tomato and a ray tracer. Frontiers in Plant Science 5, 1–7. doi.org/10.3389/fpls.2014.00048

Hayashi S, Suzuki H, 1996: Fluctuation characteristics of solar radiation in crop cultivation. Technical bulletin of Faculty of Agriculture, Kagawa University 48, 111–118 (in Japanese with English summary).

Hemming S, Duede T, Janse J, Van Noort F, 2008: The effect of diffuse light on crops. Acta Horticulturae 801, 1293–1300. doi.org/10.17660/ActaHortic.2008.801.158

Higashide T, 2009: Light interception by tomato plants (Solanum lycopersicum) grown on a sloped field. Agricultural and Forest Meteorology 149, 756–762. doi.org/10.1016/j.agrformet.2008.10.017

Hosoi F, Nakabayashi K, Omasa K, 2011: 3-D modeling of tomato canopies using a high-resolution portable scanning lidar for extracting structural information. Sensors 11, 2166–2174. doi.org/10.3390/s110202166

Jacovides CP, Tymvios FS, Asimakopoulos DN, Theofilou KM, Pashiarides S, 2003: Global photosynthetically active radiation and its relationship with global solar radiation in the Eastern Mediterranean basin. Theoretical and Applied Climatology 74, 227–233. doi.org/10.1007/s00704-002-0685-5

Jiang C, Jolkan M, Hohjo M, Tsukagoshi S, Ebihara M, Nakaminami A, Maruo T, 2017: Responses of leaf photosynthesis, plant growth and fruit production to periodic alteration of plant density in winter produced single-truss tomatoes. Horticulture Journal 86, 511–518. doi.org/10.2503/horj.OKD-060

Li T, Heuvelink E, Duede TA, Janse J, Gort G, Marcelis LFM, 2014: Enhancement of crop photosynthesis by diffuse light: Quantifying the contributing factors. Annals of Botany 114, 145–156. doi.org/10.1093/aob/mct071

Li T, Yang Q, 2015: Advantages of diffuse light for horticultural production and perspectives for further research. Frontiers in Plant Science 6, 1–5. doi.org/10.3389/fpls.2015.00704

Li W, Guo Q, Tao S, Su Y, 2018: VBRT: A novel voxel-based radiative transfer model for heterogeneous three-dimensional forest scenes. Remote Sensing of Environment 206, 318–335. doi.org/10.1016/j.rse.2017.12.043

Maamari F, Fontoyonnt M, Tsangrassoulis A, Marty C, Kopyluv E, Syntik G, 2005: Reliable datasets for lighting programs validation-benchmark results. Solar Energy 79, 213–215. doi.org/10.1016/j.solener.2004.12.003

McCree KJ, 1972: Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. Agricultural Meteorology 10, 443–453. doi.org/10.1016/0002-1571(72)90045-3

Ohishi N, 2016: Non-disruptive evaluation of leaf area index using diffused light sensor for tomato cultivation. Journal of Society of High Technology in Agriculture 28, 125–132 (in Japanese with English summary). doi.org/10.2525/shita.28.125

Ohashi Y, Ishigami Y, Goto E: Estimation of the light environment inside a tomato canopy in a greenhouse by using the ray tracing method. Acta Horticulturae (in press).

Papadopoulos AP, Ormrod DP, 1990: Plant spacing effects on yield of the greenhouse tomato. Canadian Journal of Plant Science 70, 565–573. doi.org/10.4141/cjps90-071

Perez RA, Costes E, Théveny F, Griffon S, Caliman JP, Dauzat J, 2018: 3D plant model assessed by terrestrial LiDAR and hemispherical photographs: A useful tool for comparing light interception among oil palm progenies. Agricultural and Forest Meteorology 249, 250–263. doi.org/10.1016/j.agrformet.2017.11.008

Sameshima R, 1999: Estimating the absorptivity of solar radiation in soybean canopies for use in crop models. Journal of Agricultural Meteorology 51, 37–45. doi.org/10.2480/agrmet.51.37

Sarlikioti V, de Visser PHB, Buck-Sorlin GH, Marcelis LFM, 2011: How plant architecture affects light absorption and photosynthesis in tomato: towards an ideotype for plant architecture using a functional-structural plant model. Annals of Botany 108, 1065–1073. doi.org/10.1093/aob/mcr221

Takada Y, Komine H, Masuo W, Mochizuki E, Kimura H, 2005: Study on the evaluation method of energy saving in electric lighting by daylight illumination (Part 1) Verification of the simulation accuracy for the indoor daylight illuminance distribution based on simulation software of SUPERLITE and RADIANCE. The Society of Heating, Air-Conditioning Sanitary Engineers of Japan, 2227–2230 (in Japanese with English summary). doi.org/10.18948/shasetaikai.2008.3.0_2227

Zhang Y, Teng P, Aono M, Shimizu Y, Hosoi F, Omasa K, 2018: 3D monitoring for plant growth parameters in field with a single camera by multi-view approach. Journal of Agricultural Meteorology 74, 129–139. doi.org/10.2480/agrmet.D-18-00013