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Light distribution in Chinese solar greenhouse and its effect on plant growth

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Abstract

Chinese solar greenhouse (CSG) is universally applied in northern China for producing horticultural products. CSG is characterized by the unbalanced structures with an arched front roof face to the south side and a thick wall as well as back roof in the north side. Such structures affect light distribution in the greenhouse. This study aims to investigate the light distribution properties in CSG from north to south sections, and to investigate tomato plant growth performance in the corresponding locations. Experiments were carried out in a CSG which was divided into three equal sections from north to south side. Tomato was grown in the greenhouse. Results showed that PAR intensity in the south and middle sections of CSG was permanently higher than the north section. This resulted in a distinct plant growth performance in CSG. Specifically, plants grown in the north section of CSG exhibited a shade avoidance response with stem elongation phenotype and leaf expansion. Furthermore, the north-plants showed lower leaf photosynthetic capacity which correlated with a lower total nitrogen and chlorophyll contents in comparison with the plants grown in the middle and south sections. Taken together, plants in the north section of CSG produced less total biomass than the middle and south section plants. We conclude that plant growth is not uniform in CSG due to heterogeneous light distribution which was caused by unbalanced greenhouse structures. This study may provide sound evidence for exploring a proper lighting strategy as well as fine crop management in CSG.

Keywords: Chinese solar greenhouse, light distribution, plant growth, tomato, Solanum lycopersicum.

Introduction

Chinese solar greenhouse (CSG) is the most widely used greenhouse for producing horticultural products in northern China. The universal applicability of CSG is mainly due to the relatively low construction cost and zero heat energy input even during the coldest winter season when outside temperature falls below -10 ºC (Tong *et al.*, 2013). Therefore, these greenhouses play pivotal role for extending the growing season and guarantee the year round production of horticultural products in northern China. CSG is typically characterized by its unbalanced structures with an arched front roof face to the south side and a thick wall as well as back roof (i.e. made of soil, brick or other materials) in the north side (Fig. 1).

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Detailed information regarding structure of CSG is presented by Tong *et al*. (2013). The arched front roof is covered by a plastic film during the day and with a thermal blanket added during night to maintain the heat inside. The thick back wall functions to absorb and preserve solar energy during day and release energy during night. It is obvious that these structures provide a good thermal condition for plant growth and development when outside temperature is low. Many studies have focused on optimizing the structures and thermal insulation of CSG (Tong *et al*., 2009, 2013; Zhang *et al*., 2016). However, studies rarely paid attention to the light conditions, particularly light distribution in CSG and its effect on plant growth. Light distribution in greenhouses is often affected by the greenhouse structures and facilities (Li *et al*., 2014b), as well as light direction (Li *et al*., 2014a). The unbalanced structures of CSG might affect light distribution as the north wall and back roof may cast shadow and consequently affect the direction and intensities of incident light. This may occur particularly on clear days when a large amount of direct solar radiation exists which arrive in a straight line from the sun without being scattered.

Light is the most important factor in determining plant growth and production. Marcelis *et al*. (2006) summarized a range of information and concluded that for most greenhouse crops 1% light increase results in 0.5-1% increase in production when averaged over a prolonged period. To obtain a higher production, therefore, improving greenhouse transmissivity and applying assimilation light are commonly considered (Heuvelink *et al*., 2006). Apart from production, plants are highly plastic to their growing environment in which the individual organisms can alter their development, morphology and physiology (Givnish, 1988). It is well known that in many plant species the photosynthetic capacity depends on the prevailing light condition (González-Real *et al*., 2007; Niinemets, 2007; Li *et al*., 2014a). Plant morphology involves in resource acquisition is often show functional patterns of plasticity, for instance low photon flux density results in a greater leaf area relative to plant biomass (Evans and Poorter, 2001), and a higher stem elongation (Ford, 2014). These specific alterations can optimize the light interception and absorption, and consequently can partly compensate functionally for the inevitable reductions in total plant growth and biomass that occur under conditions of resource limitation (Sultan, 2000). The differences in plasticity properties are most likely occur in CSG as light intensities may differ greatly between south and north side of CSG due to the unbalanced greenhouse structures. Furthermore, horticultural product quality partly depends on the product morphology and uniformity, which are also largely affected by greenhouse light condition (Kays, 1999). For fruit vegetables, the market value in a large part depends on the flavor and taste that are related with the carbohydrate as well as water content, which are determined by the plant growing environment in the end, particularly light condition (Mattheis and Fellman, 1999). Taken together, the unevenly light distribution in CSG might result in heterogeneous product quality in a batch of harvest.

The objective of this study is to identify the light distribution properties in different sections of CSG from north to south side, and to investigate the plant growth performance in the corresponding locations. Our hypothesis is that light intensity in the north section of CSG is lower than the south section, this result in different plant growth performance from north to south sections. To test this hypothesis, a study was conducted in a CSG where photosynthetic active radiation (PAR) was continuously measured from north to south section. Tomato, the most commonly growing plants in CSG, was used in this study.

Materials and Methods

Plant material and growth condition

Tomato (*Solanum lycopersicum,* cv. 'Ruifen882'; Rijk Zwaan, De Lier, the Netherlands) seedlings were planted in a CSG (with ridge height of 4.5 m, back roof height of 3.8 m, and span of 10 m) on 3 February and were grown until 3 June 2016. The CSG had an area of 600 m^2 (60m × 10m) and located in Shunyi district, Beijing (40 °N, 116 °E). Plant rows were in north to south orientation with a length of 8 m, which was divided into three equal sections, i.e. north (N), middle (M), and south (S) sections. These three individual sections were considered as three treatments where plant samples and PAR intensity were collected. Plants grown on each end rows with one m length were considered as border plants. The distance between rows was alternating between 60 and 90 cm, resulting in a double row followed by a path. Stem density was 3.5 stems m^{-2}. Plants were grown on substrate (peat/ perlite/ vermiculite= 1/1/1) with drip irrigation. Mean pH of the irrigation water was 5.8 and mean EC was 3.9 dS m^{-1}. The greenhouse climate (i.e. temperature, air humidity and CO_2 concentration) was controlled by opening and closing of the greenhouse windows, this is the standard way for climate management in CSGs. Solar radiation was continuously measured outside the greenhouse with a pyranometer (model CMP3, Kipp and Zonen, Delft, The Netherlands). Greenhouse temperature and humidity were measured by thermo recorder (TR-72wf-H, T&D Corporation, Japan), CO_2 concentration was measured by CO_2 recorder (TR-76U, T&D corporation, Japan). During the experiment, average daily outside global radiation was 20 MJ m^{-2} d^{-1}; average day/night temperature inside the greenhouse was 27(±4) °C/ 19(±3) °C, average CO_2 concentration was 370 µmol mol^{-1} and relative humidity was 65%.

PAR distribution measurement

PAR intensity in each section of the CSG was continuously recorded with a quantum sensor (LI-190R, LI-COR, Lincoln, USA) at 10 min intervals. Each sensor was equipped with a customized bracket at 2.5 m above the ground (Fig.1).

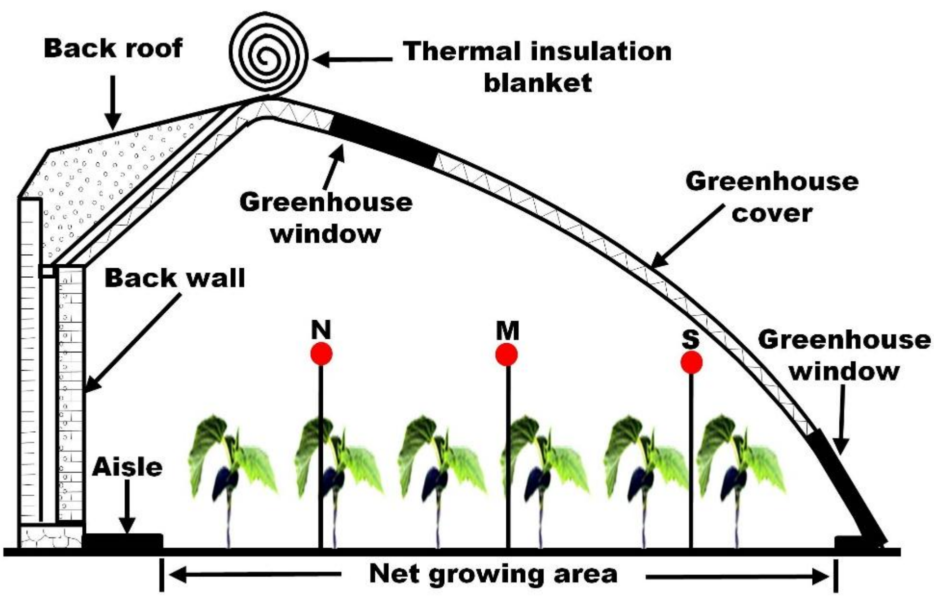

Fig. 1. Schematic diagram of cross section of Chinese Solar Greenhouse (CSG). N, M and S represent the location of quantum sensors for photosynthetic active radiation (PAR) measurements

Crop growth and measurement of morphological parameters

Plants were destructively measured at 15 weeks after planting. Six plants from each section were randomly selected, which resulted in 6 replicates. Fresh and dry weights of plant organs (leaves, stems and trusses) were determined. Plant organs were dried for at least 48h at 80 °C in a ventilated oven. Numbers of leaves, stems as well as plant height were determined. Ripe fruits were harvested at the end of the experiment to determine the fruit dry matter content. At 16 weeks after planting, ten leaf samples were randomly collected at leaf number ten (leaf number one was the uppermost leaf longer than 5 cm) from each section of CSG, subsequently 20 leaf discs, 1.6 cm in diameter, were punched out to determine the specific leaf area (SLA). SLA was calculated by dividing the area of total leaf discs by their dry weight. The length and width at the widest point of each leaf of the six randomly selected plants at each greenhouse section was non-destructively determined. Leaf length × leaf width indirectly reflects the leaf area as indicated by Li *et al*. (2014a).

Photosynthesis light response curve measurements

Photosynthesis light response and PSII operating efficiency (Φ_{PSII}) were measured with a portable gas exchange device (LI-6400; LI-COR, Lincoln, USA) equipped with a leaf chamber fluorometer (Part No. 6400-40) at leaf number ten. At each greenhouse section, six leaves from six rows were randomly selected for six light response curves. Measurements were carried out between 9:00 and 15:00. The starting level of PAR was 400 µmol m^{-2} s^{-1}, followed by 200, 100, 50, 0, 600, 900, 1200 and 1600 µmol m^{-2} s^{-1} PAR. The highest PAR intensity was applied at the end of measurements to avoid photoinhibition (Leverenz *et al*., 1990). VPD in the leaf chamber was maintained within 0.5-1 kPa; air temperature and CO_2 concentration in the leaf chamber were maintained at 25 °C, and 400 µmol mol^{-1}, respectively.

Measurement of leaf optical properties

At each greenhouse section, relative reflectance and transmittance of leaves were measured on six randomly selected leaves from leaf number ten (leaf number one was the uppermost leaf longer than 5 cm) with a spectrometer (Ocean optics USB2000+, Dunedin, USA) and two integrating spheres (FOIS-1, ISP-REF, Dunedin, USA). Leaf absorptance was calculated based on the reflectance and transmittance.

Measurement of chlorophyll fluorescence

In each greenhouse section, the maximum PSII efficiency (F_v/F_m) was measured on four fully expanded leaves at leaf number five with the portable gas exchange device equipped with a leaf chamber fluorometer (Part No. 6400-40) at four time points (9:00, 11:00, 13:00, and 17:00) on a clear day. A dark adapting leaf clip holder was used for dark adaptation for 30 min prior to each measurement. During measurements the flash intensity was 8500 µmol $m^{-2}s^{-1}$, measuring beam intensity was 1 µmol m^{-2} s^{-1}.

Measurement of leaf chemical compositions

During destructive measurements, dry leaf samples were collected for determining total nitrogen content with an elemental C/N analyzer (model EA 1108, FISONS Instruments, Milan, Italy). Meanwhile, twelve leaf discs, 1.6 cm in diameter, were punched out from randomly selected six leaves at leaf number ten from each greenhouse section; they were used to determine chlorophyll content. Ethanol was used as solvent and the absorbance of the extracts was measured using a UV-spectrophotometer (UV-1800, Shimadzu, Japan). The chlorophyll concentrations were then calculated using the equations from Ritchie (2006).

Statistical analysis

The non-rectangular hyperbola function (Eq. 1) was fitted to the measured photosynthetic light response data (Thornley, 1976).

$$P_n = \frac{aI_a + P_{max} - \sqrt{(aI_a + P_{max})^2 - 4aI_a\Theta P_{max}}}{2\Theta} - R_d \qquad (1)$$

where Pn is net leaf photosynthesis rate (µmol m^{-2} s^{-1}); Ia is the PAR absorbed by the leaf (µmol m^{-2} s^{-1}), which was estimated from the incident PAR multiplied by the absorption coefficient of single leaves (see 2.5); Pmax is maximum net leaf photosynthetic rate (µmol m^{-2} s^{-1}); a is the leaf photosynthetic efficiency (µmol CO_2 µmol^{-1} photons); Θ is the curvature parameter; and Rd is dark respiration (µmol m^{-2} s^{-1}).

Differences in plant growth characteristics were evaluated by analysis of variance (ANOVA), using SPSS 19th edition. Assuming replications in one greenhouse as being independent. *P*-values smaller than 0.05 was considered as significantly different.

Results

PAR distribution

Incident PAR intensity differed remarkably at different sections of CSG from north to south direction on clear days (Fig. 2). Specifically, the incident PAR intensity at north section apparently was lower than the middle and south section during a whole day period, such difference was not occur between middle and south section except a slightly higher incident PAR at south section during the midday (Fig. 2A). The cumulative incident PAR intensity during the growing season in north section of the CSG was 38% and 41% lower than the middle and south section, respectively. Furthermore, the differences in PAR intensity among the three sections were varied with the solar position during a day, (Fig. 2B). PAR intensity in the north section was about 50% lower than the average greenhouse PAR intensity (i.e. average PAR intensities over the three sections) at early morning and late afternoon when solar position is low, while PAR intensity was about 20% lower during the midday. In the middle and south sections, PAR intensities were always higher than the average greenhouse PAR intensity, but with a larger difference in early morning and late afternoon compared with midday (Fig. 2B).

Plant growth and morphological characteristics

Plant total dry weight in the north section of CSG was significantly lower than the middle and south sections, while no significant difference was observed between the middle and south sections (Fig. 3). Similar phenomenon was observed for the dry weight of leaves, stems as well as trusses (Table 1). Furthermore, plants grown in the south section of CSG showed a higher dry matter content for the whole plants as well as ripe fruits (Table 1). The higher PAR intensity in the middle and south section of CSG did not affect dry matter partitioned into the plant organs, except in the south section where a higher dry matter partitioned into the truss was observed (Table 1).

In terms of plant morphology, SLA of single leaf in the north section of CSG was significantly higher than the middle and south section grown plants, indicating a thinner leaves (Fig. 4A). Furthermore, higher PAR intensity in the middle and south section resulted in a more compact plants with smaller individual leaves (Fig. 4B) and shorter plants in comparison with those plants grown in the north section (Table 1).

Leaf photosynthesis and photoinhibition

Leaf photosynthetic capacity in the middle and south sections of CSG was higher than the north section as indicated by a significantly higher P_{max} (Fig. 5A). Similarly, PSII operating efficiency (Φ_{PSII}) was also higher in the middle and south sections under high PAR levels (Fig. 5B). For the photosynthesis light response curve parameters *a*, *Θ*, and R_d, no significant differences were observed.

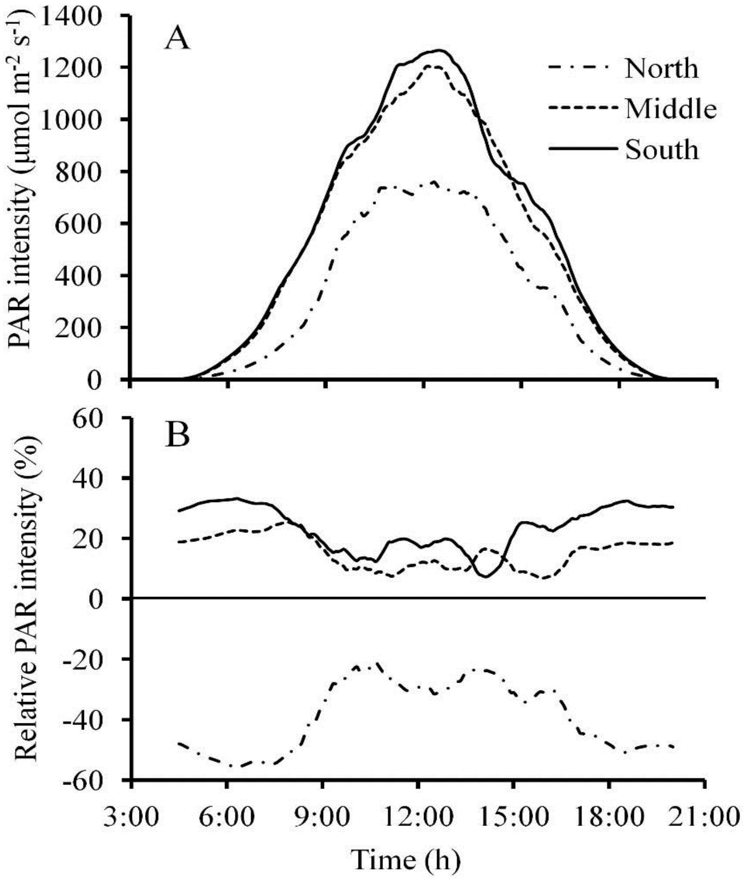

Fig. 2. Photosynthetic active radiation (PAR) intensity inside Chinese Solar Greenhouse (CSG) on clear days as measured by a point sensor. A represents PAR intensity distribution in the three sections of CSG on clear days (data are average over four clear days). B represents PAR intensity of each section relative to average PAR intensity over the three sections (i.e. horizontal line cross 0 of y-axis).

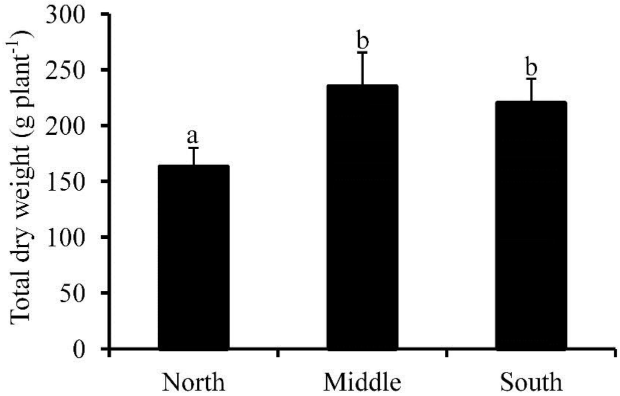

Fig. 3. Plant total dry weight in three sections of Chinese Solar Greenhouse (CSG). Error bars represent mean±SE (n=4). Different letters show statistically significant differences (*P* < 0.05).

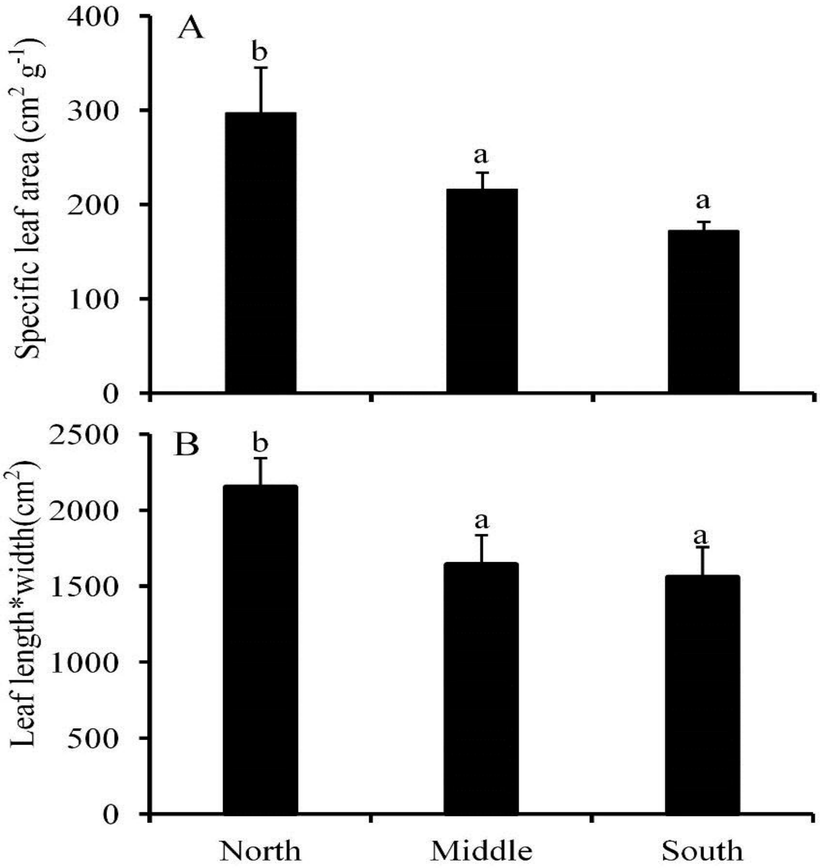

Fig. 4. Leaf morphology in different sections of Chinese Solar Greenhouse (CSG). A represents specific leaf area (SLA) of leaf number ten from top canopy. B indicates leaf length*width, leaf samples were averaged down the canopy and over six plants at each section. Error bars show mean±SE (n=6). Different letters show statistically significant differences (*P* < 0.05).

Table 1. Plant growth parameters in the three sections of Chinese Solar Greenhouse.

Greenhouse section	Plant height (cm)	Number of leaves	Stem dry weight (g plant^{-1})	Leaf dry weight (g plant^{-1})	Truss dry weight (g plant^{-1})	Dry matter partitioning to stem (%)	Dry matter partitioning to leaf (%)	Dry matter partitioning to truss (%)	Dry matter content of whole plant (%)	Dry matter content of ripe fruit (%)
North	207 b	20	25.2 a	52.8 a	85.2 a	15.5	32.4	52.2 a	7.1 a	5.5a
Middle	191ab	21	35.7 b	75.3 b	124.0 b	15.3	32.1	52.6 a	7.9 ab	6.1ab
South	179 a	20	31.7 ab	62.2 ab	126.2 b	14.3	28.2	57.6 b	8.6 b	6.6b

Means of each parameter followed by different letters within one column differ significantly (*P* < 0.05) as described by the least significant difference (LSD) test.

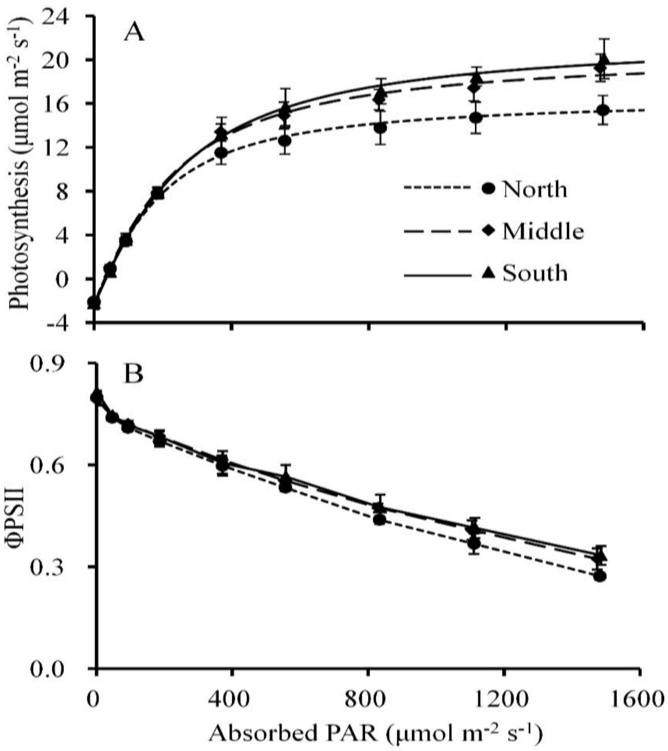

Fig. 5. Leaf photosynthetic rate (A) and PSII operating efficiency (Φ_{PSII}) (B) of leaf number ten (leaf number one was the uppermost leaf longer than five cm) in response to absorbed PAR intensity at different sections of CSG. In X-axix absorbed PAR= Incident PAR provided by the measuring equipment×leaf absorptance. Points indicate mean±SE (n=6). Lines through data point in A represent the fit of the non-rectangular hyperbola function (Eq.1).

On a fully clear day, F_v/F_m showed a diurnal variation trend (Fig. 6). When leaves were exposed to the full irradiance (midday), F_v/F_m was reduced compared with measurements in the morning, suggesting photoinhibition occurs. The decrease in Fv/Fm was more pronounced in the south and middle sections of CSG in comparison with the north section. At 13:00 Fv/Fm was reduced by 12%, 17%, and 21% in the north, middle and south sections, respectively, compared with Fv/Fm at 9:00, while Fv/Fm increased in the afternoon (at 17:00) with limited differences occur among the three sections.

Leaf optical and biochemical properties

In the visible region (400-700nm), leaf absorptance was about 95% or even higher from 400 to 500 nm and around 670-690 nm, while it showed a large decrease from 500 to 580 nm and a drastic drop from 700 nm (Fig. 7). In the three sections of CSG, leaf absorptance showed similar values in the large part of the visible region except green region (500-580) where leaf absorptance was slightly higher in the south section in comparison with middle and north sections of CSG.

At the crop level, significantly higher total nitrogen concentration was observed in the south section compared with the north section plants (Table 2). Similarly, south section plants also showed higher chlorophyll content, while no difference in chlorophyll a/b ratio was observed among the three sections (Table 2).

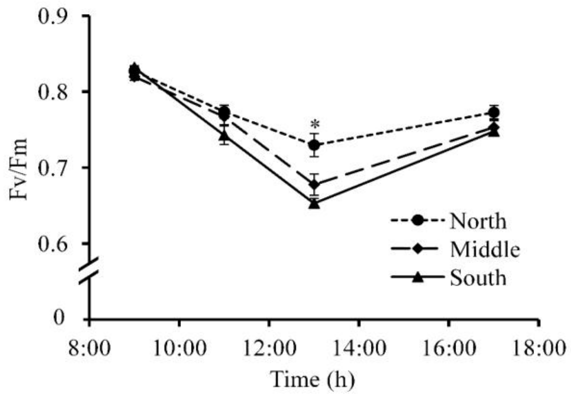

Fig.6. Maximum PSII efficiency (F_v/F_m) of leaf number five (leaf number one was the uppermost leaf longer than five cm) on a clear day. Error bars represent mean±SE (n=4). Asterisk indicates significant differences (*P*<0.05).

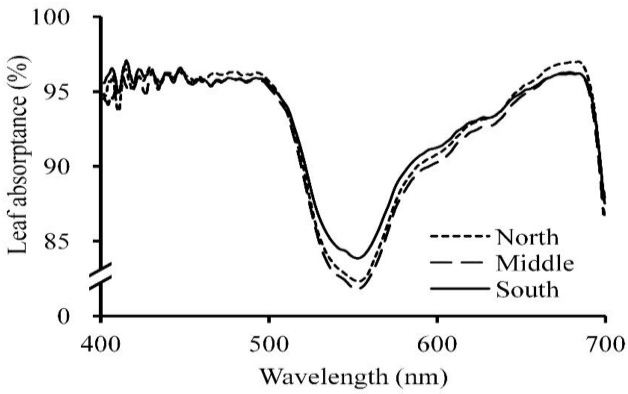

Fig. 7. Percentage of leaf absorptance spectra of leaf number ten (leaf number one was the uppermost leaf longer than five cm) in three sections of Chinese Solar Greenhouse (CSG) (N=6)

Table 2. Leaf chemical components in three sections of Chinese Solar Greenhouse

Greenhouse section	Total nitrogen content (%)	Chl (a+b) (mg m^{-2})	Chl a/b ratio
North	3.1 a	454 a	3.8
Middle	3.4 b	464 a	3.9
South	3.6 b	492 b	3.8

Means of each parameter followed by different letters within one column differ significantly (*P* < 0.05) as described by the least significant difference (LSD) test.

Discussion

Light is the most limiting factor for greenhouse production, because other factors such as water, minerals, CO_2 supply, pests and diseases are in general well under control in greenhouses. Light is heterogeneously distributed in greenhouse, which to a large extent affecting production (Acock *et al*., 1970; Li *et al*., 2014a, 2016). It is obvious that the more homogeneous light distribution in the greenhouse the higher crop production, because leaf photosynthetic rate shows a curvilinear response to the light flux density (Marshall and Biscoe, 1980). In conventional glasshouses, the unevenly light distribution is characterized by temporal and spatial variation of PAR intensity at certain point, which is mainly caused by the fraction of direct radiation, as well as the greenhouse construction and equipment cast shade, consequently resulting in shade-spots and lightflecks that dynamically changes with solar position (Li *et al*., 2014a, 2014b). Such variation in PAR intensity can be minimized by applying diffuse glass covering materials (Hemming *et al*., 2007). In CSG, however, the unevenly PAR intensity distribution is more severe, which is characterized by a permanently higher PAR intensity in the south and middle sections compared with the north section (Fig. 2). Such spatial differences in PAR intensity resulted from the unbalanced greenhouse structures of which the north wall and back roof cast shadow and consequently reduce the incident PAR intensity. To our knowledge, we are the first to pay attention to the light distribution in CSG and its effect on plant growth.

Light is the driving force for photosynthesis, therefore, crop growth to a large extent depends on the light it receives. It is clear that plant total biomass increases as the plant captures more light. We showed that in the CSG plant total dry mass in the north section was 31% and 26% lower in comparison with the middle and south sections, respectively (Fig. 3). This corresponds with the PAR distribution pattern of which the cumulative incident PAR during the growth season in the north section was 38% and 41% lower than the middle and south sections, respectively. This is comparable with the rule of thumb that for most greenhouse crops a 1% increase in light results in 0.5-1% increase in plant production when averaged over a prolonged period (Marcelis *et al*., 2006). Plant resource allocation also varies with the level of irradiance to which plants are acclimated (Niinemets, 2007; Poorter *et al*., 2012). Previous studies have reported that changes at the whole-plant level to an increase in light are a decreased fraction of biomass allocated to leaves (Poorter and Nagel, 2000). However, the differences in dry matter partitioned into the leaves were not significant among the three sections of CSG although distinct differences in PAR intensity exist (Table 1). This is not surprising as in many instances biomass allocation to leaves is not particularly sensitive to growth irradiance (Poorter and Nagel, 2000). At the leaf level, a given amount of biomass can be spread over a small or a large area, which is often reflected by SLA (i.e. leaf area per unit leaf dry mass). We observed that SLA was significantly higher in the north section compared with the middle and south sections of CSG, indicating a thicker leaves in the middle and south sections. This is in consistent with the general paradigm that plants grown in high light generally have thick leaves with a low SLA (Givnish, 1988; Evans and Poorter, 2001; Poorter *et al*., 2010). Fully grown tomato plants are often source limited even during the summer season with high PAR levels (de Koning, 1994; Heuvelink, 1996; Li *et al*., 2015). Tomato fruits are the most important sink organs that attract assimilates, this results in a higher dry matter partitioned into trusses in the south section where high PAR level may lead to more assimilates available (i.e. increasing source strength). Apart from dry mass production and allocation, light also affect plant morphology (Sultan, 2000; Hogewoning *et al*., 2010). It is well known that sun plants (such as tomato) often exhibit a shade avoidance response (i.e. plants show stem elongation in response to shading) under low light condition (Givnish, 1988). The increased plant height (Table 1) and larger individual leaf area (Fig. 4B) in the north section of CSG are clear adaptive characteristics. In response to low light, plants exhibit a rapid extension growth, in this way it can enhance its chances to capture more PAR (Sarlikioti *et al*., 2011; Ford, 2014). For most vegetables, a higher dry matter content is usually associated with a better texture of the derived product. In this context, tomato fruits from the south section of CSG are more tasteful than the north section fruits which showed a lower dry matter content (Table 1). Therefore, we can reason that tomato fruits harvested from the CSG might not have a uniform quality.

Plant physiological properties are closely correlated with their prevailing growth microclimate (Ellsworth and Reich, 1993; Niinemets, 2007; Trouwborst *et al*., 2011). A higher PAR intensity in the middle and south sections of CSG resulted in a higher maximum leaf photosynthetic capacity (Fig. 5A); this is a typical plant acclimation property under increased irradiance (Boardman, 1977; Trouwborst *et al*., 2011). However, the light limited leaf photosynthetic efficiency (*a*) was hardly affected by the different PAR level in the three sections (Fig. 5A). Similar phenomenon was also observed in many other studies (Boardman, 1977; Trouwborst *et al*., 2011; Li *et al*., 2014). Furthermore, acclimation of plants under high light also including an increased nitrogen and chlorophyll content (Table 2), which can be the reasons for an increased maximum leaf photosynthetic capacity which is linearly related to leaf nitrogen content (Evans, 1989). The slightly higher absorptance of south section leaves (Fig. 7) is mainly due to the higher chlorophyll content which plays a pivotal role in determining the leaf absorptance (Evans and Poorter, 2001). Although thicker leaves were observed in the south section of CSG as indicated by a lower SLA (Fig. 4A), leaf absorptance is independent of SLA (Evans and Poorter, 2001). In nature, plants often encounter light intensities that exceed their photosynthetic capacity (Ort, 2001); this leads to photoinhibiton that is a result of the balance between the rate of photodamage to PSII and the rate of repair (Long *et al*., 1994; Takahashi and Murata, 2008). On the middle of clear days, we observed a higher maximum PSII efficiency (F_v/F_m) in the north section of CSG in comparison with the middle and south sections (Fig. 6), suggesting occurrence of less photoinhibition in the north section. On the other hand, plants grown in the middle and south sections of CSG are more susceptible for photoinhibiton due to the high PAR level. The reversible change in F_v/F_m was observed in the afternoon (Fig. 6), indicating photoinhibition due to the reversible inactivation of PSII rather than photodamage that correlates with the loss of D1 protein (Long *et al*., 1994; Demmig-Adams *et al*., 1996; Demmig-Adams, 2000; Ort, 2001).

Due to the heterogeneously light distribution characteristics, care must be taken when selecting plant samples from CSG for experimental purpose as distinct plant growth performance may mislead the objective investigation. Recently, fog and haze weather often occurs in northern China caused by air pollution, which remarkably reduces global radiation, and consequently affects plant growth. Therefore, supplementary lighting is considered to compensate for the reduced PAR level. Considering the unbalanced PAR distribution in CSG, this study may provide sound evidence for exploring a proper lighting strategy that could maintain a relatively uniform PAR distribution in CSG.

Conclusions

Plant growth is not uniform in CSG due to the heterogeneous light distribution as characterized by a permanently higher PAR intensity in the middle and south section of CSG compared with the north section.

Acknowledgements

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