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Spatial distribution of light interception by different plant population densities and its relationship with yield

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ABSTRACT

Light interception (LI) by the canopy is an important environmental factor that determines dry matter production and crop development. Using a geostatistical sampling-based method, we studied the spatial distribution of LI at different points, in different layers and profiles and in the entire cotton canopy. The results showed that the LI decreased with increasing height. During early development, the horizontal changes in LI were large for a given vertical point. However, the horizontal changes in LI were smaller during later development. Profile maps of the LI for the six plant densities showed that different LIs occurred during the early growth stage. In addition, the linear regressions between the total accumulated LIs of the different layers and the cottonseed yield revealed that the LI in the bottom layer and in the middle of two cotton rows significantly contributed to the cottonseed yield. Thus, a higher economic yield could be obtained by improving the micro-environment in these two layers.

1. Introduction

Light interception (LI) by the canopy is an important environmental factor that determines dry matter production and crop development (Chenu et al., 2005; Escobar-Gutiérrez et al., 2009). Photosynthetically active radiation (PAR), which is solar radiation with wavelengths of 400–700 nm (Asrar et al., 1989), is part of the light radiation spectrum that is used by green plants to produce dry matter through photosynthesis (Marini and Marini, 1983). The amount of light intercepted by the crop canopy reflects the physiological processes that occur in the canopy, the microclimate situation, and water dynamics (Singer et al., 2011).

The interception of light by the crop canopy is complicated and is affected by the solar angle, the orientation of the plant row, the canopy architecture, the diffuse proportion of incoming radiation, and the leaf optical properties (Wagenmakers and Callesen, 1995; Giuliani et al., 2000; Mariscal et al., 2000; Nouvellon et al., 2000). Particularly, canopy architecture, which is affected by the intrinsic architectural traits of the plants and the practice of canopy management, substantially affects LI (Wiechers et al., 2011; Zhang et al., 2015a). To quantify the light in the canopy, Beer's law was used to calculate the light intensity within each layer of the canopy at a specific height (Monsi and Saeki, 1953). These authors proposed that the vertical distribution of PAR in the crop canopy is a mathematical function of the extinction coefficient (K) and leaf area index (LAI). Consequently, many studies have focused on these two parameters (Nilson, 1971; Suits, 1972; Ross, 1981; Goel and Strebel, 1984; Campbell, 1990; Wang et al., 2007). However, this mathematical function was not satisfied by the actual observations (Wilson et al., 1992).

Simultaneously, three-dimensional digital methods based on information technology have been used to simulate the distribution of light in plant canopies (Mariscal et al., 2000; Chenu et al., 2005; Munier-Jolain et al., 2013). These studies include the studies of Ross and Marshak (1988), Chelle and Andrieu (1998), Chelle and Saint-Jean (2004), etc. However, these models did not consider the mutual interactions between the plant organs (Andrieu et al., 1995). Additionally, these methods include large computing workload and datastorage capacities, and the model parameters are difficult to obtain. To consider spatial heterogeneity, Munier-Jolain et al. (2013) created the multi-annual-weed dynamics model

Abbreviations: Ir, the intercepted PAR rate; LAI, leaf area index; LI, light interception; PAR, photosynthetically active radiation; PARt, the incident transmitted PAR; PARr, the incident reflected PAR; Rr, the reflected PAR rate; Tr, the transmitted PAR rate.

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Table 1
The mean daily temperatures, cumulative hours of sunshine, cumulative heat units of ≥10 °C during the cotton growing stage (April–October), and total precipitation in 2013 and 2014.

Year	Mean temperature	Sunshine	Heat units	Precipitation
2013	22.0 °C	1157 h	4494 °C day	430 mm
2014	22.0 °C	1044 h	4713 °C day	658 mm

FlorSysfor to simulate the LI in a heterogeneous canopy. However, this model was too complicated for common use.

Geostatistics provide a versatile tool for environmental disciplines with high spatial heterogeneity, such as agriculture, aquiculture, hydrology, geology, meteorology, soil science, ecology, petroleum engineering, forestry, meteorology and climatology (Francescangeli et al., 2006; Fortin et al., 2012; Griffith, 2012; Arbia, 2014). Recently, we used geostatistics to successfully measure canopy light and to quantify the spatial distribution of light in the heterogeneous canopies of cotton based on geostatistical sampling (Zhi et al., 2014). The objectives of this study were to generate more knowledge regarding the LIs at different points, in different profiles and layers, and at different plant population densities based on geostatistical sampling. In addition, we aimed to clarify the major canopy function layers of LI for cotton yield to provide guidance for plant training, optimal crop population density selection, row spacing designation, fertilizer and water inputs which can increase the LI and cotton yields.

2. Materials and methods

2.1. Experimental design

A field experiment was conducted in 2013 and 2014 at the experimental station of the Institute of Cotton Research of the Chinese Academy of Agricultural Sciences in Anyang, Henan, China (36°06′N and 114°21′E). A randomized experiment was designed with 6 treatments and 3 replicates on clay loam soils containing total N, P, and K concentrations of 0.65, 0.01 and 0.15 g kg^{-1}, respectively. The cotton hybrid CRI 6913 was planted at six densities (4.50, 6.75, 9.00, 11.25, 13.50, and 15.75 plants m^{-2}). Each plot covered an area of 64.0 m^2 (8.0 m wide and 8.0 m long), and a row spacing of 0.8 m was used. The land was plowed and irrigated before planting. The cotton was managed using a normal planting production system, with planting dates of 18 April, 2013 and 29 April, 2014. The weather conditions for the area are provided in Table 1. All experimental plots were sown, irrigated, and fertilized uniformly. And the weeds, diseases, and pests were controlled.

2.2. Acquisition and calculation of PAR data

The incident transmitted PAR (PARt) and the reflected PAR (PARr) were measured using the spatial grid method at stable positions in six cotton plant population density plots at 40, 46, 54, 65, 79, 87, 95, 102, 116, 128, 139, and 146 days after planting in 2013 and at 28, 38, 49, 58, 69, 79, 90, 104, 112, 121, and 134 days after planting in 2014 (Fig. 1). Then, the transmitted PAR rate (Tr), reflected PAR rate (Rr) and intercepted PAR rate (Ir) were calculated using the following formulas (Zhi et al., 2014):

$$\mathrm{Tr} = \frac{\mathrm{PARt}}{\mathrm{PARI}} \quad (1)$$

$$\mathrm{Rr} = \frac{\mathrm{PARr}}{\mathrm{PARI}} \quad (2)$$

$$\mathrm{Ir} = 1 - \mathrm{Tr} - \mathrm{Rr} \quad (3)$$

where PARI is the incident PAR above the canopy (μmol m^{-2} s^{-1}) and PARt and PARr are the incident transmitted PAR (μmol m^{-2} s^{-1}) and reflected PAR (μmol m^{-2} s^{-1}), respectively, at each grid position in the canopy. Through spatial interpolation with Kriging, the Tr, Rr and Ir for the other positions were calculated. The LI of the canopy was computed as follows according to the Simpson 3/8 integration rules:

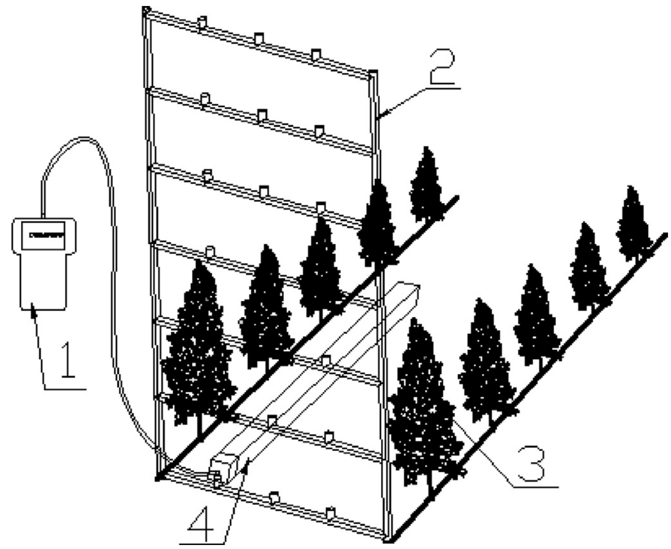

Fig. 1. Illustration of the sampling grid used to determine photosynthetically active radiation (PAR). 1. Datalogger. 2. Frame. 3. Cotton. 4. Light quantum sensor.

$$A_i = \frac{3\Delta x}{8}[G_{i,1} + 3G_{i,2} + 3G_{i,4} + \ldots + 2G_{i,\mathrm{ncol}-1} + \mathrm{Gi,\ ncol}] \quad (4)$$

$$\mathrm{Volume} \approx \frac{3\Delta y}{8}[A_1 + 3A_2 + 3A_3 + 2A_4 + \ldots + 2A_{\mathrm{ncol}-1} + A_{\mathrm{ncol}}] \quad (5)$$

where A_i is the light volume of a certain cross-sectional area; the coefficient vector is {1,3,3,2,3,3,2,...,3,3,2,1}; Δx is the vertical distance of the grid; Δy is the horizontal distance of the grid; (i, j) are grid node numbers; G(i, j) is the Kriging interpolation point; and the volume is the total LI of the canopy.

2.3. Determination of the agronomic traits of cotton

On the same day that the PAR data were acquired, three plants were randomly uprooted from the center of each test plot and were divided into roots, stems, leaves and reproductive organs in the laboratory. The leaf area was determined using a scanner (Phantom 9800xl; MiCROTEK, Shanghai, China) and the Image-Pro Plus 7.0 (Media Cybernetics, Rockville, MD, USA). Then LAI was determined on a ground area basis. The dry mass of the cotton plants, including the roots, stems, leaves and reproductive organs, was determined by drying at 80 °C to a constant weight. For each plot, the cotton seed yields were manually harvested three times in 2013 and two times in 2014 (15 September, 13 October and 7 November in 2013; 25 September, 28 October in 2014).

2.4. Statistical analysis

Stata 13.0 software (StataCorp LP, College Station, Texas, USA) and Surfer software (Golden Software Inc., USA) were used for processing data.