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RESEARCH ARTICLE

Estimating light interception using the color attributes of digital images of cotton canopies

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Abstract

Crop growth and yield depend on canopy light interception (LI). To identify a low-cost and relatively efficient index for measuring LI, several color attributes of red-green-blue (RGB), hue-saturation-intensity (HSI), hue-saturation-value (HSV) color models and the component values of color attributes in the RGB color model were investigated using digital images at six cotton plant population densities in 2012–2014. The results showed that the LI values followed downward quadratic curves after planting. The red (R), green (G) and blue (B) values varied greatly over the years, in accordance with Cai's research demonstrating that the RGB model is affected by outside light. Quadratic curves were fit to these color attributes at six plant population densities. Additionally, linear regressions of LI on every color attribute revealed that the hue (H) values in HSI and HSV were significantly linearly correlated with LI with a determination coefficient (R^2)≥0.89 and a root mean square error (RMSE)=0.05. Thus, the H values in the HSI and HSV models could be used to measure LI, and this hypothesis was validated. The H values are new indexes for quantitatively estimating the LI of heterogeneous crop canopies, which will provide a theoretical basis for optimizing the crop canopy structure. However, further research should be conducted in other crops and under other growing and environmental conditions to verify this finding.

Keywords: canopy light interception (LI), digital image, color attributes, hue

1. Introduction

Crop growth and yield depend on canopy light interception (LI), which is estimated by measuring photosynthetically active radiation (PAR) in the wavelength range of 400–700 nm (Asrar *et al*. 1989). Therefore, quantifying the PAR reaching the leaves of a crop canopy over time is an important consideration when estimating crop status and yield potential. Not only plant density but also the available leaf area and canopy structure affect PAR in the canopy (Gifford *et al*. 1984). PAR in the canopy should be measured when sunlight is unob-

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structed (Board *et al*. 1992; Egli 1994; Flénet *et al*. 1996), leading to many difficulties in obtaining accurate estimates.

Digital remote sensing imagery is one potential way to estimate LI, as some satellite or airborne sensors can detect the PAR that is reflected back to space (Janjai and Wattan 2011). In the last 20 years, many studies have obtained PAR estimates based on satellite data. These studies include those conducted by Frouin and Gautier (1990), Eck and Dye (1991), Pinker and Laszlo (1992), Van Laake and Sanchez-Azofeifa (2004), Liang *et al*. (2006), Schiller (2006), and Zheng *et al*. (2008). The drawbacks of these methods include the high cost of image acquisition from satellites, the risk of cloud interference when capturing the images, the infrequency of satellite passes, and the time interval between image capture and data use (Li *et al*. 2010).

With the development of portable high-resolution digital cameras and associated computer software, these cameras have come to be used as low-cost, highly efficient tools on ground-based platforms in recent studies (Jia *et al*. 2004; Ku *et al*. 2004; Behrens and Diepenbrock 2006; Pagola *et al*. 2009). The subject can be objectively evaluated according to color attributes based on precisely recording the appearance of photographic subjects in a non-destructive manner. The red-green-blue (RGB), hue-saturation-intensity (HSI), and hue-saturation-value (HSV) color models are most frequently used in digital image processing (Sasaki *et al*. 1999).

In agriculture, several methods of measuring LI utilizing digital camera images have been proposed, as digital images can be conveniently obtained, and bright sunshine is not necessary. Other superior characteristics of digital images from plants include not being affected by the leaf angel distribution in the canopy, angle of radiation, crop type or stage of development (Gonias *et al*. 2012). The methods using digital images for estimating LI are based on several assumptions: The soil background can be distinguished from the leaves; the light transmission of leaves is low relative to light absorption; and the camera angle to the horizon approximates the solar angle (Purcell 2000).

Campillo *et al*. (2008) developed a simple, economical method for determining LI in low-lying crops using digital images obtained with a camera. Several researchers have defined the number of pixels in the green band divided by the total number of pixels for each image as the fractional canopy coverage, and a relationship between the fractional canopy coverage and fractional light interception has been established in soybean (*Glycine max* L. (Merr.)) (Purcell 2000), wheat (*Triticum aestivum* L.) (Caviglia *et al*. 2004), corn (*Zea mays* L.) (Edwards *et al*. 2005), and cotton (Gonias *et al*. 2012). However, these methods neither realized the composition of a true color nor considered the spatial heterogeneity of the PAR distribution, which is a special characteristic of the light environment. Thus, the objective of this study was to identify more accurate indexes that can be acquired conveniently and are not influenced by the light environment for quantifying the LI of cotton canopies. Based on the results, a theoretical basis for optimizing the crop canopy structure is provided.

2. Materials and methods

2.1. Experimental design

The study was conducted at the experimental station of the Institute of Cotton Research, Chinese Academy of Agricultural Sciences in Anyang, Henan Province, China (36°06´N and 114°21´E) in a clay loam soil. The land was plowed and irrigated before planting. Details of the weather conditions are given in Table 1. Six plant population densities (1.5, 3.3, 5.1, 6.9, 8.7, and 10.5 plants m^{-2}) of SCRC28 (*Gossypium*) were arranged in a randomized block design with three replicates. The planting dates were April 20, 2012, April 18, 2013 and April 29, 2014. A separate field trial was established in 2013 and 2014 using the CRI 6913 cultivar, with six densities (4.5, 6.7, 9.0, 11.2, 13.5, and 15.7 plants m^{-2}). The planting dates were April 18, 2013 and April 29, 2014. The data for CRI 6913 in 2013 and 2014 were used to validate the best model feasibility for predicting canopy LI, as obtained from cultivar SCRC28.

2.2. Acquisition and calculation of PAR data

Based on the principle that the spatial distribution of PAR is highly heterogeneous, the incident transmitted PAR (PARt) and the reflected PAR (PARr) were measured using the spatial grid method (Li *et al*. 2012a, b) at fixed positions in six cotton plant population density plots at different growth stages. The spatial distances between two typical cotton rows and from the ground to the canopy were divided to produce grids with 0.20 m spacing. PARt and PARr were then measured in each grid using a light quantum sensor (LI-191SA, LI-COR, Lincoln, NE, USA) and a data logger (LI-1400, LI-COR, Lincoln, NE, USA) at approximately 10:00 a.m. ±1 h (Fig. 1). The incident PAR of the sun was

Table 1 Mean daily temperatures, cumulative hours of sunshine, cumulative heat units of ≥10°C in the cotton growing stage (April–October), and total precipitation in 2012, 2013 and 2014

Year	Mean temperature (°C)	Sunshine (h)	Heat units (°C d)	Precipitation (mm)
2012	22.3	1 092	4 758	523
2013	22.0	1 157	4 494	430
2014	22.0	1 044	4 713	658