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The Consequences of Plant Architecture and Spatial Distribution of Light Interception on Cotton Growth and Yield

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ABSTRACT

The architecture of the canopy tends to affect how light is reflected and distributed within it. Rational modelling and trimming can improve crop architecture, maximize the use of space, light, and resources such as land, and lay the groundwork for initial maturing, and maximum yield. Determining the interception of light inside the canopy is critical aimed at increasing the population's photosynthetic production. By implementing cultural practices that produce optimal plant populations and alter the plant canopy components, it is possible to maximize light utilization in the production of cotton. In order to forecast the expected yield for uses like crop management and agronomic decision-making, as well as to investigate potential impacts of environmental alteration on food security, crop growth models are used to estimate the correlation between plants and the environment. In this study, we highlight the light interception, canopy architecture and their use in crop growth models to improve crop productivity. Constructing a strong technological system capable of phenotyping crops in a high-throughput, multidimensional, large-data, efficient, and mechanically determining manner is the ultimate objective.

Key words: Cotton, photosynthesis, light-energy.

INTRODUCTION

The most significant textile fiber in the world, cotton (*Gossypium*), comprises approximately 25% of all fiber use worldwide (USDA-ERS, 2017). Hence, increasing the production of cotton is crucial to meeting the demands of more than nine billion people for fiber by 2050. According to Norman and Campbell (1989), crop functions like the generation and consumption of light-energy are impacted by the architecture of the crop canopy. By changing the canopy structure, it is possible to enhance plant photosynthesis and plant photosynthesis and the potential for crop production. The volume of the canopy is essential for plant photosynthesis, fruiting and accumulation of biomass. Chlorophyll, the green pigment found in plants, depends on sunlight for its light energy in order to photosynthesize and grow (Zafar et al., 2022). Light attenuation has a substantial impact on the total rate of photosynthesis along with the accumulation of organic matter in plants, especially cotton. The leading factor behind plant photosynthetic processes is photosynthetically active radiation (PAR), which consists of wavelengths that green plants absorb and utilize for photosynthesis. The amount of PAR that reaches the canopy's components is determined by spatial canopy interception, which also aids in determining the ideal canopy form for a particular crop (Xing, 2018). Cotton production is greatly influenced by the quality and duration of light. Cotton production is greatly influenced by the quality and duration of light. Cotton, a crop that enjoys the light, need a lot of sunny days to gather its ideal biomass, which results in high productivity (Manan et al., 2022).

Water transport, interception of light, transpiration, as well as carbon acquirement and distribution are all significantly influenced by canopy architecture (Da Silva et al., 2014b; Gao et al., 2018). As a result, numerous researchers have worked to identify the ideotype, or ideal plant architecture. Understanding the geometrical and topological properties of crops is beneficial in the field of crop production because it allows for better shaping of crops, which enhances crop quantity, regularity, and quality of production (Zafar et al., 2021). The potential for

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increased crop productivity can be enhanced by optimizing canopy structure (Stewart et al., 2003; Giunta et al., 2008). Finding the best canopy structure to maximize plant photosynthesis is one way to increase yield (Murchie et al., 2009; Zhu et al., 2010). The proportions of the canopy are an essential component of the structure of the canopy and is essential for production of plant biomass, fruit, and photosynthesis. However, evaluation of canopy size becomes a constraint that restricts cotton breeding and hereditary studies, particularly for large crop inhabitants and high-dimensional characters (White et al., 2012; Cobb et al., 2013). Cotton (and other) breeding programs and genetics studies might benefit from accurate high throughput methodologies for assessing canopy size (Reynolds & Langridge, 2016). Two main kinds of canopies in a crop like cotton: open canopies (Reta-Sánchez & Fowlerb 2002), these canopies are closely related to the structure and shape of the leaves; a mutant's deeply divided okra-shaped leaf allows for an open structure, whereas a normal or weakly divided leaf type gives the plants a closed structure. These two distinct canopies have various effects on light interception and have an impact on the final yield. According to Xing et al. (2018) the yield distribution can be successfully managed and by initially improving the Light Interception dispersion within the plants canopy, one can afterwards have an influence on the yield of cotton and fiber quality. For the okra-leaf and standard varieties, radiation values usage efficiency were calculated to be 1.897 and 2.636 $g.MJ^{-1}$ of intercepted photosynthetically active radiation, respectively, according to Gonias et al. (2011). This made it abundantly obvious how crucial canopies that permit sun radiation penetration are.

High-Throughput Phenotyping on Cotton

Recent developments in phenotyping technology for cotton (*Gossypium hirsutum* L.) has produced device to increase the efficiency of data collection and analysis. High-throughput phenotyping (HTP) is a quick and noninvasive method for monitoring and assessing a variety of phenotypic variables linked to growth, yield, and stress tolerance. Plant morphological and physiological features are measured via plant phenotyping genetically, environmentally, and managerially (Yang et al., 2017). It has historically been difficult to phenotype large numbers of plants because the measurements of the parameters are labor and resource-intensive (Qiu et al., 2018). Nevertheless, innovations in phenotyping enabled by the introduction of technology will be very beneficial to the research on plants. High throughput phenotyping (HTP), a noninvasive and transparent method of evaluating compound plant features, is a potential technology that can assist in finding resolution to the age-old "10 Billion People Question" in the field of plant breeding (Ray et al., 2013; Tester & Langridge 2010).

A unique approach to crop phenotyping research has evolved as a result of the progress of machineries for creating realistic 3D crop models. The 3D crop model, which is a massive point cloud dataset, incorporates more advanced phenotypic characteristics of crops that can be collected either by using a laser or indirectly from multidimensional and transparent photos using remote sensing data and computer vision techniques (Comba, 2020, Sanz, 2018). The LAI along with additional growth indices can be estimated using the structure from movement approach, use to create point clouds from the crop canopy's RGB image in order to extract virtual 3D Model (DSM). The accuracy and feasibility of assessing crop phenotypic traits utilizing compact 3D spatial clouds have been demonstrated in numerous research. Using the SfM (Structure from Motion) technique, Mathews (2013) produced a 3D point cloud model. To evaluate the LAI dispersion of large vineyards, a simplified point cloud processing method was put forth. Low-density point clouds could have had an impact on the projected results, though. Han et al. (2019) discovered that the height of plants as assessed by the UAV platform was closely matched to the height measured manually when using the UAV to capture time-series photos for 3D modeling of field breeding plots. According to Zermas et al. (2020) the 3D maize model that was rebuilt using the SfM method can accurately and automatically extract the phenotypic traits of a single plant. He discovered that the height of a single corn plant was determined with 89.2% accuracy and the LAI with 92.5% accuracy.

Solar Radiation and Radiation Use Efficiency of Cotton

Plant development can be fuelled by solar radiation for free, but only the 400-700 nm section of the spectrum is directly capable of driving photosynthesis, which is defined as photosynthetically active radiation (PAR) (Noriega et al., 2021). The foundation of crop economic yield is crop biomass productivity, which is directly reflected by a crops capacity to absorb and transform PAR. One of the most important factors affecting agricultural productivity and output is solar radiation interception. Seasonal production, especially of biomass crops, is anticipated to face challenges as a result of this factor and the unpredictable nature of weather. The Radiation use efficiency determined across numerous sowing seasons could give a greater comprehension of biomass, the physiological capacity of sorghum to generate dry matter under a range of environmental factors, including air temperature and solar radiation (Chavez et al., 2022). The rate of biomass formation is primarily influenced by the amount of PAR received from the sun provides and the efficiency of the crop canopy for PAR absorption. As a result, under optimal crop development conditions, total dry vegetative matter relies on how much radiation the crop canopy absorbs. Figure 1 showing the effect of solar radiation on cotton production.

Cropping methods effectiveness, particularly that of intercrops, in capturing and using resources is characterized by light interception (LI) and light use efficiency (LUE). The correlation between cumulative intercepted PAR in field crops and accumulated biomass is frequently linear (Zhang, 2007). Light use efficiency is the name of this relationship's slope (Monteith, 1977; Sultana et al., 2023). Increased solar radiation absorption, increased efficiency of light usage, or a combination of the two can all lead to increased productivity (Willey, 1990). An accurate description of the leaf area index (LAI), the light extinction coefficient for IPAR (K), and RUE are necessary for effective plant growth modelling. When in the same field, two kinds of plants are grown side by side, light interception may increase due to either a longer time of soil coverage (temporal advantage) or a further broad soil cover

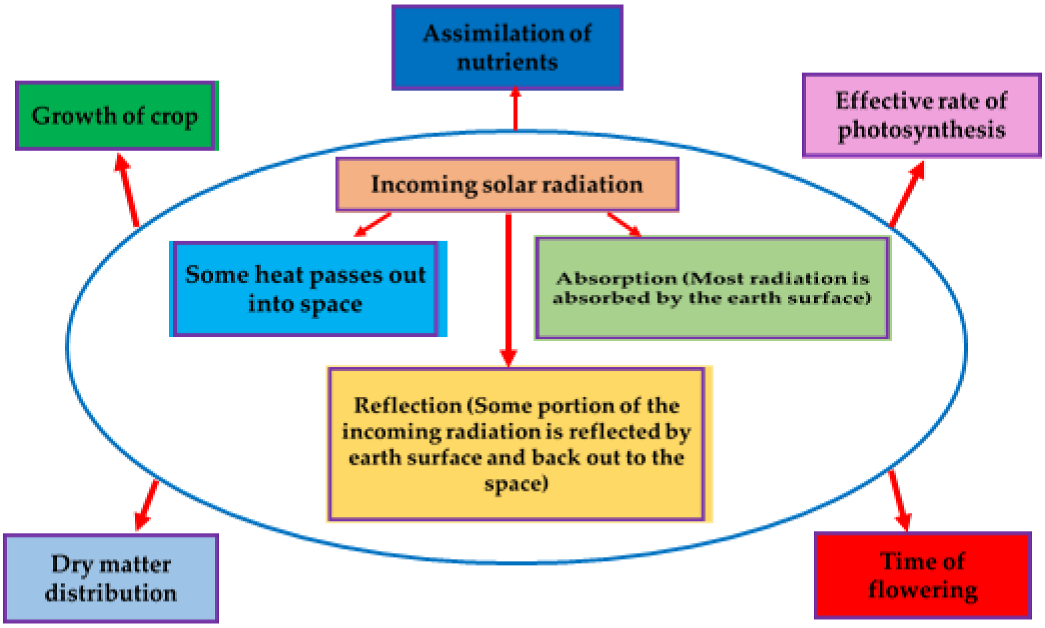

Fig. 1: Representation of solar radiation components and how they affect crop production.

(spatial advantage) (Keating & Carberry, 1993). Since there is no competition between the component crops that have different growth seasons, resource usage efficiency is not likely to be significantly impacted. In intercrop systems, the amounts of incoming PAR that are absorbed by component crop canopies mostly rely on the leaf area index and canopy structure (Bastiaans et al., 2000).

Canopy Architecture and Leaf Area Index

The amount of light that can enter the canopy and how much it impacts the rate of photosynthesis are both greatly influenced by canopy architecture (Song et al., 2013). A closed canopy of plants has a variation in light availability from top to bottom of about 20 to 50-fold. Variations in the spectral dissemination of the photosynthetic photon flux density (PPFD) inside the canopy is one of the causes of this, and changes in leaf orientation, spatial arrangement, shape and arrangement relative to the sun (Murchie & Reynolds, 2013) are important factors influencing light interception. The spatial arrangement of plant density, specifically, the canopy architecture, affect how much light is available. For instance, leaf gross photosynthetic rate (Pn) develops gradually from the bottom to the top of the canopy but light interception falls exponentially. These variations in the canopy's light availability are brought on by variations in the leaf and canopy architectural features (Zhang et al., 2016). Leaf characteristics, such as the leaf area index (LAI) and leaf mass per unit area (LMA), play a significant role in the ability of leaves to capture light and photosynthesis under the developing canopy (Yang et al. 2017). In general, variation in light absorption are brought on by crop development. For instance, according to Zhang et al. (2016), the generation of dry matter (DM) is always positively associated with light absorption. In crop development, the canopy extinction coefficient (K) is crucial. This value is determined by the canopy structure, species, and sowing pattern (Soleymani, 2018).

Crop canopy alteration and changes in leaf area index are the results of all agronomic activities, including spacing and population densities. To increase growth and raise the leaf area index, it's crucial to use nutrients, moisture, and growth regulators like Gibberellins in balance. Also, there are opportunities to enhance agricultural photosynthesis performance (Chrispeels & Sadava, 2003) by expanding the range of light that may be used for photosynthesis and introducing C4 photosynthesis to C3 plants (Éva et al., 2018). To obtain high photosynthetic rates, a high LAI is necessary. Certain crop plants have been discovered to increase their maximum total above-ground output at a LAI of eight. Research on cotton plants with mutant okra shapes revealed that dwarf plants with short, erect leaves produced more yield compared to plants with big leaves (Andres, 2016). Therefore, growing cotton plants having broad canopies will increase yield such as those found in okra-type crops in which the most light permeates the canopies than that of the typical okra-type cotton. Several studies have shown that the most significant aspect in creating an ideal canopy structure with a decent LAI and porosity-a crucial criterion to describe the canopy's ability to transmit light-is adequate planting density (Stewart et al. 2003). Due to its benefits, such as their capacity to quickly and repeatedly record data, high resolution, and low cost, unmanned aerial vehicles (UAVs) are being used more for agricultural growth monitoring. LAI is a crucial factor in determining crop canopy structure and unharmed growth. For correct nutritional diagnosis and cotton canopy structure and unharmed growth. For correct nutritional diagnosis and cotton fertilization, precise cotton LAI monitoring is important (Fan et al., 2022).

3D Crop Growth Model Used in Cotton, Wheat and Maize

Since the early 1960s, researchers have been focusing extensively on how plants absorb light. Simple models of light interception have been created for single plants, crop rows, and continuous canopies. Crop geometry has been used to examine more complicated models, and some researches have attempted to represent plant competition.

Large areas have been managed using cotton simulation models like GOSSYM-COMAX, its use has largely been limited to conventional row spacing, near-optimal water and nitrogen availability, and for soil conditions assumed to be uniform. Net photosynthesis in GOSSYM model is determined by subtracting respiration from gross photosynthesis. The potential gross photosynthesis of a canopy is multiplied by the percentage of light interception, ground area per plant, water stress reduction factor, and CO_2 correction factor. This formula is used to express gross photosynthesis, which is presented like below

Pg = pstand x int_ x popfac x ptsred x pnetcor x 0.001 (1)

Where int_ is the percentage of light that is intercepted by a plant, popfac is the area of soil per plant, ptsred is a water stress reduction factor, pnetcor is a CO_2 correction factor, and 0.001 is used to convert in gram (Jallas et al. 1998).

To address the limitations of previous models, a new light interception model introduced by Jallas et al. (1998). This method does not require the user to provide any more information. The goal was to swap out the current model in a clear manner. This suggests that if a user simulates the harvests from the previous year, they must get the same outcomes (only when using "traditional" row spacing). According to Thornley and Johnson (1990), the "% of intercepted light" in the revised model is as follows:

Int_ = 1 – (Tg + Tc)

Where Tg is the light that reaches the ground without passing through the canopy and Tc is the light that passes through the canopy. Tc expressed as

$Tc = (1 - Tg)e^{-KL}$

Where K is the canopy's light extinction coefficient and L is the LAI divided by (1 – Tg) ratio that represents the effective leaf area index.

One most recent investigation by Bai et al. (2016), revealed that, for all genotypes used in experiment in each year, iPAR exhibited a highly significant exponential association with LAI (R2 0.86, P> |t| :0.001). These were the fitting equations:

Equation A: $\ln(Y) = 0.55 \times \ln(X) - 0.98$, N = 54, $R^2 = 0.86$;

The PAR that crops absorb (APAR) is positively correlated with growth rate, which in turn is correlated with grain set and yield in wheat (Andrade et al., 2005; Lake & Sadras, 2016). The ratio of incident PAR to the amount of this radiation that is absorbed by green area (fAPARg) is known as the APAR. Remote sensors are an incredible tool for tracking vegetation radiation capture because the fAPARg coincides with various vegetation indices (Di Bella et al., 2004; Gitelson et al., 2014). Crop biomass production and yield are frequently estimated and analyzed by using the radiation capture and use efficiency framework. According to this concept, harvest index (HI, The ratio of grain biomass to total biomass), radiation use efficiency (RUE), and absorbed radiation (APAR) are the three factors that determine yield in wheat:

$\text{Yieldgm}^{-2} = \text{APARMJm}^{-2} \times \text{RUEgMJ}^{-1} \times \text{HI}$ …… (3)

Crop modelling is now a widely used method for evaluating the productivity of the land under various crop systems (Kirkegaard et al., 2014; Wang et al., 2008). One of the most popular agricultural systems models is the APSIM modelling framework (Holzworth et al., 2014; Keating et al., 2003; Wang et al., 2002), which simulates the growth, yield, and resource use efficiency of major crops and diverse cropping systems, as well as the effects of different farming techniques like fallowing, rotations, tillage, and grazing (Pembleton et al., 2013; Thorburn et al., 2001; Zeleke, 2017). Jahangirlou et al. (2023), applied APSIM-Maize (APSIM version 7.10) model which was utilized to simulate the growth and grain yield of two cultivars of maize. APSIM is a simulation model for modular process-based cropping system. Considering soil parameters, weather data, and agricultural practices, it simulates the development of a similar maize field on a regular time-step. Grain yield simulation in APSIM is an estimation of the ratio of grain number to grain size. The grain protein concentration of maize is also simulated by APSIM as a feature of dry mass and N acquisition into the grain. The parameters required for foretelling starch and oil deposition throughout grain development were calculated by adjusting a Three-Parameter Logistic Model (3PLM) to experimental data from a previous study, demonstrated in days after flower initiation. SigmaPlot V.12 was used to fit curves and calculate the parameters of the logistic equation:

$$f(x) = \frac{a}{1 + e^{-(x-c)/b}} \quad \ldots\ldots\ldots \ (4)$$

Where x is the number of days following flowering and a is the maximum concentration of starch and oil measured at biological ripeness. The slope and abscissa of the mid-height point, which represent the initial value parameter and theoretical growth rate of storage compounds, respectively, are parameters b and c. The yield and storage constituents of maize, including starch, oil content, and protein were predicted using a combination of APSIM and logistic regression models as a function of genetics and management practices.

Research Findings on Cotton

In cotton (*Gossypium hirsutum* L.), the amount of PAR intercepted within the canopy affects yield and other agronomic factors. Xing et al., determined that, because-of higher LI in the middle and upper canopy, cotton cultivars with long branches (loose-type) intercepted more LI than did cultivars with short branches (compact-type). This study also determines that, despite having a higher LI, loose-type varieties did not significantly outperform compact-type varieties in terms of yield because of a lower harvest. The cotton yield for loose-type cotton may therefore be further increased by raising the harvest index by modifying the source-to-sink relationship. Furthermore, researchers found a positive association between canopy-accumulated LI and the accumulation of reproductive organ biomass, showing that increasing LI is crucial for cultivar-specific yield increase. Additionally, yield distribution beneath the canopy significantly correlated vertical LI distribution along a linear path. Jie An et al. (2023), find out that, light was intercepted more effectively by the looser and tower-formed cotton varieties (on average 28.6%) and had a higher LAI (on average 34.2%) than compact cotton varieties, which led to a greater cotton yield (on average 14.8%). Furthermore, the flower initiation and boll-forming phases, when the average plant height (94.6 cm), LAI (3.58), and biomass (15,006 kgha^{-1}) all reached its peak, were also when the high light interception rate took place, according to polynomial correlation. Additionally, yield was strongly positively linked with both light utilization efficiency (LUE) (R = 0.36) and intercepted IPAR (R = 0.7). Ultimately, the results show that planting cotton genotypes with looser and tower-type canopy will increase cotton output and light use efficiency in China's Yellow River basin and other places with similar climates.

Conclusion

Light interception and the efficiency of light-energy transformation will both increase as a crop's light-energy usage rate rises. In the process of photosynthesis, chlorophyll is essential for the absorption and processing of light. Canopy size is a key component of plant canopy structure, which has a significant impact on agricultural functions like production and stress tolerance. The manual measurement of multi-dimensional features like predicted leaf area and canopy volume is time-consuming and inaccurate. To measure and track plant canopy development, field-cantered high throughput profiling equipment using imaging skills can quickly collect data of crops in the field. This study set out to create a content of description of 3D imaging method and model development in the field. The assortment of optimal architectural forms offers a manner and route for additional creative investigation into 3D visual structures, and so offers conceptual and practical assistance for crop structural arrangement. Interception of light and photosynthesis were exclusively simulated in 3D canopy models in several researches, for which certain relationships were obvious and considerable variations between various types of designs were found. The canopies foliage's ability to reflect light cannot be precisely measured in the field due to technical limitations.

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