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Identification of plant configurations maximizing radiation capture in relay strip cotton using a functional–structural plant model

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ABSTRACT

One of the key decisions in crop production is the choice of row distance and plant density. The choice of these planting pattern parameters is especially challenging in heterogeneous systems, such as systems containing alternating strips. Here we use functional–structural plant modelling to address the problem of identifying optimal row distances and plant density in a heterogeneous crop system. We compare radiation capture in sole cotton and relay strip cotton, remaining after harvest of wheat from a wheat–cotton relay strip intercrop. We compare light interception in the two systems under different scenarios of row distance and plant density. Light interception calculations with the functional–structural plant model were evaluated using field observations. Light interception by cotton was mainly determined by row distances and to a lesser extent by plant density. Light interception was reduced by the gaps between the strips in strip cotton. Plant density (per unit area of the whole system) providing maximum light interception was lower in relay strip cotton than in normal cotton. Plastic responses of cotton to canopy heterogeneity, accounted for in the model, did not result in full radiation capture in strip cotton. The gaps between the rows in strip cotton allowed light penetration to deeper canopy layers relevant for the reduction of fruit abortion rate. We conclude that relay strip cotton cannot attain the same light interception as sole cotton, due to the gaps between the strips. Increasing plant density was insufficient to bridge the gap. Thus, the maximum light interception in strip cotton is lower than in sole cotton, and is achieved at a lower overall plant density. FSP modelling provided a suitable tool to identify row distance and plant densities providing high light interception in a heterogeneous canopy.

1. Introduction

Intercropping has several virtues, such as high light interception (Zhang et al., 2008b; Solanki et al., 2011), high productivity per unit land (Szumigalski and Van Acker, 2008; Mao et al., 2012; Sadeghi et al., 2012), efficient use of water (Gao et al., 2009; Morris and Garrity, 1993) and nutrients (Li et al., 2001), sequestration of organic carbon and nitrogen in soil (Cong et al., 2014), and suppression of pests and diseases (Andow, 1991; Zhu et al., 2000). Realization of the benefits of intercropping with respect to productivity and resource use efficiency requires a planting pattern that enables the plants to capture the available resources as completely as possible (Midmore, 1993; Worku and Demisie, 2012; Mattera et al., 2013). However, in mixtures, the ability of one species to capture resources will usually be constrained by competition for space with the other species (Zhu et al., 2014). This is even the case in relay intercrops, where the intercropped species have only partly overlapping growing periods, due to the competition for row space. Thus, relay intercrops consist of strip crops with empty space between the strips during the part of the growing season that the companion crop is not growing. This reduces their radiation interception and productivity. Crop system design with simulation models may be used to find the optimal system for radiation capture.

In China, cotton is grown on an area of 5.2 million hectare, and the yearly production is 6.67 million tones. Different cultivation systems with large differences in row spacing, plant density and

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plant height are in use in different regions according to the growing conditions. In the Yellow River basin, part of the cotton is grown as a strip intercrop with wheat (Zhang et al., 2007; Dai and Dong, 2014). In the wheat–cotton intercropping system, wheat strips are sown in October/November, with strips of bare soil between them. Cotton is sown in these bare strips in April. After wheat harvest in June, the cotton grows as a sole crop. After wheat harvest, cotton plants can only cover the space previously occupied by wheat if the wheat strips are narrow enough. Strip width needs therefore to be carefully chosen to minimize competition from the wheat towards cotton and maximize radiation interception when the cotton is growing alone.

The cotton plant is a perennial with indeterminate growth. Cotton plant architecture strongly responds to plant population density, pruning, shoot topping and strip intercropping. It has been shown that high population density and narrow row/strip spacing increase early light interception in cotton (Kaggwa-Asiimwe et al., 2013; Mao et al., 2014). Further work is needed, however, to identify optimal planting patterns of strip cotton, derived from relay strip intercropping with wheat, to maximize radiation interception.

It is attractive to dynamically model light interception in heterogeneous canopies based on the architectural dynamics and light interception of the plant stand as implemented in functional–structural plant (FSP) models (Godin and Sinoquet, 2005; Vos et al., 2010). FSP models simulate 3D growth and development of individual plants in stands, and light interception and distribution in the canopy is a function of row and plant distances and plant architecture (Vos et al., 2010; Munier-Jolain et al., 2013; Zhu et al., 2015). Gu et al. (2014) developed an FSP model for cotton, named CottonXL. CottonXL simulates the development of leaves and fruits (squares, flowers and bolls), plant height and branching in response to plant density and use of the growth regulator mepiquat chloride (MC), which is widely used in cotton cultivation worldwide (Mao et al., 2014; Ren et al., 2013). Crop development is driven by thermal time using algorithms of Zhang et al. (2008a). Plant structural responses to plant density, plant growth regulator and topping were parameterized at a high level of detail and validated in independent experiments, both in sole crops of cotton and in strip intercrops with wheat, under different regimes of growth regulator, thus making the model suitable for a wide range of situations (Gu et al., 2014; Wang et al., 2014). However, until now, calculation of light interception has not been implemented in CottonXL and such calculations have not before been tested, particularly not in heterogeneous stands, derived from intercropping.

The objective of the present study was to assess the distribution and interception of light in heterogeneous canopies, such as those of cotton remaining after wheat harvest in a wheat–cotton relay strip intercrop, and to identify planting patterns that contribute to high radiation interception in the relay strip crop that remains after harvest of the first crop, i.c. wheat. To achieve this objective, CottonXL was extended with functionality for radiation interception at the leaf level, and its predictions were tested with light measurements taken in heterogeneous cotton crops (after wheat harvest in intercrop). After validation, we used the model to perform virtual experiments in which cotton light interception was simulated under various scenarios for row distance and plant density of cotton in sole and strip crops.

2. Materials and methods

2.1. Model description

CottonXL (Gu et al., 2014) is a model for the structural development of cotton under the influence of temperature, plant density and the use of the growth regulator mepiquat chloride (MC). Plant development is driven by thermal time with a base temperature of 12 °C and an optimum temperature of 25 °C (Wang et al., 2014). The model is implemented in the GroIMP plant simulation platform (Hemmerling et al., 2008) and uses a time step for integration of 1 days. A developmental delay of intercropped cotton as compared to sole cotton of 4.7 physiological days (days required under optimal temperature) is accounted for by multiplying the development rate of cotton in intercrops with a delay coefficient until the time of wheat harvest (Zhang et al., 2008c).

Cotton XL was parameterized using experimental field data for architectural traits such as leaf and internode size distribution as well as leaf and branch angles, in relation to cropping system (monoculture and intercropping), plant population density (from 1.0 to 9.0 plants m^{-2}) and application of mepiquat chloride, a growth regulator resulting in compact cotton architecture (Ren et al., 2013; Mao et al., 2014). Plastic responses in those architectural traits were therefore calibrated as input, not simulated as output. Model output showed good agreement with field observations of leaf area index (LAI), plant height, number of branches and plant geometry both in sole crop and intercrop systems at various plant densities (Gu et al., 2014).

The ability to calculate light interception at leaf level was implemented in CottonXL by adding light sources and including parameters for the leaf optical properties. The source of the incoming light was modelled using a direct and a diffuse radiation component. Direct radiation was represented by a single light source in zenith while diffuse radiation was approximated by a virtual hemisphere of 72 directional light sources (Evers et al., 2007). The total incoming radiation intensity was fixed at 25 MJ m^{-2} day^{-1}, 85% of which was assumed to be direct radiation, and the remaining 15% diffuse for a clear day at experimental site (Zhou et al., 2004), which was consistent with the situation of field measurements. As most of the radiation came from the direct light source in the zenith, edge effects were minimal. Nevertheless, edge effects were taken into account by disregarding the outer parts of the simulated scene when making calculations on light interception. Leaf reflectance for PAR was set to 11% and transmittance to 7.6% (calculated from Gausman, 1983). Soil reflectance was set to 2.5%. Effects of light interception on growth and development of the cotton plants were not considered in the current version of the model.

2.2. Field experiments and model validation

A field experiment for the validation of light distribution and interception of the cotton model was conducted at the Institute of Cotton Research of the Chinese Academy of Agricultural Sciences, Anyang, Henan province, China (36°07′N, 116°22′E) in 2001/2002 as described by Zhang et al. (2007, 2008b). The soil at the experiment site is a sandy loam. Rainfall was 318 mm in 2002. All plots received 225 kg ha^{-1} N, 150 kg ha^{-1} P_2O_5 and 225 kg ha^{-1} K_2O as fertilizer, according to farmer's practice. Five irrigations of 50 mm each were given by flooding the field on 15 April, 2 and 21 June, 23 July and 25 August, based on crop water requirement.

The experiment comprised a sole cotton (*Gossypium hirsutum*) treatment and three relay intercrop treatments with cotton and wheat (*Triticum aestivum*) differing in the number of rows: 3 rows wheat and 2 rows cotton (3W2C), 4 rows wheat and 2 rows cotton (4W2C), and 6 rows wheat and 2 rows cotton (6W2C). Details on these designs have been given in Zhang et al. (2007). Plant distance within the cotton rows was fixed at 0.25 m, thus the overall homogenized population density (i.e., density expressed per m^{-2} of total intercrop area) varied from 4.0 plants m^{-2} in 6W2C to 6.7 plants m^{-2} in 3W2C (Table 1). The four treatments were applied in four replicates.