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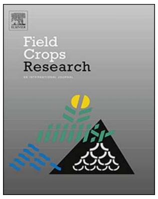

Border row effects on light interception in wheat/maize strip intercropping systems

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ABSTRACT

In strip intercropping systems, different crop rows in a complete strip usually behave differently in growth dynamics and have distinct contribution to the final yield of the system, so resources capture and utilization processes of different crop rows should be treated separately in the performance evaluation of the whole system. This study was conducted to investigate the differences in light capture among different crop rows in wheat/maize strip intercropping systems. The field experiment comprised four planting patterns: monoculture wheat, monoculture maize, six rows of wheat alternated with two rows of maize (I62), and twelve rows of wheat alternated with four rows of maize (I124). A geometrical radiation transmission model was modified to estimate instantaneous light capture by different intercropped rows, which was tested with photosynthetically active radiation (PAR) measured above and beneath the intercrop canopy. The results demonstrated that the model accurately predicted PAR transmitted through the canopy with mean absolute error, root mean square error (RMSE) and normalized RMSE of 60.2 μmol m^{-2} s^{-1}, 82.6 μmol m^{-2} s^{-1} and 5.2% respectively for I62 and of 65.9 μmol m^{-2} s^{-1}, 95.3 μmol m^{-2} s^{-1} and 5.7% respectively for I124. With assistance of the model, we found that border rows in wheat strip intercepted far greater amount of both direct and diffuse PAR than the inner rows, whereas maize border rows showed no advantage in PAR absorption due to its canopy development was constrained by the competition from wheat strip. Canopy structure character showed positive effects on radiation interception in wheat border rows and all maize rows, and plant phenotypic plasticity showed positive effects on wheat border rows but negative effects on maize border rows. The radiation transmission model presented in this work was proved to be a useful tool for calculating spatial and temporal variability of radiation in strip intercropping systems and it can be further served as a base for modeling the plant growth dynamics in strip intercrops.

1. Introduction

Intercropping, the way of growing different crop species together on a given piece of land, is a very important cropping system especially for small farms or organic farms in many areas of the world (Feike et al., 2012; Bedoussac et al., 2015). More and more attention has been received by intercropping in recent years due to its clear agro-ecological advantages over systems in which only one crop species is grown. The most remarkable advantage of intercropping is producing a greater yield or income through more efficient use of agricultural sources such as nutrient, water, heat and radiation (Willey, 1990; Thorsted et al., 2006; Lithourgidis et al., 2011; Munz et al., 2014a; Wang et al., 2015b). Moreover, intercropping can improve soil fertility, prevent soil erosion, and reduce the occurrence of diseases, insects and weeds (Hauggaard-Nielsen et al., 2013; Brooker et al., 2015; Jensen et al., 2015). It therefore has been regarded as an alternative practice for sustainable agriculture.

There is often a linear relationship between cumulative intercepted photosynthetically active radiation (PAR, 400–700 nm) and accumulated biomass in field crops (Monteith, 1977). Productivity improvement of crop systems can result from either greater interception of solar radiation, a higher light use efficiency, or a combination of the two (Willey, 1990; Keating and Carberry, 1993; Zahedi et al., 2015). The canopy structure of a monoculture is usually changed through intercropping, which would directly alter the radiation interception of the crop. Many studies have indicated that more efficient capture and use of solar radiation is a major reason for the yield advantage of intercropping over monocultures. Intercrops of two species with distinct canopy

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structure, mainly tall and short species combination, such as maize/soybean (Gao et al., 2010; Coll et al., 2012), maize/peanut (Awal et al., 2006), and sorghum/groundnut intercropping systems (Harris et al., 1987), could enhance light capture over space by improving soil coverage and reducing the proportion of light reaching the ground. In another way, intercropping short- and long-duration species, such as sorghum/pigeonpea (Natarajan and Willey, 1980), wheat/maize (Wang et al., 2015c; Gou et al., 2017), and winter wheat/cotton intercrops (Zhang et al., 2008; Mao et al., 2014), could enhance light capture over time by lengthening the period of soil coverage. Strip intercropping is the practice of cultivating two or more crops in alternate strips, which has the advantage of facilitating the application of agricultural machine compared to row intercropping (Feike et al., 2012; Hauggaard-Nielsen et al., 2013). Studies showed that strip intercropping outyielded monocropping mainly due to an increased yield in the border rows of the dominant species (Li et al., 2001; Jurik and Van, 2004; Knörzer et al., 2011; Nassiri Mahallati et al., 2015; Gou et al., 2016). Border rows and inner rows in intercropped strips behaved very differently in radiation capture and utilization, however, except for the research by Jurik and Van (2004) in which PAR interception by each crop row in corn-soybean-oat strip intercrop was measured, most previous studies deemed the strip as a whole and ignored the discrepancy among intercropped rows when analyzing radiation transmission. Therefore, it is necessary to develop a comprehensive model, which provides a better understanding of the temporal and spatial variability of radiation interception in intercropped strips and helps to identify the most suitable intercropping pattern.

Several mathematical models have been developed to depict radiation transmission in mixed canopies. Keating and Carberry (1993) concluded that if the canopy structure of an intercropping system is divided into several distinct layers by height, the daily amount of light intercepted within each layer can be calculated directly by applying the Beer's law. This method had been successfully used to estimate daily light interception in intercropping systems (Wallace, 1997; Awal et al., 2006; Gao et al., 2010; Nassiri Mahallati et al., 2015); however, for strip intercropping systems, the strips of component crops are often widely spaced, the application of the Beer's law may result in large errors. Zhang et al. (2008) proposed that the canopy structure of wheat/cotton relay intercropping systems can be described by strip-path geometry and used the row-crop radiation transmission model (Goudriaan, 1977; Pronk et al., 2003) to estimate daily light interception. Wang et al. (2015c) extended the row-crop radiation transmission model to estimate radiation interception and partitioning in strip intercropping systems after considering the heterogeneity of leaf distribution in both the horizontal and vertical directions. However, models mentioned above are more empirical and are mainly applied for calculating daily radiation capture due to their simple assumptions and ignoring the effects of light quality, crop row orientation, and the incidence angle on light transmission. Gijzen and Goudriaan (1989) developed an explanatory model for calculating light interception by row crops. The model is based on geometrical relationships between light direction and canopy architecture, which provides a practical basis for modeling light transmission in intercrops. Tsubo and Walker (2002) applied this geometrical approach to estimate the instantaneous light interception by a row-intercrop of bean and maize and Munz et al. (2014b) used it to calculate light availability for the subordinate crop within a strip-intercrop of maize and bush bean. Both studies verified that this approach was robust in describing the geometric relationship and radiation distribution in intercropping systems.

Wheat/maize strip intercropping systems are widely applied in irrigated areas of northwest china to extend the growing season and improve total crop production. Border row effects on yield advantage and nutrient uptake in this system have been investigated in depth (Li et al., 2001; Li et al., 2011; Gao et al., 2014; Cong et al., 2015); however, only a few studies has been conducted to quantify the border row effects on radiation interception (Zhu et al., 2015), though knowledge of this component is essential for exploring the physiological basis for the observed yield advantage of this system. Therefore, the objectives of the present study were to: 1) extend the geometrical radiation transmission model to calculate the variation in radiation interception by different crop rows in strip intercrops, 2) quantify the border row effects on radiation interception in wheat/maize strip intercropping systems of different canopy structure with assistance of the model, and 3) investigate the reasons contributing to the border row effects on light interception.

2. Materials and methods

2.1. Radiation transmission model

In a row crop, the inter-row spacing is much wider than the intra-row spacing, the turbid medium for radiation transmission can be assumed to be a rectangular hedgerow after neglecting the intra-row spacing. The hedgerow height (h) equals to the canopy height and the hedgerow cross-section width (w_{H}) can be calculated as the product of crop inter-row spacing (w_{R}) and the fraction of ground cover by the canopy (τ_{c}). The value of τ_{c} can be estimated as the ratio between the actual leaf area index (LAI) and the typical LAI for maximum ground cover ($3.0\ \mathrm{m}^2\ \mathrm{m}^{-2}$) when LAI is less than the typical value, else the ground was deemed as fully covered, and τ_{c} is taken as 1.0 (Christopher, 2006).

The canopy configuration and radiation extinction ability of different species in a strip intercropping are generally discrepant, and the same crop in different rows also have various hedgerow configurations due to the border row effects on crop growth. Therefore, each row in an intercropping strip could be deemed as a hedgerow. Suppose that a direct beam on the canopy surface transmits through n hedgerows before reaching the soil surface, the fraction of radiation intercepted by hedgerow numbered i, f_i, and that incident on the soil surface, f_s, are respectively given by the Beer's law:

$$f_i = \exp\left(-\sum_{j=1}^{i-1} g_{Hj} LAD_{Hj} d_{Hj}\right)[1 - \exp(-g_{Hi} LAD_{Hi} d_{Hi})] \tag{1}$$

$$f_s = \exp\left(-\sum_{j=1}^{n} g_{Hj} LAD_{Hj} d_{Hj}\right) \tag{2}$$

where g is the canopy extinction coefficient (the average projection area of canopy elements onto a surface normal to the direction of the projection); LAD is the leaf area density; d is the radiation transmission distance in the hedgerow; i is the number of the hedgerow for which light interception is calculated and j is the number of hedgerows which are traversed by the light beam; and subscripts Hi and Hj represent the hedgerow numbered i and j respectively.

The canopy extinction coefficient g is calculated with the G function (Campbell and Norman, 1998):

$$g = \frac{\sqrt{\chi^2 \cos^2\psi + \sin^2\psi}}{\chi + 1.774(\chi + 1.182)^{-0.773}} \tag{3}$$

where χ is the ratio of vertical to horizontal projections of canopy elements, which could be derived from the K function for canopy extinction coefficient in combination with the Beer's law, using the measured radiation transmittances at different solar incident angles and corresponding LAI values as inputs (Tsubo and Walker, 2002). The χ values for wheat and maize in our experiment were derived as 1.20 and 0.81 respectively (Wang et al., 2015d). And ψ is the solar zenith angle.

Assuming uniform LAD in the hedgerow, LAD can be calculated as (Tsubo and Walker, 2002):

$$LAD = LAI\frac{w_{\mathrm{R}}}{w_{\mathrm{H}} h} \tag{4}$$