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Radiation interception and utilization by wheat/maize strip intercropping systems

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ABSTRACT

Intercropping can improve productivity per unit incident radiation by increasing the interception of solar radiation and/or maintaining higher radiation-use efficiency (RUE). This study examined the changes in radiation interception and RUE of spring wheat and spring maize after the initiation of intercropping. The field experiment comprised four treatments: wheat only, maize only, six rows of wheat alternated with two rows of maize (I62), and twelve rows of wheat alternated with four rows of maize (I124). The results demonstrated that per row, wheat in I62 and I124 intercepted 17% and 9% more radiation, respectively, than the wheat sole-cropping system and maize in I62 and I124 intercepted 28% and 26% more radiation, respectively, than the maize sole-cropping system. The RUE values were 3.10 and 3.19 g MJ^{-1} for maize in I62 and I124, respectively, lower than that for the maize sole-cropping system (3.51 g MJ^{-1}). No significant difference was observed between the RUE values of intercropped and monoculture wheat. The harvest index of maize was identical in all systems, while that of the wheat was enhanced by intercropping. The grain yields of wheat in I62 and I124 were 29.2% and 10.8% higher, respectively, than that of sole wheat on per row basis and the grain yields of maize in I62 and I124 were 16.8% and 15.0% higher, respectively, than that of sole maize. Thus, increased radiation capture was the primary factor responsible for the high productivity of the wheat/maize intercropping systems. A simple model was developed to estimate radiation interception and partitioning in strip intercropping systems, considering the heterogeneity of leaf distribution in both the horizontal and vertical directions. The model may also be applicable to other strip intercropping systems.

1. Introduction

Sole-cropping systems in China experienced substantial increases in production and yield in recent decades, but these increases may have been achieved at the cost of sustainability, as increasing amounts of fertilizer, irrigation, water and agrochemicals were applied to sustain these high levels of production (Meng et al., 2012; National Bureau of Statistics of China, 1996–2012). Intercropping is the practice of simultaneously cultivating two or more crops in the same field. Compared to monoculture, the main advantage of intercropping is improved grain yield through more efficient use of resources such as radiation, water, and nitrogen (Lithourgidis et al., 2011; Willey, 1979, 1990). Moreover, intercropping can improve soil fertility, prevent soil erosion, and reduce the occurrence of diseases, insects and weeds (Lithourgidis et al., 2011; Rao and Mathuva, 2000). It has been regarded as an alternative practice for sustainable agriculture.

Hetao irrigation district in Inner Mongolia (40°19′–41°18′N, 106°20′E–109°19′E) and Hexi corridor in Gansu province (37°15′–41°30′N, 92°21′E–104°45′E), China, have similar climatic patterns characterized by abundant light and thermal resources, low humidity and limited precipitation (Bao and Fang, 2007; Dai et al., 2011). There is only one crop per year due to the short growing season. Many intercropping systems had been developed to extend the growing season and improve total crop production. Wheat/maize intercropping is now one of the

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dominant planting patterns in these areas. In this system, wheat is sown in late March and space is left open between the wheat strips to enable sowing of maize one month later. Wheat is harvested in mid-July, leaving approximately 80 co-growing days for the two crops (Zhang and Li, 2003). Many studies have conducted in recent years to investigate the nutrient uptake (Li et al., 2001; Li et al., 2011), root distribution (Li et al., 2006; Yang et al., 2010) and water-use efficiency (Fan et al., 2013; Yang et al., 2011) of this planting pattern; however, to the best knowledge of the authors, there have been few coherent attempts to quantify the radiation interception and use efficiency of the component crops, though knowledge of this component is essential for exploring the physiological basis for the observed yield advantage of this system.

Measurement of radiation capture in intercropping systems is more difficult than in sole-cropping systems because of the spatially heterogeneous canopy. Several mathematical models have been developed to estimate radiation transmission in mixed canopies. Sinoquet and Bonhomme (1992) introduced a two-dimensional radiation-transfer model based on a turbid-medium analogy, dividing the space into cells according to horizontal layers and vertical slices parallel to row orientation. Tsubo and Walker (2002) developed an explanatory model to quantify instantaneous radiation transmission in intercropped maize/soybean based on the geometrical model established by Gijzen and Goudriaan (1989) for hedgerow crops. These models can give satisfactory descriptions of light distribution in intercropped canopies, but their application is complex because a large number of input variables and complicated mathematics is required (Awal et al., 2006; Ozier-Lafontaine et al., 1997). Keating and Carberry (1993) concluded that if the canopy structure of an additive intercropping system is divided into several distinct layers by height, the daily amount of light intercepted within layer j (I_j) can be calculated directly by applying Beer's law:

$$I_j = I_{j0}(1 - \exp(-k_{j1}\mathrm{LAI}_{j1} - k_{j2}\mathrm{LAI}_{j2})) \quad (1)$$

where I_{j0} is amount of solar radiation entering the top of layer j and k_{j1}, k_{j2} and LAI_{j1}, LAI_{j2} are, respectively, for the two species, their radiation extinction coefficients and leaf area indices contained within layer j. This method is referred to here as the horizontally homogeneous leaf area (HHLA) model because it performs well only if the leaf area of each crop is horizontally homogeneous or can be assumed to be so. It had been successfully used to estimate daily light interception in crop-weed associations (Wiles and Wilkerson, 1991) and intercropping systems (Gao et al., 2010; Tsubo and Walker, 2002); however, for strip intercropping systems, the strips of component crops are often widely spaced, so application of the HHLA model 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 (RCRT) model (Goudriaan, 1977; Pronk et al., 2003) to estimate daily light interception; however, no model evaluation was shown in their text, and the assumption of strip-path geometry during co-growth may be arbitrary. The RCRT approach was also applied by Munz et al. (2014) to calculate light availability for a subordinate crop in a strip intercropping system. Knörzer et al. (2011) derived empirical equations from published investigations to quantify the shading effects of one intercropped strip on another, but these equations were site- and crop-specific, and thus, not applicable to other intercropping systems.

This study was conducted to construct a simple model for strip intercropping systems to estimate radiation interception, isolate the proportion of radiation intercepted daily by each crop and analyze radiation interception in terms of the yield advantage of wheat/maize intercropping systems.

2. Radiation transmission theory

On a daily basis, incident radiation on the crop canopy was assumed to be isotropy, i.e., homogeneous radiance from the entire sky, which enabled easy spatial integration over all directions without need to consider time of day or day of year (Goudriaan, 1977, 1988; Pronk et al., 2003). For the wheat and maize sole-cropping systems, F_{PAR} was estimated using Beer's law (Christopher, 2006; Monsi and Saeki, 1953):

$$F_{\mathrm{PAR}} = 1 - \exp(-k \times \mathrm{LAI}) \quad (2)$$

where LAI is the leaf area index of the sole crop, and k refers to the light extinction coefficient of the canopy, which means that the average relative projection area of canopy elements onto a horizontal surface (Campbell and Norman, 1998).

The development of wheat/maize intercropping was separated into three phases: phase I, after the emergence of wheat and before the emergence of maize (wheat only); phase II, after the emergence of maize and before the harvest of wheat (co-growth period); and phase III, after the harvest of wheat and before the harvest of maize (maize only). In phases I and III, there are only one crop in the intercropping field and strip-path geometry can be used to describe the canopy structure. Light intercepted by the canopy was calculated by the RCRT model. A diagram of the strip-path geometry is shown in Fig. 1. To calculate light transmitted onto the soil surface of the path, it is assumed that the crop strip is black (does not transmit light). The view factor of any point on the path is defined as the vertical projection of the unobstructed portions of the sky dome relative to the total vertical projection of the sky dome (Fig. 1). The view factor of the path, $\mathrm{FP}_{\mathrm{black}}$, can be calculated by spatially integrating the view factor of point B over the path (Goudriaan, 1977):

$$\mathrm{FP}_{\mathrm{black}} = \frac{(\sqrt{H^2 + W_{\mathrm{P}}^2} - H)}{W_{\mathrm{P}}} \quad (3)$$

where H is the plant height and W_{P} is the bare path width between the strips. The view factor of the soil surface beneath strip, $\mathrm{FS}_{\mathrm{black}}$, can be calculated in the same way:

$$\mathrm{FS}_{\mathrm{black}} = \frac{(\sqrt{H^2 + W_{\mathrm{S}}^2} - H)}{W_{\mathrm{S}}} \quad (4)$$

where W_{S} is the strip width. The assumption that the crop strip or bare path is black, will result in underestimation of light transmission onto the soil surface. According to Pronk et al. (2003), the radiation incident on top of the path is divided into two portions, $\mathrm{FP}_{\mathrm{black}}$ and $1 - \mathrm{FP}_{\mathrm{black}} \times \mathrm{FP}_{\mathrm{black}}$ transmits directly onto the path surface, while $1 - \mathrm{FP}_{\mathrm{black}}$ is attenuated by a hypothesized horizontally homogeneous canopy onto the soil surfaces of the path and the strip. The light reaching the strip transmits in the same way, except that $\mathrm{FS}_{\mathrm{black}}$ is attenuated by leaves in the strip before reaching the

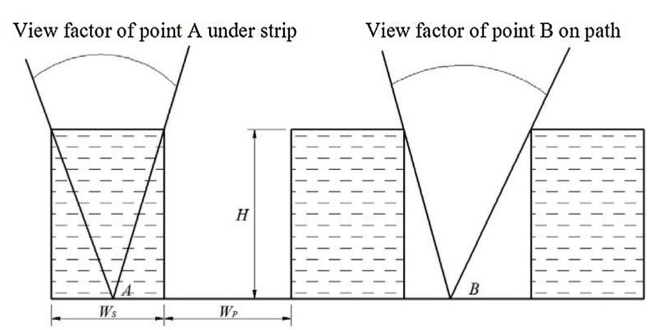

Fig. 1. Diagram of the strip-path geometry and boundaries of the sky from point B at the bottom of the path and from point A under the strip (after Pronk et al., 2003). H, strip height; W_{S}, strip width; and W_{P}, path width.