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Light interception and radiation use efficiency response to narrow-wide row planting patterns in maize

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Abstract

The light deficiency in the canopy is not the main factor limiting maize (*Zea mays* L.) production but the lower radiation use efficiency (RUE). Conservation tillage planting patterns were used to construct a sustainable agricultural system for soil protection and higher RUE. On these bases, we tried to create more uniform light distribution in crop canopy for increasing radiation use efficiency by narrow-wide row planting patterns. Maize were cultivated in three planting patterns: (1) narrow-wide rows of "30 cm + 170 cm" (P1, *i.e.* narrow row is 30 cm, wide row is 170 cm with density 6.4 plants m^{-2}), (2) "40 cm + 90 cm" (P2, *i.e.* narrow row is 40 cm, wide row is 90 cm with density 6.4 plants m^{-2}); and (3) uniform row of "65 cm" (CK, *i.e.* uniform row is 65 cm with density 6.4 plants m^{-2}). The mechanisms of the maize canopy creation during the growth development period were examined. Moreover, the fractions of light interception (*F*), leaf area index (LAI), leaf mass per unit area (LMA), canopy extinction coefficient (*K*) and RUE were compared. In three planting patterns, *K* values exhibit a P1<P2<CK feature. The differences in LMA of the three patterns were not significant (LSD, $p<0.05$). The fractions of light interception value (*F*) in P1 was significantly lower than that in P2 and CK, whereas its LAI was almost equal to that of CK and P2. RUE was the largest in P2. Therefore, with similar plant density, LAI was not affected by planting patterns. Although light interception was lower in narrow-wide row planting patterns while CK was highest in three patterns, the canopy light environment in narrow-wide row planting patterns was improved and RUE was significantly increased, especially in P2.

Keywords: conservation tillage; extinction coefficient; leaf area index; leaf mass per unit area; *Zea mays* L.
Abbreviations: DAP- day after planting; DM- dry matter; *F*- fraction of light interception; K- extinction coefficient; LAI- leaf area index; LMA- leaf mass per unit area; PAR- photosynthetically active radiation; RUE- radiation use efficiency.

Introduction

Planting pattern is an important factor for agricultural sustainability development in influencing the soil protection (Frey et al., 1999; Govaerts et al., 2006). The conservation tillage planting pattern has been proved by a number of researchers for outstanding protection of soil organic matter (Ding et al., 2011). Long-term positioning experiments have demonstrated that no till planting methods and straw returning could reduce the soil erosion and loss of surface fertile soil (Koch and stockfisch, 2006), and planting cost relative to conventional cropping patterns (Raper and Bergtold, 2007). However, some other reports showed that conservation tillage planting could increase soil compacting (Drury et al., 2003), and root could be not conductive to running water and nutrients, while the soil respiration and gas exchange are restricted (Pierce et al., 1992) which would reduce crop yield. In Northeast China, soil degradation has become an important problem constraining agricultural sustainable development. Planting patterns have been expected in northeast China to balance soil protection and crop production. Light is the key role in net primary productivity (Dewar, 1996), light availability varies with plant population spatial arrangements, especially with canopy structures. The variation in canopy light availability is a result of foliage structural and canopy architectural characteristics (Maddonni et al., 2001; Acreche et al., 2009). In growing canopies, foliar traits (such as leaf area index and leaf mass per unit area) are the important factors in leaf light-harvesting capacity and photosynthetic potentials (Niinemets and Sack, 2006). Generally, light interception varies with crop development. Dry matter (DM) production is always positively related to light interception; light interception decreases exponentially from top to bottom of canopy. Typically, foliage photosynthetic capacity (P_n) increases as the gradient from the bottom to the top of canopy increases (Niinemets, 2007). Canopy extinction coefficient (*K*) is another important factor in the Beer-Lambert Law. Its value is dictated by canopy structure, species, and planting pattern (Zarea et al., 2005). In addition to intercepted photo-synthetically active radiation (IPAR), radiation use efficiency (RUE) is important factor in crop development. RUE is commonly used to explain limited productivity; RUE is the value of the slope of the linear relationship between biomass production and IPAR (Sinclair and Muchow, 1999). Several studies have proved that RUE is determined by cultivar, temperature (Andrade et al., 1993), water (Jamieson et al., 1995), and nutrients (Rodriguez et al., 2000; Caviglia et al., 2001) as well. Planting pattern is an agronomic management system that optimizes the available natural and unnatural resources; the adjustment of row space (Sharratt and McWilliams, 2005) and density is done to improve the effect of planting patterns on crop development. Equidistant spacing among plants is commonly considered as the better planting pattern for resource capture (Bullock et al., 1988; Sharratt and McWilliams, 2005). In the present study, the effects of narrow-wide row planting patterns within conservation tillage planting system on light interception and RUE of maize (*Zea mays* L.) were investigated. The objectives were to: (1) determine the impact of canopy on light interception in narrow-wide row planting pattern, and (2) analyze the RUE of maize responses to narrow-wide row planting patterns.

Results

Light interception

Cumulative intercepted PAR started from emergence up to harvest, which ranged from ca. 14 to 21 MJ m^{-2} per day (Figure 2). For a single Beiyu288, the differences in *F* were significant among the planting patterns. Figure 3 shows the interception profile of the planting patterns under different seasonal conditions. In all the planting patterns, *F* rapidly increased until 84 days after planting (DAP) (closed canopy). During this period, the highest *F* was observed in P2, followed by P1 and CK at Beiyu288. The maximum *F* in P1, P2, and CK was 0.879, 0.98, and 0.966, respectively. After the canopy closed, the *F* curve began to fit into a slow decline stage. Beyond 128 DAP, the smooth curve did not change for P2 and CK but it fluctuated immediately for P1. The difference in *F* among the planting patterns was significant (LSD, $p<0.05$)—the difference in *F* of P1 from that of the other planting patterns was significant, whereas no significant difference between that of P2 and CK were observed (LSD, $p<0.05$). After 84 DAP until harvest, *F* in P1 was considerably lower than that in the others. In addition, a remarkably wide bare area between two narrow double rows was observed in P1; hence, *F* was rather low at noon. In contrast, *F* in P2 and CK was greater at noon. Similar results were observed in Xianyu335.

Leaf area index (LAI) and Leaf mass per unit area (LMA)

Figure 4 shows the expansion of maize LAI with time. For most crops, *F* is highly dependent on LAI. In Beiyu288, no significant difference (LSD, $p<0.05$) among P1, P2, and CK was observed. The maximum LAI was achieved at different days: the maximum LAI in P1 and CK was achieved at 84 DAP, which was earlier than P2 at 102 DAP. The maximum LAI obtained in P1, P2, and CK were 5.14, 5.38, and 5.16, respectively. For Xianyu335 and Beiyu288, the maximum LAI was achieved at 94 DAP in P1 and CK, and at 102 DAP in P2. The maximum LAI achieved were 4.73, 4.64, and 4.89 in P1, P2, and CK, respectively. In all planting patterns, once the maximum LAI was attained, the value of LAI started to decline. Moreover, the rate of decline was quite similar across the patterns and cultivars. Generally, the average canopy size for LMA was increasing among the planting patterns for both cultivars during the growth stage (Fig. 5). The largest LMA was in P2 while the lowest was in CK. For Beiyu288, the average LMA of the crops in CK and P1 during the growth stage was not significantly (LSD, $p<0.05$) lower than that in P2. The average LMA in P2 was 56.61 gm^{-2} while the maximum LMA at harvest was up to 63.82 gm^{-2}. In P1 and CK, the average LMA was 54.34 and 54.28 gm^{-2} while the maximum LMA was 62.62 and 62.94 gm^{-2}, respectively. Similar results were observed for Xianyu335. The difference in LMA among P1, P2 and CK were not significant (LSD, $p<0.05$). In P1, P2, and CK, the average LMA was 56.79, 58.39, and 57.30 gm^{-2}, respectively, whereas the maximum LMA was 62.74, 63.76, and 62.4 gm^{-2}, respectively.

Canopy extinction coefficient (K)

K is described as the fitted regression lines on the basis of IPAR and LAI. The latter is shown in Fig. 4. The starting points of the regression lines represent the time before emergence of the crops when LAI was 0. The similarity of the slope of the regression lines was tested by *t*-test. Figure 6 shows the *K* during the growth season of the two cultivars. Every single line demonstrated a linear relationship. The slope of the line was recorded as the value of *K*. For Beiyu288, *K* in P1 was lower than that in CK with similar density. The estimated *K* for individual samples had a negative correlation with LAI. The maximum *K* occurred at 84 DAP and 94 DAP. During the grain-filling period, the average *K* in P1, P2, and CK were 0.39, 0.48, and 0.56, respectively. For Xianyu335, the maximum *K* was recorded at 102 DAP.

RUE

RUE is estimated by fitted linear models, including DM and cumulative IPAR. Among the planting patterns, a strongly positive correlation was observed between aboveground biomass and cumulative IPAR. RUE (the slope of the model) was calculated for P1288 (1.372 ± 0.041 g MJ $IPAR^{-1}$), P1335 (1.490 ± 0.016 g MJ $IPAR^{-1}$), P2288 (1.482 ± 0.042 g MJ $IPAR^{-1}$), P2335 (1.575 ± 0.023 g MJ $IPAR^{-1}$), and CK288 (1.218 ± 0.011 g MJ $IPAR^{-1}$), CK335 (1.301 ± 0.013 g MJ $IPAR^{-1}$). In both cultivars, the effects of planting patterns on RUE were examined. A comparison of the planting patterns showed that RUE was the highest in P2, whereas it was the lowest in CK. No obvious difference in RUE was observed between the two cultivars, but a significant difference was found among the planting patterns (Fig. 7). For Beiyu288, RUE in P1 was higher than that in CK but the difference was not significant ($p<0.05$). Moreover, RUE in P2 was significantly higher than that in CK ($p<0.05$). Similar results were observed for Xianyu335; the difference in RUE between P2 and CK was significant as well ($p<0.05$).

Discussion

Row spacing is important in crop canopy structure (Andrade et al., 2002; Reta-Sanchez and Fowler, 2002; Sharratt and McWilliams, 2005). A better canopy structure can result in better solar radiation interception, and consequently affect light availability. The alternating wide row spacings between double rows in P1 and P2 decrease *F* throughout the whole canopy. The row spacing in traditional planting pattern, CK, is smaller and more uniform with similar plant density; hence, is more conducive for steady light capturing (Maddonni et al., 2006; Taylor et al., 1982). Our results do not agree with Westgate's (1997), but are similar to findings of several other researches (Andrade, et al., 2002; Ottman and Welch, 1989). Our results provide evidence that bigger

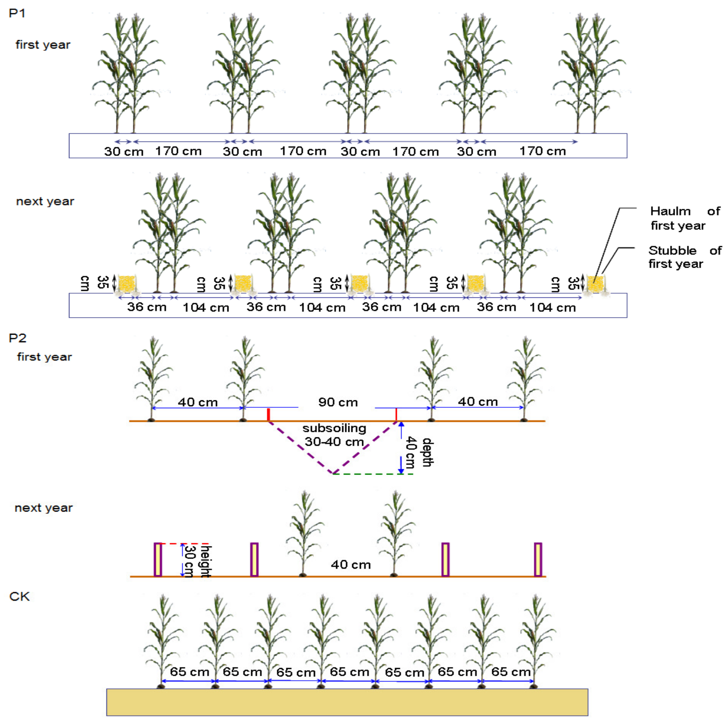

Fig 1. A schematic diagram display three planting patterns of P1, P2 and CK about two maize cultivars Beiyu288 and Xianyu335.

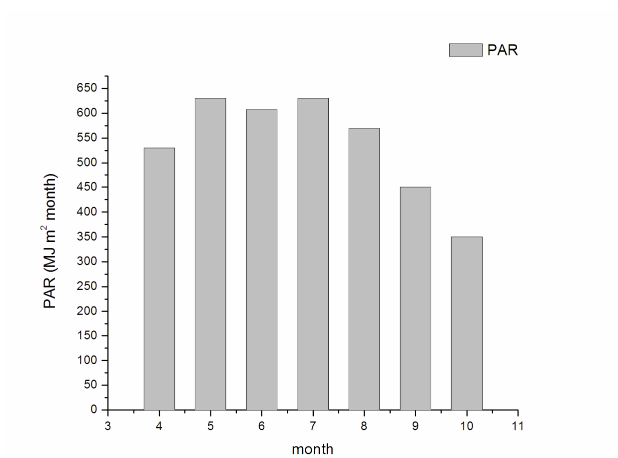

Fig 2. The depict of average photosynthetically active radiation in 2010 and 2011.

and uneven row spacing is disadvantageous to better light interception. To this end, with similar plant density, cultivars with better adaptability to the geography of the area are considered for planting to improve F during the growth stage (Stewart et al., 2003). Hence, lower *F* may lead to a relatively insufficient RUE of crops in P1 at some particular time, especially at midday. The best time for crops to assimilate C and accumulate DM during the day is between 1000 hours and 1200 hours. Wide-narrow row spacing may exhibit inferior C assimilation and DM accumulation at the vegetative stage. LAI increases with time; LAI increases until it reach its maximum value, and then it decreases gradually due to leaf senescence. At the latter stages of maize lifecycle, although light interception ratio declines as LAI decreases—as some researchers have argued (Olesen et al., 2000; Kiniry et al., 2004)—these two variables do not exhibit a typical proportional linear relationship. A reason for this seeming contradiction is that senescent leaves do not fall off from the stalk, and thus they restrict the practical availability of intercepted light. Among the different planting patterns, LAI is larger with greater plant density, while that in the other planting patters are approximately equal. Similar LAI values with different *F* values result in leaf shading in the canopy. Plants shaded for a long time have more leaf area in the lower LMA classes than the unshaded plants (Rosati et al., 2001). LMA is sensitive to environmental changes, especially to intercepted light (Terashima et al., 2001; Oguchi et al., 2003). For this reason, LMA classes in P2>P1 and CK planting patterns occur at different shaded levels. During the entire cultivation period, LMA in P2 was slightly greater than

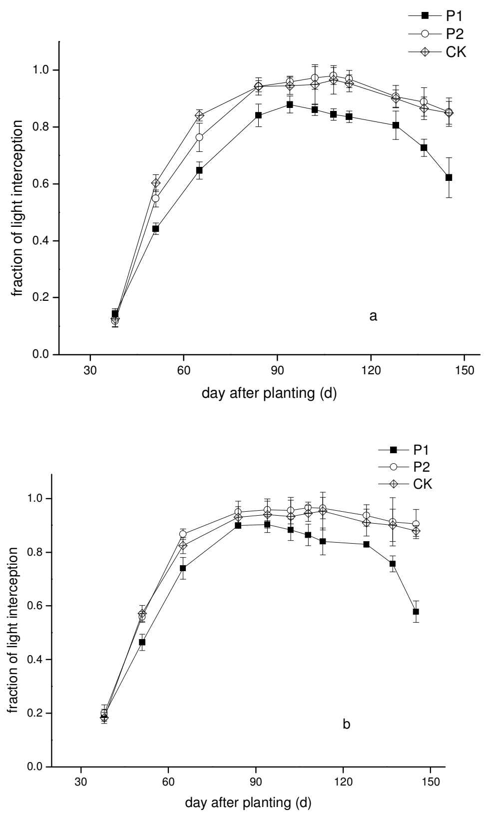

Fig 3. The dynamic changes in fraction of light interception (F) in two maize cultivars Beiyu288 (a) and Xianyu335 (b) in three planting patterns during the growing season. Means ± SD, (n=12).

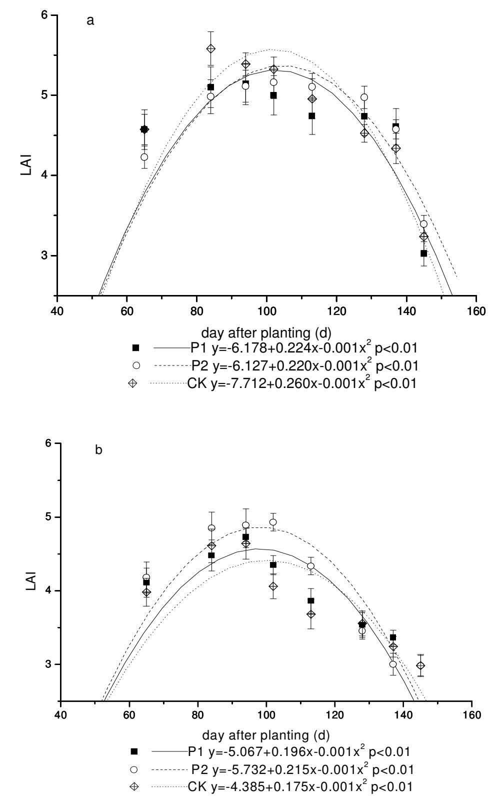

Fig 4. Changes in leaf area index (LAI) about two maize cultivars Beiyu288 (a) and Xianyu335 (b) in three planting patterns during the growing season. Means ± SD, (n=12).

that in P1 and CK. The difference in LMA among the planting patterns can be attributed to the wide row spacing with uneven density, which seems favorable for light interception in the middle and lower canopies. Meanwhile, in identical species, greater LMA is accompanied by longer lifecycle (Reich et al., 1991; Wright and Cannon, 2001), such that the condition affects the growth and production rates (Hikosaka, 2005). *K* is the most important variable in the present study. According to Monsi and Saeki's theory, when LAI is another variable, a comparable disparity between *K* and LAI does not exist. The promotion of increasing the density for decreased K values were reported by a number of articles in maize and other species (Kemanian et al., 2004; Francescangeli et al, 2006; Ruiz and Bertero, 2008). Our results show that wide-row row spacing has greater *K* than uniform row spacing. Row spacing affects *K*, and *K* decreases as row spacing increases (Flenet et al., 1996). When LAI values are similar, uniform narrow row spacing distribution results in a uniform canopy structure, such as LAI distribution, which can increase *K* significantly (Maddonni, et al., 2001). RUE of maize in among the planting patterns is comparatively different from each other. The classical canopy theory focuses on IPAR and RUE, and emphasizes IPAR response to canopy size, structure, and incident radiation (Maddonni, et al., 2001; Cirilo et al., 2009). RUE may be regarded as an inherent attribute of the species (Kiniry et al., 1989), which is regulated by stress factors (Andrade, et al., 1993; Muchow, 1989; Uhart and Andrade, 1995) After the canopy closes, maize in planting patterns with similar density accumulates relatively more DM and less *F*. Therefore, the maize in P1 and CK achieves greater RUE. If we consider *K*, lower *K* (i.e., *F* in P1 vs.CK) contributes more incident radiation at a given height in canopy. Despite having lower light interception at the vertical profile (*F* in P1<*F* in CK), the leaves with low *F* at the middle-low levels of the canopy still accept relatively more radiation for energy assimilation. Given that the maize in P2 has achieved highest RUE due to significant DM accumulation, we argue that planting patterns offset the disadvantages of higher *K* effects on canopy light interception. Crop yield depends on the photosynthetic ability of a plant. Thus, increasing the photosynthetic rate to a maximum level is the ultimate purpose of crop production (Stoskopf, 1981). Agricultural production is an organic synthesis system whose light utilization ability relies on the scale and efficiency of photosynthetic organs (Gardner et al., 1985). In either groups or individuals, photosynthesis and yield exhibit positively significant correlation (Wells et al., 1982, 1986). As we have discussed above, a reasonable canopy structure within planting pattern is conducive for higher crop DM production, and it always shows positive correlation with IPAR. Owing to the inhomogeneity of radiation distribution in space, time, and location, a varied date is usually measured (Matthews et al, 1987). Considering this special model, by artificially increasing the gap between corn rows, the features of the corns near the gaps can be fully utilized, resulting in higher DM production (Pommel et al., 2001). In the present study, the maximum RUE has been observed in P2. Despite low *F* in P1, a higher use of maize potential (high RUE) has been

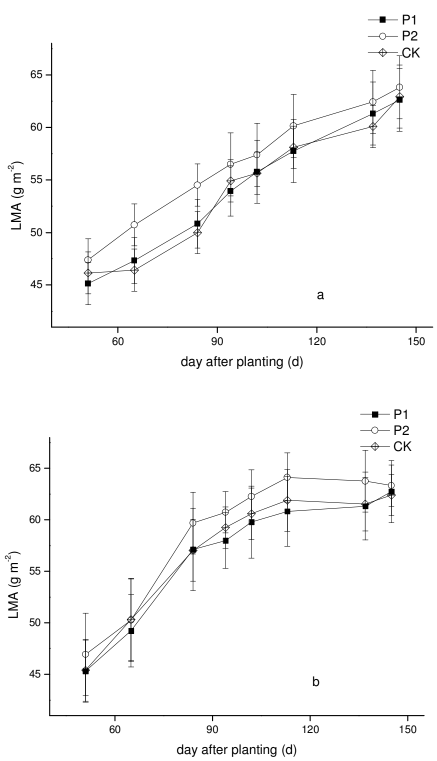

Fig 5. Changes in leaf mass per area (LMA) about two maize cultivars Beiyu288 (a) and Xianyu335 (b) in three planting patterns during the growing season. Means ± SD, (n=12).

observed. We conclude that the adoption of P1 and P2 planting patterns can maximize RUE, which maybe could offset the loss of yield arise from soil protection within conservation tillage system.

Materials and methods

Field experiment design

The present study was conducted at the Dehui Research Station in Changchun, Jilin Province (43°39′ N, 80°25′ W; 375 masl) during the cropping season—from April to September—in 2010 and 2011. Two compact-type cultivars of maize were used, Beiyu288 and Xianyu335, and grown in black soil-clay system. Figure 1 shows the three planting patterns adopted: (P1) "30+170" wide-narrow row planting (no till), i.e., narrow row measures 30 cm, wide row 170 cm, density of 6.4 plants m^{-2}, and a rotation in the wide row region the following year; (P2) "40+90" wide-narrow row planting, i.e., narrow row measures 40 cm, wide row 90 cm, density of 6.4 plants m^{-2}, the creation of sub soiling district in the wider row region, and rotation in the sub soiling district the following year; and (CK) single line planting—the most popular planting pattern in China—with row spacing of 65 cm and density of 6.4 plants m^{-2}. In 2010, the experimental plots were randomly complete blocks with four replicas each (each single block had an area of 100 m^2); in 2011, the plot (single plot) had an area of ≥667 m^2. All plots were treated with basal fertilizers. Ammonium nitrate, P_2O_5, K_2O was applied (NPK; 2:1:1). Two sound seeds were planted per hole, and the healthier seedling was selected after emergence. The

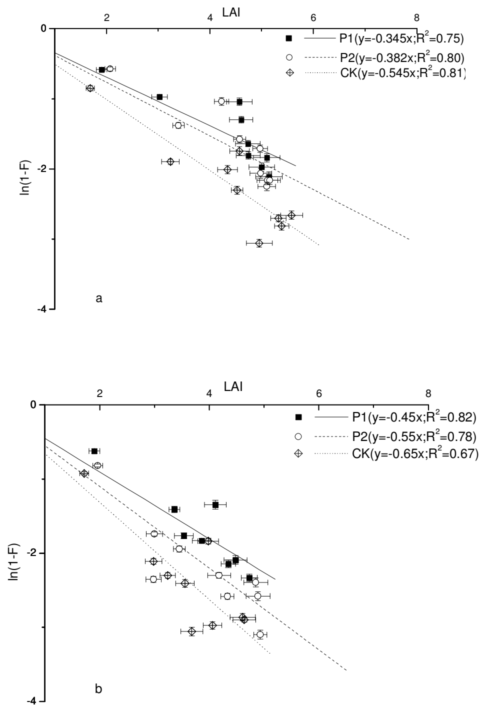

Fig 6. The schematic regression of Extinction coefficient (K) by fraction of light interception (F) and leaf area index (LAI) about two maize cultivars Beiyu288 (a) and Xianyu335 (b) in three planting patterns.

ground was prepared to capture only rainfall for irrigation. Finally, the crops were treated against pests, weeds, and diseases.

Plant sampling, measurement, and calculation

Light interception

Radiation interception is calculated using the following formula:

$$F=(1-\frac{I_o}{I_t})\times 100\% \quad (1)$$

where F is the fractional amount of radiation interception, I_o is the measured incident PAR on the surface of the ground, and I_t is the radiant flux density on top of the canopy measured by using an LI-190 quantum sensor (LI-COR, Lincoln, NE). The value of I_o was measured at the vertical height level by using a 191-SB line quantum sensor (LI-COR, Lincoln, NE). The measurements were performed following Gallo and Daughtry's procedure (1986) with a few modifications. The modifications were made given that the row spacing of P1 and P2 was not uniform; hence, the row spacing that crosses three rows had to be divided into two sections. Only then that I_o was measured. All measurements were performed at 1000 h to 1400 h in a clear day at intervals of ~7–15 d, depending on weather conditions. Cumulative PAR (PAR_c) is computed using a formula (3) that includes the daytime-integrated fraction of IPAR (F_d) and incident PAR_c. The value of incident PAR_c was measured by the weather station near the experimental site. PAR is assumed to

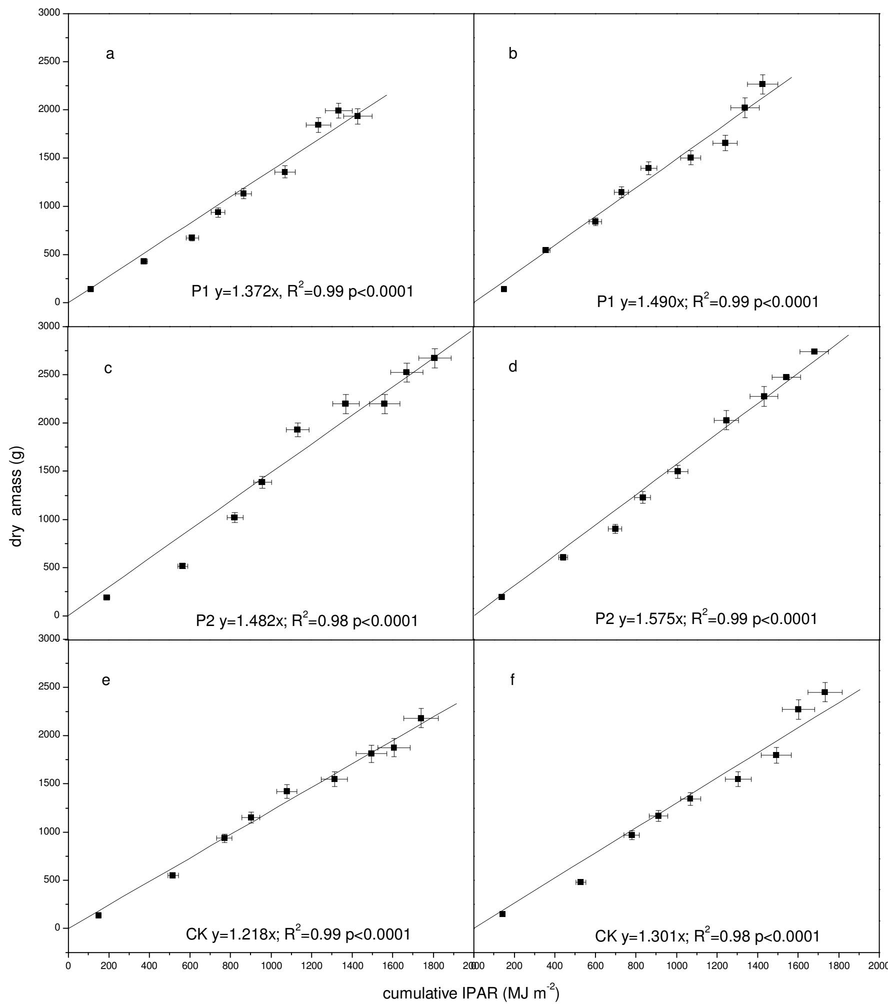

Fig 7. The schematic mathematic regression of radiation use efficiency (RUE) calculated by the dry matter (DM) and cumulative intercepted photosynthetic active radiation (IPAR) about two maize cultivars Beiyu288 (a, c, e) and Xianyu335 (b, d, f) in three planting patterns.

be 50% of the total solar radiation (Monteith, 1977). Daily fraction of light interception is calculated from midday value (Charlesedwards and Csiro, 1984):

$$F_d = \frac{2F}{(1+F)} \quad (2)$$

Where F_d is the daytime-integrated fraction of IPAR, and F is the value from Equation (1). Hence, the total PAR_c ($PAR_{c,t}$) can be calculated as

$$PAR_{c,t} = \sum_{d=emergence}^{d=t} (F_d \times IPAR_{c,d}) \quad (3)$$

Leaf area index (LAI), leaf mass area (LMA), and dry matter (DM) weight

Leaf samples were randomly gathered from five successive plants with three replicates at big plot and four replicas at randomly plot. Leaf area is calculated by lamina length × maximum width × 0.75. LAI is estimated as a measured mean of an individual plant leaf area multiplied by the number of plants per unit area. The crops were harvested every week, the dry mass weight was measured, and then the leaves were separated from the whole plant. . The leaf and non-leaf organs were then dried separately in an oven for 72 h at 80 °C. Subsequently, LMA and (DM) weight were measured.

Canopy extinction coefficient (K)

K is the profile of light vertically passing through the canopy; hence, its value depends on canopy spatial structure and incident radiation distribution. *K* is computed using the classical exponential formulation. Expressed below is a modified Beer-Lambert law (Monsi and Saeki, 2005):

$$I_o = I_t e^{-K \times LAI} \quad (4)$$

where I_o is the incident radiation at the surface of the ground, I_t is the incident radiation on top of the canopy, LAI is the leaf area index from top to ground, and *K* is the canopy extinction coefficient.

Radiation use efficiency (RUE)

RUE is calculated using the following equation (Plenet et al., 2000):

$$RUE = \frac{DM_d - DM_{d-1}}{PAR_{c,d} - PAR_{c,d-1}} \quad (5)$$

where DM_d and DM_{d-1} are the dry matter weight weighed at days d and $d-1$, and $IPAR_{c,d}$ and $IPAR_{c,d-1}$ are the calculated cumulative intercepted photosynthetic radiation at days d and $d-1$, respectively.

Statistical analysis

All statistical data were analyzed using MS Excel and SPASS 11.5. Graphs were constructed using OriginLab 7.5. Analysis of variance (ANOVA) was performed to analyze significant differences in the measured dates compared with the means of these dates. The level of significance is 0.05(α). Multiple comparisons were used to test least significant difference (LSD) at 0.05(α).

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