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Full Length Research Paper

Effect of phosphorus application and strip-intercropping on yield and some wheat-grain components in a wheat/maize/potato intercropping system

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Intercropping of bread wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and potato (*Solanum tuberosum)* has been practiced in North-West China in the last several decades; however, the effects of this intercropping and phosphorus addition on crop yield and some wheat-grain components have not been adequately investigated. A 2-year field experiment was conducted from 2002 to 2003 in irrigated areas in North-West of China to investigate how phosphorus fertilizer application and intercropping of wheat/maize/potato impact on the crop yield and wheat-grain components such as protein content, wet gluten and sodium dodecyl sulphate (SDS) sedimentation. The results indicated that bread wheat and maize achieved higher yields in the intercropping system than in the monoculture system over the 2 years, and the wheat-grain had higher protein content, wet gluten and sodium dodecyl sulphate (SDS) sedimentation in the intercropping system than in the monoculture system. Better utilization of resources through border row effect and preventing competition between species over growing period have been indicated as the major factors contributing to the increased crop yield and wheat-grain components. Phosphorus application significantly increased crop yields and improved wheat-grain components; however, the optimal application rate for achieving highest protein content was at 150 kg ha^{-1}. The practical implication of the present study was that to obtain good yield and better wheat-grain components, a combination of intercropping and application of phosphorus fertilizer at a rate of approximately 150 kg ha^{-1} was found as one of the most practical options.

Key words: Border-row effect, intercropping, phosphorus, wheat-grain components, wheat/maize/potato, yield.

INTRODUCTION

Intercropping offers an opportunity for utilizing niche differences between crop species when the intercropped species have different resources requirements in time and/or space, or when one species is able to provide resources to the other (Firbank and Watkinson, 1990). However, other agricultural benefits of intercrops include reductions in pests, diseases (Trenbath, 1993; Björkman et al., 2007), weeds (Banik et al., 2006), nitrate nitrogen leaching (Whitmore and Schröder, 2007), soil erosion (Kirchhof and Salako, 2000), improved ground cover (Altieri, 1999), higher nutrient retention (Lithourgidis et al., 2011) and enhanced water-use efficiency (Gao et al., 2009).

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Intercropping has been practiced in Northwest of China for about 2000 years (Li et al., 2005). Intercropping systems of wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.), maize/faba bean (*Vicia faba* L.) and common wheat/maize/potato (*Solanum tuberosum* L.) were introduced to Gansu Province of North-West China since the 1960s, and have been proved to be an efficient way to boost productivity and to resolve the conflict between ever increasing population and gradually decreasing of arable lands.

There have been many studies on cereal/cereal and cereal/legume intercropping systems. Most of these studies focused on above-ground interactions between crops of maize/soybean (*Glycine max* L.) (Herbert et al., 1984), maize/cowpea (*Vigna unguiculata* L.) (Watiki et al., 1993; Dahmardeh et al., 2010), winter wheat/clover (*Medicago sativa* L.) (Thorsted et al., 2006), pigeonpea (*Cajanus cajan* L.)/maize (Makumba et al., 2009), wheat/cotton (*Gossypium hirsutum* L.) (Zhang et al., 2008), wheat/maize and wheat/soybean (*Glycine max* L.) (Li et al., 2001a, b). These studies indicated that there were significant yield advantages of intercropping. For example, the value of land equivalent ratio (LER) for faba bean/maize intercropping was between 1.21 and 1.23 based on total (grain + straw) yield and from 1.13 to 1.34 based on grain yield (Li et al., 1999). For wheat/maize intercropping, LER was indicated to be between 1.21 and 1.58 based on grain yields (Li et al., 2001a).

Apart from crop yield, achieving higher grain quality is another objective in intercropping systems. The component of wheat-grain is influenced by a number of factors, including cultivar (Rharrabti et al., 2003), soil nutrient (Erekul and Köhn, 2006) and cultivation practices (López-Belldo et al., 1998; Singh et al., 2010). López-Bellido et al. (1998) reported higher wheat-grain protein content for conventional tillage than for no tillage. They also recorded differences in alveograph parameters between the two tillage systems. However, no significant difference was found by Cox and Shelton (1992) in a similar study. It was reported that rotations including a legume crop prompted an increase in protein content, due to the legumes' ability to fix atmospheric N_2 and to increase residual soil N (Borghi et al., 1995; López-Belldo et al., 1998). Nitrogen and sulphur fertilizer have been indicated to have a positive effect on wheat-grain components (Flæte et al., 2005; Garrido-Lestache et al., 2005; Salah, 2006). But the effect of phosphorus fertilizer on wheat-grain components was less clear, particularly for the intercropping systems. Some studies indicated that the effect of phosphorus on wheat-grain components depended on factors such as cultivar, soil available phosphorus, phosphorus application rate, time and methods (Jiang et al., 2006; Sun et al., 2006).

The majority of the previous studies associated with wheat-grain components mainly focused on monoculture systems. Few studies have been conducted to investigate the effect of intercropping on wheat-grain components. Also the interactions of intercropping and phosphorus on overall crop yield and wheat-grain components have not been adequately investigated. Given the importance of the wheat/maize/potato intercropping system in the agricultural industry and the increased growing area in North-West China, we conducted a two-year study in a one-ripening region to investigate the effect and mechanisms of intercropping and phosphorus application on crop yields and wheat-grain components in a wheat/maize/potato intercropping system. The objectives of the present study were to improve our understandings of the ecological processes in the wheat/maize/potato intercropping system and to provide practical implications for intercropping management in North-West China and areas with similar climates.

MATERIALS AND METHODS

Site description

The field experiments were conducted at Chengzhuang, Jingtai County, Gansu Province, China (103°33'E, 36°43'N, 16 31m asl) for two consecutive growing seasons from 2002/2003. The site is located about 5 km Southeast of Jingtai County Township with irrigation from the Yellow River. The long-term average annual precipitation is 216 mm, and the long-term average annual mean temperature is 10°C with a frost-free period of 159 days, and the accumulated temperature above 10°C year^{-1} is between 3000 to 3800°C. Climate records during the experiment period were presented in Figure 1. All climatological data mentioned above were obtained from the Jingtai Station of China Meteorological Administration. According to soil analysis prior to sowing, The soil of the study area has a pH of 8.21, organic carbon level of 16.24 g kg^{-1}, total N level of 2.12 g kg^{-1}, and available P and K were 8.74 and 147.2 mg kg^{-1}, respectively.

A split-plot design was used in the field experiment. The largest plots were the three whole fields (block) as three replicates, each of which was split in four, and one of four planting models (only common wheat, only maize, only potato and common wheat/maize/potato intercropping) was allocated at random to a quarter of each block. Each planting model plot was also split into four, and one of four phosphorus level (four levels of P_2O_5: P1 = 0 kg ha^{-1}, P2 = 75 kg ha^{-1}, P3 = 150 kg ha^{-1} and P4 = 225 kg ha^{-1}) was allocated at random (independently for each plant model plot and each block), and the plot size of each phosphorus level was 44.4 m^2 (10 m × 4.44 m). The cultivars used in the experiments were Yongliang 4, Zhongdan 2 and Keshan 6 for common wheat, maize and potato, respectively, which were selected through a pilot trial. Phosphorus was applied as basal fertilizer; evenly broadcasted and mixed into the top 20 cm soil of the whole plot prior to sowing. All plots were given an uniform application rate of 450 kg N ha^{-1} as urea (46% N), one-third (150 kg N ha^{-1}) of which was applied into wheat as basal fertilizer prior to sowing, and two-thirds (300 kg N ha^{-1}) of which were applied into maize at the planting stage (90 kg N ha^{-1}), the pre-tasseling stage (180 kg N ha^{-1}) and the ear-filling stage (30 kg N ha^{-1}).

All plots obtained the same amount of irrigation water during the growth period. Maize strips each plot were covered with plastic mulch. In strip intercropping system, wheat, maize and potato were planted in alternating strips: 0.72 m width for wheat with 6 rows, 0.12 m between rows; 0.80 m width for maize with 2 rows, 0.4 m between rows; 0.70 m width for potato with 2 rows, 0.35 m between rows. Each plot contained two wheat, two maize and two potato strips (Figure 2). In only systems, row spaces were 12, 40 and 50

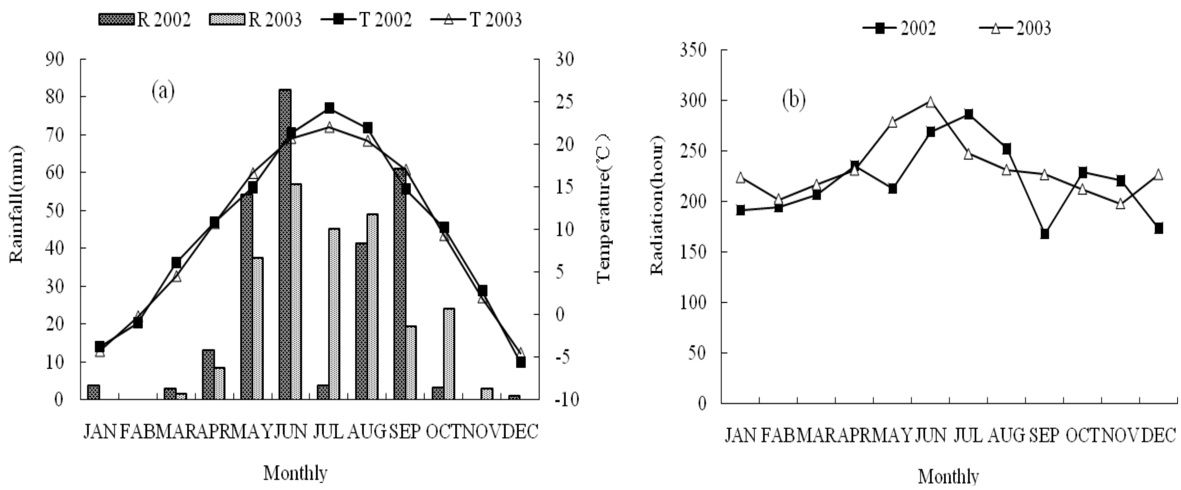

Figure 1. Monthly rainfall (a), average temperature (a) and radiation (sunshine hours) (b) for two year 2002 and 2003 at the field experiment site.

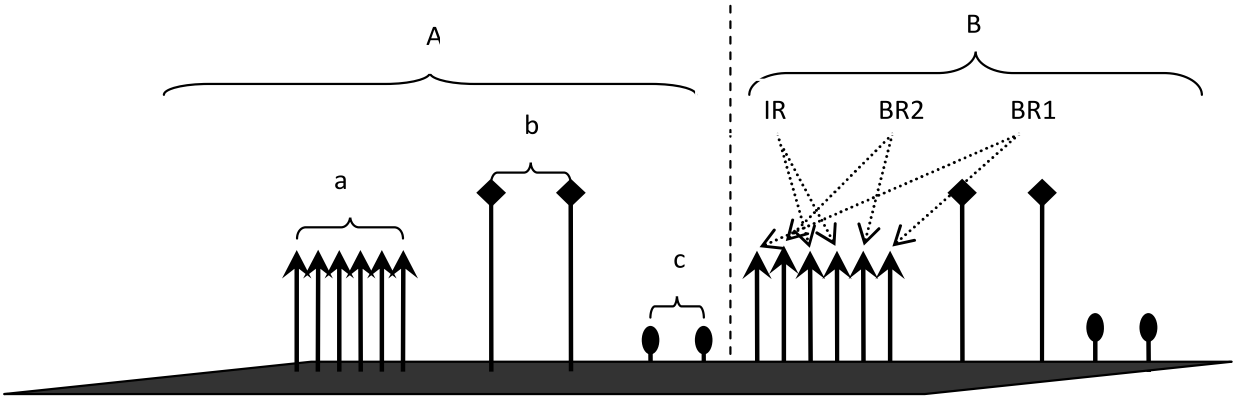

Figure 2. Diagram of planting pattern for plot of wheat/maize/potato strip-intercropping. Each plot contained two wheat/maize/potato strips (A and B). a, wheat strip with 6 rows at 0.12 m between row; b, maize strip with 2 rows at 0.40 m between; c, potato strip with 2 rows at 0.35m between. IR, The inner rows; BR1, the border row 1; BR2, the border row 2.

cm for common wheat, maize and potato, respectively, which were the same to the local practice. In the 2003 experiment, wheat was sown on March 17 and harvested on July 28; maize was sown on April 13 and harvested on October 2; potato was sown on March 31 and harvested on September 25. In the 2002 experiment, wheat was sown on March 12 and harvested on July 22; maize was sown on April 8 and harvested on September 29; potato was sown on March 29 and harvested on September 24.

Measurements

Grain yield were determined by harvesting all plants in a sampling area. To determine the border-row effects, the intercropped wheat samples were taken in border row 1 (BR1), border row 2 (BR2) and inner rows (IR) (Figure 2), respectively. Wheat-grain seeds were milled into flour using a CD-2 laboratory mill (Tripette & Renaud, France). Samples were conditioned to 15% moisture 24 h before milling according to the method of Timms et al. (1981). Wheat-grain protein contents were determined by near-infrared reflectance spectroscopy 8600. SDS sedimentation was determined by an AACC56-63 (He et al., 2003). The wet gluten was determined using gluten index instrument produced by Petron Company of Sweden, which included glutomatic 2200, centrifuging instrument 2015 and roasting instrument 2020 according to Li (2003). Gluten was separated from whole wheat meal by washing (Glutomatic 2200), and then centrifuged (centrifuging instrument 2015) to force the wet gluten through a specially constructed sieve under standard conditions. The total weight of this gluten was taken as the gluten quantity. Three replicates were conducted for all above laboratory measurements.

Statistical analysis

The overall statistical significance of the treat effects was determined using R version 2.13.0 (R Development Core Team, 2011; http://www.r-project.org/) according to split-plot design. The error structure was defined with the plot sizes listed from largest to smallest. Fisher's least significant difference (LSD) test was used to determine the significance of the difference between various experimental treatments. Statistical significance was declared at

Table 1. Analysis of variance (Mean square)of grain yield and quality affected by phosphorus rate and planting model at a 2-year experiment.

Source	Df	Wheat yield (kg ha^{-1})×10^4	Maize yield (kg ha^{-1})×10^4	Potato yield (kg ha^{-1})×10^4	Protein (%)	Gluten (%)	SDS (ml)
Y	1	0.16	23.97	193.04	1.74	11.73*	8.68*
PM	1	2060.55***	8454.44***	196.96	11.78***	21.59***	11.17**
Y×PM	1	25.28**	50.69	0.21	0.06	0.20	0.01
Error a	4	0.56	60.91	33.42	0.09	0.11	0.33
P	3	1751.71***	5302.10***	18596.33***	16.94***	50.81***	0.06
Y×P	3	17.44**	0.19	77.55	0.13	0.08	0.02
PM×P	3	160.77***	69.65	1316.92***	1.12***	1.31*	0.47
Y×PM×P	3	3.48	15.73	106.27	0.08	0.10	0.10
Error b	24	2.65	25.96	117.92	0.13	0.33	0.34

Y: Year including 2002 and 2003; PM: planting model including intercrop and monoculture; P: phosphorus rates were 0, 75, 150 and 225 kg ha^{-1}, respectively. *, **, ***, indicate significant at P < 0.05, 0.01 and 0.001, respectively.

P < 0.05, except where otherwise specified.

To compare intercropping yields with monoculture yields, the land equivalent ratio (LER) was used in data analyses and reporting the results. It was calculated by using the following formula (Zhang et al., 2007):

$$LER = \frac{Y_{w,i}}{Y_{w,s}} + \frac{Y_{m,i}}{Y_{m,s}} + \frac{Y_{p,i}}{Y_{p,s}}$$

Where $Y_{w,i}$, $Y_{m,i}$, and $Y_{p,i}$ were respectively wheat, maize and potato yield in wheat/maize/potato intercropping system, and $Y_{w,s}$, $Y_{m,s}$ and $Y_{p,s}$ were grain yield in corresponding monoculture systems.

RESULTS

Yield

Common wheat

The wheat-grain yield was significantly higher in intercropping system than monoculture regardless of phosphorus application rates and experimental years (*P* < 0.001, Table 1 and Figure 3A). For example, intercropping increased wheat-grain yield by 27.72% comparing to the monocultures with the treatment of P4. Increased phosphorus application increased the yield of both intercropping and monoculture (*P* < 0.001, Table 1 and Figure 3A). Compared to P1 (no phosphorus application), P4 increased wheat-grain yield by 51.81% in intercropping system. Significant interaction was also found between plant models and P rates, indicating that yield advantage of intercropping changed with the level of phosphorus application (*P* < 0.001, Table 1).

Maize

Maize yield was significantly higher in intercropping than in monocultures regardless of phosphorus application (*P* < 0.001, Table 1 and Figure 3B). Compared to monocultures, yield of intercropped maize was higher by 18.48% (P1) to 21.08% (P4). Phosphorus application had significant effect in increasing maize yield for both intercropping and monocultures (*P* < 0.001, Table 1 and Figure 3B). When P4 was applied, the yield was the highest in both years regardless of plant model. Compared to wheat-grain yield, no significant interaction between phosphorus rate and plant model was also observed for maize yield (Table 1).

Potato

In contrast to the yield of wheat and maize, potato yield was not significantly different between intercropping and monocultures (Table 1 and Figure 3C). The intercropping generally decreased potato yield with the exception of P1 treatment; for example, yield of intercropped potato in P4 was 95.53% as much as that of monoculture. However, phosphorus application significantly increased potato yield for both intercropping and monocultures (*P* < 0.001, Table 1 and Figure 3C), Similar to wheat and maize, the highest potato yield was obtained in P4 in both experiment years regardless of plant model. Furthermore, significant interactions were also found among phosphorus rate and planting model (*P* < 0.001, Table 1).

Land equivalent ratio (LER)

The LER of intercropping was 1.13 when averaged over two years. It was indicated that wheat, maize and potato intercropping system had a substantial yield advantage when comparing to single crop systems (LER = 1.00; Figure 4), regardless of phosphorus application. Phosphorus rates had no significant influence on LER in the intercropping system (*P* > 0.05, Figure 4). The

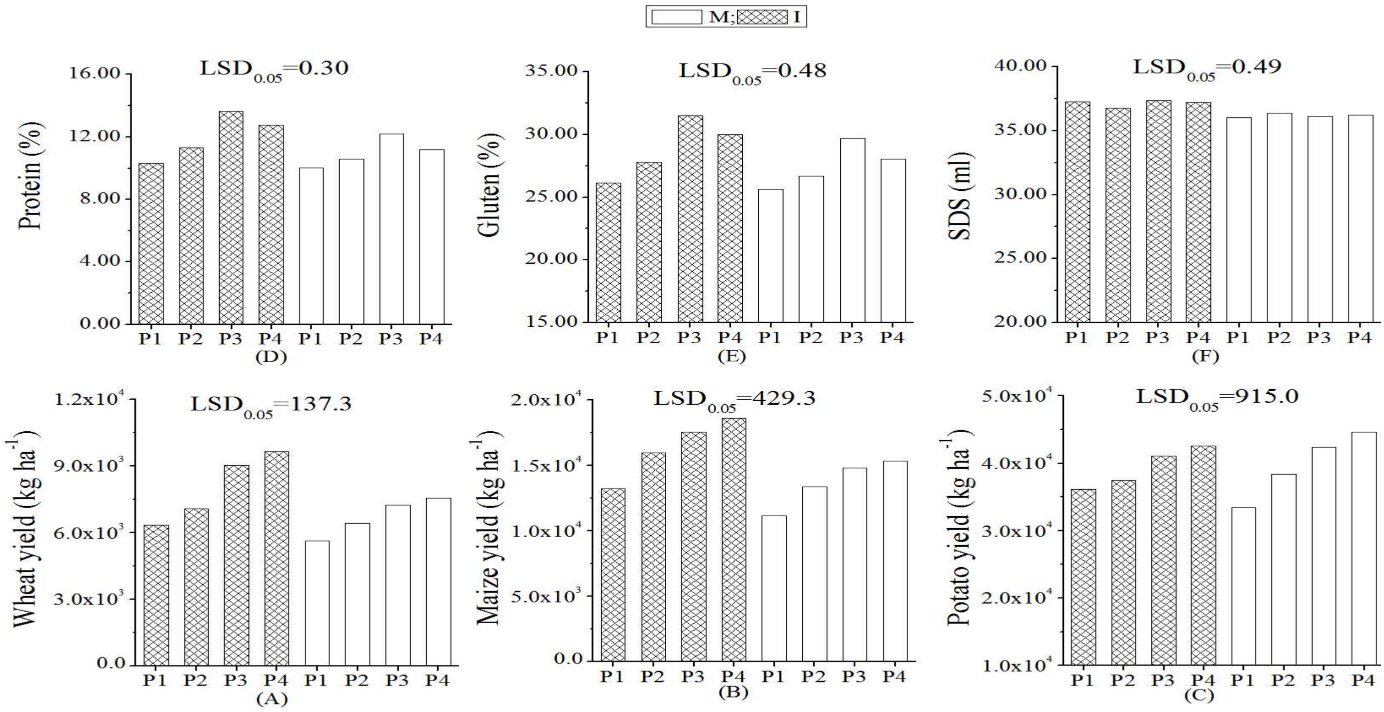

Figure 3. Effect of different plant model and phosphorus application rates on crop yield and quality at a two-year field experiment. P1, P2, P3, P4 were phosphorus rates at 0, 75, 150 and 225 kg ha^{-1} in intercropping system, respectively. Crop yields of intercrop (wheat, maize and potato) were converted to 100% population based on the crop proportion in strip-intercropping system. I, intercrop; M, monoculture. SDS: sodium dodecyl sulphate sedimentation, the same bellows.

averaged LER over two years in intercropping varied from 1.09 (P2) to 1.15 (P4) under all treatment of phosphorus.

Wheat-grain components

Protein content

Wheat-grain protein content was significantly higher potation intercropping system than that of the monoculture in both years ($P < 0.001$, Table 1 and Figure 3D); for example, intercropping increased wheat-grain protein content by 11.77% comparing to the mono-cultures with the treatment of P3. Phosphorus application also significantly increased the wheat-grain protein content for both intercropping and monoculture ($P < 0.001$, Table 1 and Figure 3D). The highest wheat-grain protein contents (13.62% in intercropping and 12.19% in monoculture, based on average of two years) were achieved by the treatment of applying 150 kg ha^{-1} phosphorus fertilizer. The interaction between phosphorus rate and plant model on wheat-grain protein content was significant ($P < 0.01$, Table 1).

Wet gluten

Wheat intercropped with maize and potato had higher grain wet gluten than that in the monocultures ($P < 0.001$, Table 1 and Figure 3E). For example, intercropping increased grain wet gluten by 5.96% with the treatment of P3. The highest increase in wheat-grain wet gluten (7.00%) was observed for the intercropped wheat under phosphorus application of 225 kg ha^{-1} (P4). Effect of phosphorus application on wheat-grain wet gluten was similar to that on protein content ($P < 0.001$, Table 1 and Figure 3E). On average, the highest wheat-grain wet gluten contents (31.49% in intercropping and 29.72% in monoculture) were obtained with P3 treatment (Figure 3E). Significant difference in wet gluten was recorded between years ($P < 0.05$, Table 1). The favorable weather condition in 2002 resulted in higher grain wet gluten content. The interaction of planting model × phosphorus rate was significant on wet gluten ($P < 0.05$, Table 1).

Sodium dodecyl sulphate (SDS) sedimentation

Planting model had a significant influence on wheat-grain SDS sedimentation over the two years as a whole ($P < 0.01$, Table 1 and Figure 3F). For example, intercropping increased wheat-grain SDS sedimentation by 2.70% with the treatment of P4. The highest increase in SDS sedimentation 3.47% was observed for the intercropping with no phosphorus treatment. In contrast to wheat-grain

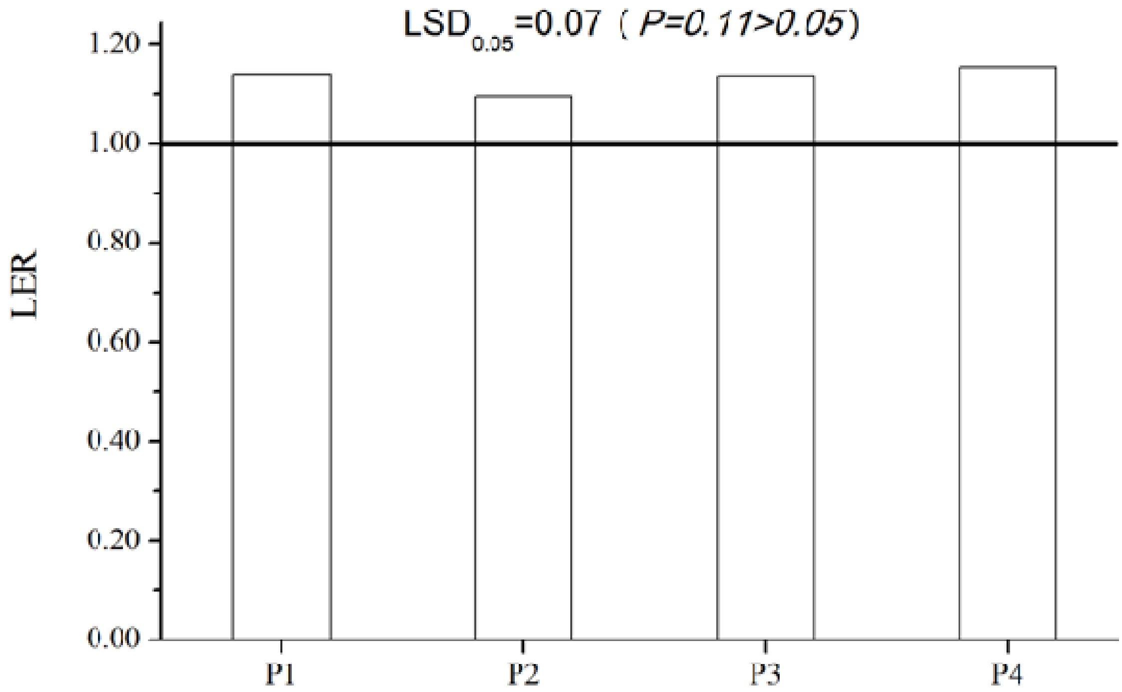

Figure 4. Land equivalent ratio (LER) of the intercrop comparing to that of the monocultures on the two-year average from 2002 to 2003. (-), LER in monoculture system (LER=1).

protein content and wet gluten, phosphorus application had no significant effect on grain SDS sedimentation (Table 1). Grain SDS sedimentation in 2002 was slightly higher than that in 2003 regardless of the planting model and phosphorus rate ($P < 0.05$, Table 1 and Figure 3F).

Border-row advantage of wheat yield and components

Wheat yield

Border row types (BRT) had significant influence on wheat yield (Table 2). Wheat-grain yield decreased in the order of BR1 > BR2 > IR > M (monoculture) when averaged over two years. Wheat-grain yield in BR1 of the intercropping increased by 18.40, 21.75, 51.52, and 54.39% for the treatments of P1, P2, P3, and P4, respectively, when compared to the inner row (IR) (Table 3). It was indicated that higher border-row advantage was achieved with the higher phosphorus rates (P3 and P4). When compared with the monoculture, wheat-grain yield over two years increased from 23.63% (P2) to 65.41% (P4) for the BR1, from 4.99% (P2) to 11.82% (P3) for the BR2 and from 1.54% (P2) to 7.14% (P4) for the IR (Table 2), indicating that yield increase in intercropped wheat not only achieved from the border row but also from the inner rows.

Protein content

Wheat-grain protein content differed significantly in different border rows (Table 2). When averaged over the two years, grain protein content for BR1 increased from 2.95% (P1) to 10.45% (P4) comparing to that for the IR, and increased from 5.35 (P1) to 19.56% (P4) comparing to that for the monoculture (Table 3). Phosphorus application (P2, P3 and P4) enhanced the border-row effects when comparing to the treatment of no phosphorus application (P1) (Table 3).

Wet gluten

Border row types (BRT) had significant influence on wheat wet gluten (Table 2). On average over two years, wet gluten in the BR1 was higher than that in IR by 0.91% (P1), 0.75% (P2), 5.69% (P3) and 6.29% (P4), respectively (Table 3). When compared with the monoculture, wheat-grain wet gluten increased from 2.94% (P1) to 11.32% (P4) for the BR1, from 1.03% (P1) to 5.44% (P2) for the BR2 and from 2.02% (P2) to 4.87% (P4) for the IR (Table 3).

Sodium dodecyl sulphate (SDS) sedimentation

Similarly to wheat-grain wet gluten, significant differences

Table 2. Wheat-grain yield, wheat-grain protein content, wheat-grain wet gluten and wheat-grain SDS located at different row positions for sole (M), inner rows (IR),border row 1 (BR1) and inner border row 2 (BR2) in a two-year field experiment.

Phosphorus rates	BRT	Yield (kg ha^{-1})	Protein (%)	Gluten (%)	SDS (ml)
P1	BR1	6966.0	10.58	26.39	37.79
	BR2	6204.5	10.09	25.90	36.99
	IR	5883.7	10.27	26.15	37.06
	M	5623.4	10.04	25.63	36.03
P2	BR1	7948.8	11.93	27.68	38.06
	BR2	6750.4	11.03	28.15	36.06
	IR	6528.6	10.93	27.48	36.26
	M	6429.5	10.60	26.70	36.40
P3	BR1	11423.1	14.16	32.94	38.09
	BR2	8105.1	13.50	30.37	37.13
	IR	7539.2	13.21	31.17	36.88
	M	7248.4	12.18	29.72	36.14
P4	BR1	12486.2	13.37	31.23	38.10
	BR2	8351.5	12.73	29.27	36.78
	IR	8087.2	12.10	29.38	36.79
	M	7548.5	11.18	28.05	36.24
	$LSD_{0.05}$	107.5	0.35	0.56	0.71

from different border row types and monoculture were also found in wheat SDS sedimentation over two years as a whole (Table 2). SDS sedimentation in the BR1 increased by 1.95% (P1) to 4.97% (P2) for IR and by 4.57% (P2) to 5.38% (P3) for the monoculture (Table 3), respectively.

DISCUSSION

Yield advantages of strip-intercropping

Intercropping systems have long been recognized to be generally more productive than sole crops grown on the same area of land (Li et al., 2001a; Tefera and Tana, 2002; Zhang et al., 2007; Dahmardeh et al., 2010). This higher productivity of intercropping systems is generally attributed to the differences in the use of resources among crops (Baumann et al., 2002) or in another term, niche complementarities. The niche complementarities among crops are achieved through maximizing the use of resources over time and space, and in the meantime reducing the inter-species competitions (Li et al., 2001a, b; Zhang et al., 2008). The result obtained from the present study showed that strip-intercropping of wheat/maize/potato has significant positive effects on wheat and maize yield. The major factor underlining this significant increase in yield is the better utilization of growing space over time. For example, the wheat-grain yield increased in the order of inner rows (IR), border row 2 (BR2) and border row 1 (BR1) when compared with monoculture (M) (Table 2), showing that not only border rows in the intercropping achieved higher grain yield gain, the inner rows also benefited from accessing more space comparing to the monoculture. This result is consistent with the result obtained from a similar study in which wheat was intercropped with maize and soybean (Li et al., 2001a). The increase in maize yield is generally considered as a better utilization of space over the growing season as wheat was harvested in late July which gave approximately two months' time for maize to grow without competition of solar radiation, water and nutrients from wheat.

However, intercropping slightly reduced the potato yield compared to potato monoculture, which may be attributed to the greater competitive ability of maize for resources after the harvest of wheat. Maize, as a C_4 species, has much higher light use efficiency and more rapid growth rate than potato, a C_3 plant. Moreover, maize exceeded potato in canopy height and therefore resulted in stronger competition in light interception. Olasantan and Lucas (1992) had noted that canopy height is one of the important features that determine competitive ability of plants for light. Palaniappan et al. (1985) observed that

Table 3. Increasing ratio of wheat-grain yield, protein content, wet gluten and SDS of wheat located at different row positions.

P	BRT	Yield	Protein	Gluten	SDS
	BR1/IR	1.1840	1.0295	1.0091	1.0195
	BR1/BR2	1.1227	1.0482	1.0189	1.0216
P1	BR1/M	1.2388	1.0535	1.0294	1.0489
	BR2/IR	1.0545	0.9822	0.9904	0.9979
	BR2/M	1.1033	1.0050	1.0103	1.0267
	IR/M	1.0463	1.0232	1.0202	1.0288
	BR1/IR	1.2175	1.0918	1.0075	1.0497
	BR1/BR2	1.1775	1.0818	0.9834	1.0555
P2	BR1/M	1.2363	1.1256	1.0369	1.0457
	BR2/IR	1.0340	1.0093	1.0246	0.9946
	BR2/M	1.0499	1.0406	1.0544	0.9907
	IR/M	1.0154	1.0310	1.0292	0.9962
	BR1/IR	1.5152	1.0719	1.0569	1.0327
	BR1/BR2	1.4094	1.0491	1.0847	1.0258
P3	BR1/M	1.5760	1.1624	1.1084	1.0538
	BR2/IR	1.0751	1.0217	0.9744	1.0067
	BR2/M	1.1182	1.1079	1.0218	1.0273
	IR/M	1.0401	1.0844	1.0487	1.0205
	BR1/IR	1.5439	1.1045	1.0629	1.0356
	BR1/BR2	1.4951	1.0499	1.0667	1.0357
P4	BR1/M	1.6541	1.1956	1.1132	1.0513
	BR2/IR	1.0327	1.0521	0.9964	0.9999
	BR2/M	1.1064	1.1388	1.0436	1.0150
	IR/M	1.0714	1.0824	1.0474	1.0151

BR1/IR, the ratio of border row 1 to inner row; BR1/BR2, the ratio of border row 1 to border row 2. BR1/M, the ratio of border row 1 to monoculture; BR2/IR, the ration of border row 2 to inner row; BR2/M, the ratio of border row 2 to monoculture; IR/M, the ratio of inner row to monoculture.

when one component was taller than the others in an intercropping system, the taller component intercepts majored share of the light such that the growth rates of the two components would be proportional to the quantity of the photosynthetic active-radiation they intercepted. The land equivalent ratio (LER) for the intercropping treatments over all levels of phosphorus application in the two growing seasons was 1.13. This is lower than the results obtained by Liu et al. (2008), who observed that the LERs ranged from 1.30 to 1.41 in a wheat/maize intercropping system. This was maybe because the lower potatoes yield in this study reduced the overall value of LER.

Wheat-grain components' superiority of intercropping

Very little is known from the literature about the effect of intercropping on wheat-grain quality. A few studies have indicated that intercropping generally increased grain protein, such as intercropping of legume with maize (Ghanbari-Bonjar and Lee., 2003; Dawo et al., 2007) and intercropping of winter wheat (*Triticum aestivum* L.) and white clover (*Trifolium repens* L.) system (Thorsted et al., 2006). The results obtained from the present study are generally in agreement of the previous studies and have indicated that intercropping wheat with maize and potato significantly increased wheat-grain protein content, wet gluten content and SDS sendimentation. Higher protein content in wheat-grain often results in higher wet gluten and SDS sendimentation (Paul et al., 2007). There is a significant border-row effect on wheat-grain protein content (Table 2). Wheat-grain protein content in the BR1 was significantly higher than that in the IR and in the monoculture regardless of the phosphorus application rates, indicating that border-row effect was at least one of the reasons why intercropping with maize and potato increased wheat-grain protein content. Wheat-grain yield and grain protein content generally have a negative linear relationship (Erekul and Köhn, 2006), that is, increased protein content would generally decrease wheat grain yield. The most frequently quoted reasons for this are energy constraints and dilution effects (López-Bellido et al., 1998; Tahir et al., 2006). However, the current study showed that intercropping enhanced both wheat-grain yield and grain protein content. When averaged over the two growing seasons, intercropping increased wheat yield, protein content, wet gluten and SDS sedimentation by 19.52, 9.01, 4.87 and 2.66%, respectively. Thus the present study proved that wheat-grain yield and grain protein content can be increased together through proper intercropping, as has been proposed by Debaeke et al. (2002) who advocated achieving higher crop yield and better grain quality through appropriate intercropping management.

Effects of phosphorus on crop yield and wheat-grain components

Phosphorus application generally increased crop yields and improved wheat-grain component in the present study. Results from previous studies differ depending on cultivar, soil fertility, soil type and planting model. Generally adequate phosphorus application could enhance nitrogen uptake from the soil by improving root function such an root growth, root enzyme activities and root life time (Sun et al., 2002; Li et al., 2003). Phosphorus application increased the activities of nitrate reductase, glutamine synthetase and endopeptidase in flag leaves during the early and middle grain filling stages (Wang et al., 2006). Although crop yields increased linearly with the increased phosphorus application rates, wheat-grain protein content and wet gluten increased at rate from 0 to 150 kg ha^{-1}, and decreased at the rate of 225kg ha^{-1} (P4). These results are in line with the findings of Jiang et al. (2006) in which wheat-grain protein peaked at the phosphorus rate of 144 kg ha^{-1} for a high-gluten wheat and at 108 kg ha^{-1} for a low-gluten wheat. A similar result also obtained by Sun et al. (2006). The reason behind this phenomenon is not clear; however, it indicates that there is an optimum phosphorus rate for obtaining the highest wheat-grain protein content. This result may have important management implications for growing high protein wheat.

Conclusions

The present study indicated that strip-intercropping of wheat/maize/potato in North-West of China had signify-cantly benefit in increasing wheat and maize yield with an average land equivalent ratio (LER) of 1.13. More impor-tantly intercropping also significantly improved wheat-grain component in terms of the protein content. This has been considered difficult as increased yield generally results in lower grain protein content. Thus the present study proved that wheat yield and grain protein content could be increased simultaneously through appropriate intercropping. Better utilization of resources through border row effect and preventing competition between species over growing period have been indica-ted as the major factors contributing to the increased crop yield and improved wheat-grain components. Phosphorus applica-tion significantly increased crop yield and wheat-grain protein content; however, the optimal phosphorus rate for achieving highest protein content was at 150 kg ha^{-1}. The practical implication of the present study was that to obtain good yield and better wheat-grain compo-nents, a combination of intercropping and application of phosphorus fertilizer at a rate of approximately 150 kg ha^{-1} was found as one of the most practical options.

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