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Boosting system productivity through the improved coordination of interspecific competition in maize/pea strip intercropping

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ABSTRACT

Intercropping has been considered to be an effective approach for producing large quantities of grain per unit of land. Maize (*Zea mays* L.)/pea (*Pisum sativum* L.) strip intercropping may serve as a model for effectively boosting a system's productivity. However, how intercropped pea may compete for soil N sources with intercropped maize under various levels of N availability is unknown. Here, we determined the level of interspecific competition during the pea/maize cogrowth period, N_2 fixation of pea, complementary growth effect on maize, and yield responses of the two component crops. The field experiment was conducted at Wuwei Experimental Station in northwestern China from 2012 to 2014. Different N management practices were implemented in the pea/maize systems. Intercropped pea was the dominant plant, as shown by the highly positive competitive ratio (averaging 1.35) and its aggressivity (averaging 0.31) values compared with intercropped maize. Ameliorating N application in the maize/pea strip intercropping intensified the interspecific competition, improved the N_2 fixation of intercropped pea and increased the complementary growth of intercropped maize. On average, the N management system with 45 kg N ha^{-1} applied as the first topdressing plus 135 kg N ha^{-1} as the third topdressing increased the competitive ratio and aggressivity by 8% and 32%, respectively; improved N_2 fixation of the pea by 39%; enhanced the complementary growth of maize by 10%; and boosted the grain yield by 13% (maize) and 6% (pea) compared to the N management system with 135 kg N ha^{-1} as the first and 45 kg N ha^{-1} as the third topdressing. Significant positive correlations were found among the interspecific competition, N_2 fixation, and grain yield, clearly showing that improved coordination of interspecific competition can boost system productivity in maize/pea strip intercropping.

1. Introduction

Currently, the greatest challenges faced globally are biodiversity loss and food security (Brooker et al., 2015). Drivers such as land-use change (e.g., cultivated land diverted for industry and urban construction), resource limitation, increasingly severe climate change and an ever-growing population have led to the above challenges becoming even more serious. Intercropping, with two crop species cultivated on the same area of land, is a promising way to tackle these issues (Lithourgidis et al., 2011; Brooker et al., 2015). Allocation of the land area in an appropriate ratio to the intercrops and improved field configuration can enhance land utilization efficiency (Lithourgidis et al., 2011). This can enable intercropping systems to produce a high quantity of grain on a limited land area and with little negative impact on the environment (Hauggaard-Nielsen and Jensen, 2001; Agegnehu et al., 2006). Usually, the component species in intercropping systems occupy different niches and thereby enhance the utilization of resources (Sainju et al., 2010). Consequently, intercropping improves the yields of the component crops (Yang et al., 2011; Fan et al., 2012).

The intercropping of a cereal with a legume is a preferred system for achieving increased food supply and reduced environmental feedback. Efficient cereal/legume intercropping often facilitates N use through complementarity and/or N transfer (Rao et al., 1987; Li et al., 2009) and thereby reduces the heavy depen-

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dence of crop production on industrial N inputs. Large areas of cereal/legume intercropping exist in the tropics and in temperate regions (Fuentes Ramírez et al., 1998; Agegnehu et al., 2006). Compared with conventional monoculture systems, the risk of crop failure in intercropping is generally low, whereas the yield stability is generally high (Hauggaard-Nielsen and Jensen, 2001; Tsubo et al., 2005). The synergized interrelation is attributable to favorable outcomes, for which intercropping facilitates the growth of the component crops through (i) the complementary use of both industrial and atmospheric N sources (Corre-Hellou et al., 2006), (ii) improved interspecific root interaction between the two crop species for nutrient sharing (Li et al., 1999), and (iii) optimized interspecific competition and decreased intraspecific competition (Hauggaard-Nielsen and Jensen, 2001). With the mutual benefits that exist in cereal/legume intercropping, the system productivity is greatly promoted but with a lower input (Herridge et al., 2008).

Generally, the interspecific interactions, i.e., competition and facilitation, coexist and play an important role in the system productivity (Li et al., 2003; Hauggaard-Nielsen and Jensen, 2005 Hauggaard-Nielsen and Jensen, 2005). Two main theoretical bases explain the yield advantage of intercropping: (i) the competition between the two species in the mixture shall be lower than competition within the same species (i.e., intraspecific competition) (Vandermeer, 1990), and (ii) the interspecific facilitation, which refers to the resource utilization should be greater than the interspecific competition (Zhang and Li, 2003). The first theory recommends that interspecific competition needs to be minimized by the selection of suitable cultivars or arranging reasonable seeding ratios (Dhima et al., 2007). The second theory suggests that interspecific competition needs to be reduced to achieve higher facilitation in a "competition-recovery production principle" (Zhang and Li, 2003). The mechanisms involved in these two theoretical bases are as follows: (i) root intermingling will generate the transfer of some substances during the cogrowth period, and (ii) the earlier harvest of the intercropped legume will lead to a vigorous recovery effect on the growth of the cereal that is harvested later (Li et al., 1999).

Maize (*Zea mays* L.)/pea (*Pisum sativum* L.) strip intercropping is a successful cereal/legume model and is established largely in northwestern China (Chai et al., 2013). The system has been improved by actions such as the allocation of suitable strip ratios, interspace, and planting densities in this area. Employing the "competition-recovery production principle" in this cropping system may achieve great advantages in system productivity. Different N management systems, where various ratios of base N to topdressing N are used to create different levels of resource competition in four maize/pea intercropping systems, would allow the determination of the effect of the "competition-recovery production principle." Therefore, the primary objective of this study was to investigate how interspecific interactions would affect the system productivity of maize/pea intercropping. We hypothesized that the grain yield of maize/pea intercropping could be promoted through i) the enhanced N_2 fixation of intercropped pea and ii) the improved complementary growth of intercropped maize. In testing the hypothesis, we determined i) the interspecific competition, ii) the N_2 fixation of intercropped pea, and iii) the complementary growth of intercropped maize.

2. Materials and methods

2.1. Experimental site

The experiment was conducted in 2012, 2013 and 2014 at the Oasis Agricultural Experimental Station (37° 30′ N, 103° 5′ E; 1776 m a.s.l.) of Gansu Agricultural University, Gansu, China (Fig. 1). Located in the eastern part of the Hexi Corridor of northwestern China, this station is in the temperate arid zone in the hinterland of the Eurasian Continent. The long-term (1960–2009) solar radiation is 5.67 kJ m^2, the annual sunshine duration is >2945 h, and the mean annual temperature is 7.2 °C, with accumulated temperature above 0 °C of >3513 °C and above 10 °C of >2985 °C, and a frostfree period of 156 d. This area represents a typical agroecosystem with abundant resources for one growing season but insufficient resources for two and is particularly suitable for intercropping. The mean annual precipitation is 155 mm, occurring mainly in June to September, and the potential evaporation is greater than 2400 mm. The soil was classified as an Aridisol (FAO/UNESCO, 1988) with a soil bulk density in the 0–110 cm soil depth averaging 1.44 g cm^{-3}. The total nitrogen (N), available phosphorous (P), available potassium (K) and organic carbon (OC) in the top 30 cm of soil are 0.94 g kg^{-1}, 29.2 g kg^{-1}, 152.6 g kg^{-1} and 11.3 g kg^{-1}, respectively.

2.2. Experimental design and crop management

The experimental design was a split plot in randomized complete blocks with three replicates. Three cropping systems (sole pea, sole maize and maize-pea strip intercropping) formed the main plots, and three N fertilizer management systems (N1, N2 and N3) with one control (N0, 0 kg N ha^{-1}) formed the subplots. The sole maize treatment received N fertilizer at 450 kg N ha^{-1} as urea (46-0-0 of N-P_2O_5-K_2O), with 20% of the total N (i.e., 90 kg N ha^{-1}) evenly broadcasted and incorporated into the top 30 cm of soil using shallow rotary tillage prior to seeding (as base fertilizer), and the remaining 80% (i.e., 360 kg N ha^{-1}) was divided into three portions as topdressing (implemented at typical maize growth stages, i.e., at jointing, pre-tasseling and 15 d post-flowering). For N1, N2 and N3, the first topdressing was implemented at maize jointing (pea flowering), with the respective amounts of 10%, 20% and 30% of the total N (i.e., 45, 90 and 135 kg N ha^{-1}); the second was at maize pre-tasseling (pea harvesting), with the same amount of 40% of the total N (i.e., 180 kg N ha^{-1}); and the third was at 15 d post-flowering, with the respective amounts of 30%, 20% and 10% of total N (i.e., 135, 90 and 45 kg N ha^{-1}) (Table 1). Therefore, N1, N2 and N3 represent the N difference at the first and third topdressing and are equivalent to the N rate of 45 kg N ha^{-1} at first topdressing plus 135 kg N ha^{-1} at third topdressing, 90 kg N ha^{-1} at first topdressing plus 90 kg N ha^{-1} at third topdressing, and 135 kg N ha^{-1} at first topdressing plus 45 kg N ha^{-1} at third topdressing. The sole pea treatment received the same amount of N fertilizer according to the sole maize with base fertilizer N (pre-seeding) plus topdressing N at maize jointing (pea flowering). Intercrops received the same area-based N fertilizer as the corresponding sole crops (Table 1). For the application of N fertilizer in intercropping systems, maize and pea strips were separately managed, i.e., the N fertilizer in the maize strips and pea strips was separately applied and corresponded to the sole maize and sole pea fertilizer. Therefore, the intercropping systems received a relatively lower total N than corresponding sole maize, taking into consideration the N available in the pea strips after the pea harvest. All plots received P fertilizer at 150 kg P ha^{-1} as a base fertilizer; then, for the plots without N fertilizer, calcium superphosphate (0–16-0 of N-P_2O_5-K_2O) was used, while for the plots with N fertilizer, diammonium phosphate (18–46-0 of N-P_2O_5-K_2O) was used. For the topdressing of N fertilizer in the maize strip, a 3-cm diameter hole (10-cm deep) was made 4–5 cm away from the maize stem, the fertilizer was applied in the hole, and the hole was compacted with soil.

Field pea (cv. Long-wan 1) and maize (cv. Xian-yu 335) were relay planted in 2012, 2013 and 2014 in a strip intercropping system (Table 2). Each plot was 45.6 m^2 (5.7 m × 8 m) in size with a 50 cm wide by 30 cm high ridge built between the two neighboring plots to eliminate potential water and fertilizer movement. In