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Postprint: Response of Interspecific Competitiveness and Yield to Belowground Interactions and Density Interactions in Barley/Pea Intercropping System

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Abstract

Interspecific relationships are an important biological basis for high yield and efficient resource utilization in intercropping systems. Revealing the effects of interspecific relationships on intercropping yield has important theoretical significance for optimizing intercropping techniques. This study conducted a pot experiment, designing two types of interspecific interaction relationships—complete root separation (above-ground interaction) and no separation (above- and below-ground interaction)—and two barley planting densities (15 plants · pot^{-1}, 25 plants · pot^{-1}), to investigate the effects of root interactions and dense planting on the interspecific competitive and complementary relationships and yield in barley-pea intercropping systems, aiming to provide a theoretical basis for establishing management techniques to improve intercropping yield through optimizing interspecific relationships. The results showed that: 1) Compared with monoculture, intercropping increased the population dry matter accumulation by 3.6%~11.3%, with the contribution rate of below-ground interactions being 53.9%~63.5%; increasing barley planting density increased the population dry matter of the no root separation intercropping treatment by 12.5%~14.4%, and that of the complete root separation intercropping treatment by 3.3%~6.7%. Similarly, compared with monoculture, intercropping increased the population grain yield by 8.6%~38.8%, with the contribution rate of below-ground interactions being 2.4%~16.2%; increasing barley planting density increased the grain yield of the no separation and separation intercropping treatments by 7.0%~10.9% and 1.2%~2.6%, respectively, indicating that below-ground root interactions are an important foundation for dense planting in intercropping systems. 2) Intercropping increased the harvest index of both barley and pea, with increases of 8.7%~21.0% for barley and 3.3%~31.7% for pea; the harvest index of intercropped barley increased with increasing barley planting density, whereas the harvest index of intercropped pea decreased with increasing barley planting density, with the decreasing effect being more pronounced under the complete root separation treatment. 3) Below-ground interactions with no root separation increased the Land Equivalent Ratio (LER) of the intercropping population, while increasing barley planting density decreased LER, indicating that below-ground root interactions are the main cause of intercropping advantages. 4) Below-ground interactions significantly increased the average competitiveness of barley relative to pea throughout the entire growth period, with a growth rate of 40.1%~89.1%; increasing barley planting density increased the average competitiveness by 11.0%~49.9%. 5) The grain yield of the intercropping population showed a quadratic relationship with the average competitiveness of barley relative to pea throughout the entire growth period; when this competitiveness was 0.35 and 0.13, respectively, it was conducive to obtaining high yields of intercropped barley and pea. This study demonstrates that moderately increasing the competitive advantage of barley by increasing barley planting density (such as 25 plants $\cdot$ pot^{-1} in this study), particularly the competitive advantage of barley during the grain-filling stage, is beneficial for improving the overall yield of the intercropping population.

Full Text

Competitiveness and Yield Response to Belowground Interaction and Density in Barley-Pea Intercropping System

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Abstract

Interspecific relationship is an important biological basis for high yield and efficient resource utilization in intercropping systems. Revealing the effects of interspecific relationships on intercropping yield provides crucial theoretical guidance for optimizing intercropping techniques. This study investigated the effects of root interaction and planting density on interspecific competition, complementarity, and yield in barley-pea intercropping through a pot experiment. Two types of interspecific interactions were designed: complete root separation (aboveground interaction only) and no root separation (both aboveground and belowground interaction), combined with two barley planting densities (15 plants $\cdot$ pot^{-1} and 25 plants $\cdot$ pot^{-1}). The results showed that: (1) Compared with monoculture, intercropping increased total dry matter accumulation by 3.6%-11.3%, with belowground interaction contributing 53.9%-63.5% of this increase. Increasing barley planting density enhanced dry matter accumulation by 12.5%-14.4% under no root separation and by 3.3%-6.7% under complete root separation. Similarly, intercropping increased total grain yield by 8.6%-38.8% compared with monoculture, with belowground interaction contributing 2.4%-16.2%. Increasing barley density raised grain yield by 7.0%-10.9% under no root separation versus only 1.2%-2.6% under root separation, indicating that belowground root interaction is fundamental to dense planting in intercropping systems. (2) Intercropping increased harvest index (HI) of barley by 8.7%-21.0% and pea by 3.3%-31.7%. The HI of intercropped barley increased with barley density, while that of intercropped pea decreased, with the decline being more pronounced under root separation. (3) No root separation increased land equivalent ratio (LER), while high barley density decreased LER, suggesting that belowground root interaction is the primary driver of intercropping advantages. (4) Belowground interaction significantly increased barley' s competitiveness relative to pea throughout the co-growth period by 40.1%-89.1%; increasing barley density further enhanced average competitiveness by 11.0%-49.9%. (5) A quadratic relationship existed between total grain yield of the intercropping system and barley' s average competitiveness relative to pea. Optimal yields were achieved when competitiveness values were approximately 0.35 for barley and 0.13 for pea. The study demonstrates that moderately enhancing barley' s competitive advantage, particularly during the grain-filling stage, by increasing planting density (e.g., 25 plants $\cdot$ pot^{-1} in this study) can improve overall intercropping system productivity.

Keywords: Barley/pea intercropping; Root separation; Belowground crop interaction; Crop yield; Land equivalent ratio; Competitiveness

Introduction

The efficient resource utilization and yield advantages of intercropping have been extensively documented. Interspecific competition and complementarity between crops are key determinants of intercropping advantages and have long been a focal area in multiple cropping research. During the co-growth period, intercropping provides a foundation for ecological niche differentiation in time and space for crops with different resource demand characteristics, facilitating efficient resource utilization through interspecific complementarity. After the short-duration crop is harvested, temporal and spatial compensation effects allow crops to recover from early growth inhibition caused by competition during the co-growth period, resulting in overall yield advantages. This demonstrates that rational utilization of interspecific relationships can achieve mutual yield increases and efficiency gains. Ecological studies further indicate that under certain conditions, belowground root interactions and the movement of nutrients and water in soil are more important than aboveground interactions, with ecological niche separation being the primary ecological mechanism generating intercropping advantages. Additionally, because intercropped crops occupy separated aboveground and belowground ecological niches, they maximize resource utilization of light, heat, water, and nutrients through temporal niche separation and spatial niche complementarity, thereby generating intercropping advantages. Dense planting is also an important measure for high yield in intercropping, yet research on interspecific relationships and productivity under different density conditions remains limited. Systematic studies on density and interspecific relationships are essential for further exploiting the effects of dense planting. Root separation methods can be used to distinguish the contributions of aboveground and belowground components to yield and are effective for determining competition and complementarity between paired crops. However, theoretical foundations for improving intercropping system productivity through regulation of interspecific competitiveness remain insufficient. Among various intercropping patterns, cereal-legume intercropping has attracted considerable attention due to nitrogen fixation by legumes, increased biodiversity, and improved resource utilization efficiency, and is considered an important direction for future sustainable agriculture. In barley (*Hordeum vulgare* Linn.)/pea (*Pisum sativum* Linn.) intercropping systems, an interspecific nitrogen nutritional complementarity mechanism exists, where barley competes for soil nitrogen, reducing inhibition of nitrogenase activity by soil nitrogen and promoting atmospheric nitrogen fixation by peas.

Therefore, this study used a typical barley/pea intercropping system to quantify the effects of barley planting density on interspecific competitiveness under both complete root separation (aboveground interaction only) and no root separation (aboveground and belowground interaction) conditions, and to reveal the regulatory effects of root interactions on competitiveness under dense planting. The objective was to provide a theoretical basis for enhancing yield effects in intercropping systems through regulation of crop competitiveness.

1. Materials and Methods

1.1 Experimental Materials

The experiment was conducted in a solar greenhouse at Gansu Agricultural University from March to July in 2012 and 2013. The tested soil was a clay loam collected from Xiajiajing, Qinwangchuan, with organic matter content of 12.9 $g \cdot kg^{-1}$, ammonium nitrogen 2.9 $mg \cdot kg^{-1}$, nitrate nitrogen 5.0 $mg \cdot kg^{-1}$, total phosphorus 0.4 $g \cdot kg^{-1}$, and available phosphorus 0.1 $g \cdot kg^{-1}$. Phosphorus fertilizer (KH_2PO_4) was applied at 0.1 $g(P_2O_5) \cdot kg^{-1}$(soil), and no nitrogen fertilizer was applied to any treatment. The barley cultivar was ‘Ganpi 4’ (*Hordeum vulgare* L. cv. Ganpi 4) and the pea cultivar was ‘Longwan 1’ (*Pisum sativum* L. cv. Longwan 1).

1.2 Experimental Design

This was a pot experiment using ceramic pots 30 cm in diameter and 45 cm high, each containing 14 kg of soil. Three cropping patterns were established: monoculture pea, monoculture barley, and barley-pea intercropping. For intercropping, two root partition treatments were implemented: no root separation and complete root separation using plastic film (0.025 mm thickness). Each crop occupied half of the cultivation area (before soil filling, pots were divided into two equal left and right sections with a wooden board; plastic film was placed in one section to cover the entire area; soil was added simultaneously to both sections while gradually removing the wooden board; after 7 kg of soil was added to each section, the board was completely removed; the upper edge of the plastic film extended above the soil surface to distinguish the two sections; barley and pea were uniformly sown in the two sections). Two barley density gradients were established, forming seven treatments in total (Table 1), with three replications per treatment and four sampling times throughout the growth period, totaling 12 pots per treatment.

In 2012, barley was sown on March 31 and harvested on July 14, while pea was sown on April 1 and harvested on July 2. In 2013, barley was sown on March 31 and pea on April 1, with both crops harvested on June 24.

1.3 Measurement Indicators

1.3.1 Aboveground Dry Weight Sampling began 20 days after pea emergence, with four total samplings. The first three samplings were at 20-day intervals, corresponding to barley tillering, heading, and grain-filling stages, while the fourth sampling occurred at maturity (timing based on actual crop harvest). Whole-pot sampling was conducted, with three pots sampled per treatment each time. Samples were killed at 105 °C and dried at 80 °C to constant weight for calculating aboveground dry matter weight per pot.

1.3.2 Yield At crop maturity, grain yield and biological yield were harvested per pot, and harvest index was calculated.

Harvest Index = Grain yield / Biological yield

1.3.3 Interspecific Relationships **Land Equivalent Ratio (LER):**

$$LER = \frac{Y_{ib}}{Y_{sb}} + \frac{Y_{ip}}{Y_{sp}}$$

where Y_{ib} and Y_{ip} represent yields of intercropped barley and pea, respectively, and Y_{sb} and Y_{sp} represent yields of monoculture barley and pea. LER > 1 indicates an intercropping advantage, while LER < 1 indicates a disadvantage.

Interspecific Relative Competitiveness (Abp):

$$Abp = \frac{Y_{ib}}{Y_{sb} \times Z_b} - \frac{Y_{ip}}{Y_{sp} \times Z_p}$$

where *Abp* represents barley's competitiveness relative to pea. Abp > 0 indicates barley is more competitive than pea, while Abp < 0 indicates barley is less competitive. Z_b and Z_p represent the proportions of barley and pea in the intercropping system, respectively (both 0.5 in this experiment).

1.3.4 Contribution Rates Contribution Rate of Belowground Interaction (RCT):

$$RCT = \frac{YI - YRI}{YI} \times 100\%$$

where YI is the dry matter or yield of crops without root separation, and YRI is that with root separation.

Contribution Rate of Density (RCTD):

$$RCTD = \frac{YD_2 - YD_1}{YD_1} \times 100\%$$

where YD_2 is the dry matter or yield at high density under the same interspecific relationship, and YD_1 is that at low density.

1.4 Data Processing

Data were organized using Microsoft Excel 2007, and statistical analysis and correlation analysis were performed using SPSS 17.0.

2. Results

2.2 Grain Yield and Harvest Index of Barley-Pea Intercropping Under Different Treatments

Density and interspecific interaction significantly affected the yield and harvest index of intercropped barley and pea (Table 2). In both 2012 and 2013, compared with the average of corresponding monoculture yields, intercropping increased total grain yield by 8.6%-38.8%, with belowground interaction contributing 2.4%-16.2%. Increasing barley planting density increased grain yield by 7.0%-10.9% under no root separation versus only 1.2%-2.6% under root separation, demonstrating that no root separation effectively enhances the positive effects of density.

On the same land area basis, intercropped barley grain yield was 10.0%-57.6% higher than monoculture barley, while intercropped pea yield was 2.9%-42.9% higher, indicating that intercropping improved grain yields of both crops. Under the same intercropping components, barley grain yield with no root separation was 1.1%-16.7% higher than with only aboveground interaction. Increasing barley density increased intercropped barley yield by 9.7%-26.6%. Pea grain yield with both aboveground and belowground interaction was 3.9%-20.8% higher than with only aboveground interaction, while pea yield decreased by 7.5%

when intercropped with high-density barley. This suggests that increasing the density of the competitively superior species can improve its grain yield but reduces that of the inferior species.

Both density and belowground interaction significantly increased the harvest index (HI) of intercropped barley and pea. Intercropped barley HI was 8.7%-21.0% higher than monoculture barley. Under no root separation, intercropped barley HI was 3.1%-11.3% higher than with only aboveground interaction, and increasing barley density increased barley HI by 2.2%-8.2%. Intercropped pea HI was 3.3%-31.7% higher than monoculture pea. Under no root separation with high barley density, pea HI was 4.9%-7.7% higher than with only aboveground interaction, while root separation decreased pea HI by 5.4%-17.9% when barley density increased. This indicates that increasing the density of the competitively superior species in intercropping can improve its HI but reduce that of the inferior species, with root separation having a more pronounced negative effect.

2.3.1 Land Equivalent Ratio Under Different Intercropping Treatments

The land equivalent ratio (LER) was greater than 1 under no root separation for all intercropping treatments, but less than 1 during barley heading and grain-filling stages under complete root separation with only aboveground interaction. Among different interspecific interactions, LER was highest under no root separation with low density (I1), being 11.1%-11.6% higher than no root separation with high density (I2), and 40.0%-50.4% (PI1) and 72.4%-84.0% (PI2) higher than complete root separation at low and high densities, respectively, reaching significant levels. This demonstrates that belowground interaction and appropriate planting density improve land use efficiency.

As shown in Figure 2 [Figure 2: see original paper], the barley-pea intercropping system exhibited strong complementarity throughout the co-growth period under no root separation, with increased barley density reducing this complementarity. Under complete root separation, complementarity was strongest during barley tillering and maturity stages, and similarly decreased with increased barley planting density.

2.3.2 Competitiveness Dynamics in Barley-Pea Intercropping System

In both 2012 and 2013, competitiveness was minimal during the early co-growth stage but increased significantly as barley developed relative to pea, reaching maximum advantage during barley flowering to grain-filling stages before declining sharply, showing a unimodal trend (Figure 3 [Figure 3: see original paper]). Barley' s average competitiveness relative to pea throughout the entire growth period was 40.1%-89.1% higher under no root separation than under complete root separation. Increasing barley planting density increased average competitiveness by 11.0%-49.9%. Particularly during barley heading and grain-filling stages, no root separation significantly enhanced barley' s competitiveness relative to pea by 35.3%-66.0% and 25.6%-44.3%, respectively.

2.4 Correlation Between Competitiveness and Intercropping System Grain Yield

A significant quadratic correlation existed between barley' s average competitiveness relative to pea throughout the growth period and total grain yield of the intercropping system (Figure 4 [Figure 4: see original paper]). When average competitiveness ranged from 0 to 0.35 for barley and 0 to 0.13 for pea, grain yields of both intercropped barley and pea increased continuously with increasing barley competitiveness. When competitiveness exceeded 0.35 for barley or 0.13 for pea, grain yields declined, indicating that maintaining appropriate competitiveness levels is beneficial for yield improvement. Therefore, managing barley-pea intercropping systems to maintain optimal competitiveness represents a viable approach for achieving higher yields.

Correlation analysis between barley' s competitiveness relative to pea at four measurement times and grain yield showed that early-stage competitiveness was positively correlated with later-stage competitiveness. Furthermore, competitiveness during barley' s peak growth period (grain-filling stage) was significantly positively correlated with intercropped barley grain yield (Table 3). This suggests that appropriately regulating barley' s competitiveness during the co-growth period can improve intercropping yield, with the barley grain-filling stage being a critical management period for yield optimization through interspecific competitiveness regulation.

3. Discussion

3.1 Response of Intercropping Yield to Aboveground and Belowground Interactions

The high yield, high efficiency, and improved resource utilization (water, nutrients, light, and heat) of intercropping have been widely confirmed. Research indicates that belowground root interactions and rhizosphere processes contribute substantially to intercropping advantages, with spatial distribution and morphological differences of root systems determining nutrient and water uptake. Interspecific interactions expand the spatial ecological niche of root systems, extending the ecological niche for water and nutrient absorption and increasing the effective space for nutrient acquisition. Root separation alters root morphology in intercropped crops, reducing water-fertilizer exchange in soil and spatial compensation effects, thereby decreasing intercropping advantages. However, few studies have examined the effects of dense planting and root interactions on interspecific relationships in intercropping. Therefore, this experiment investigated the influence of root interactions and dense planting on interspecific competition, complementarity, and yield in barley-pea intercropping.

In the barley-pea intercropping system, total grain yield was 8.6%–38.8% higher than monoculture, with belowground interaction contributing 2.4%–16.2%. Belowground root interaction enhanced the positive effects of density increases, indicating that dense planting is an important measure for achieving high yields in intercropping. Strengthening belowground root interactions is a crucial pathway for intercropping yield increases, a conclusion supported by many scholars. Root separation had more significant effects on component yield of intercropped barley than on pea, suggesting that intercropping advantages in barley-pea systems are attributed to spatial overlap of barley root systems and water-nutrient exchange in the rhizosphere, with more pronounced effects at high barley planting densities. Therefore, management practices such as planting patterns, irrigation methods, fertilization, and density can be used to regulate spatial distribution and morphology of root systems in intercropping systems, fully utilizing rhizosphere compensation effects to maximize belowground interaction contributions and optimize yield and benefit gains.

3.2 Relationship Between Different Interspecific Interactions and Intercropping Advantages

Intercropped crops compete for shared space and resources but also exhibit complementarity due to increased resource availability from modifications of the microenvironment by component crops. Competition and complementarity coexist, with their relative magnitude and importance changing throughout crop development. When total competition exceeds complementarity during the growth period, resource utilization capacity declines, showing intercropping disadvantages; conversely, when complementarity exceeds competition, resource utilization increases, showing intercropping advantages and achieving system stability. In this study, pea was at a competitive disadvantage for resources during the co-growth period with barley, exhibiting lower growth rates. Intercropping systems with belowground interactions showed intercropping advantages, while systems with only aboveground interaction (root separation) showed disadvantages during barley heading and grain-filling stages, primarily due to differences in phenological characteristics and temporal-spatial patterns of resource demand between the two crops. Additionally, barley, as a gramineous crop, has strong competitive ability, vigorous growth, and causes shading of pea, representing another major reason for competitive differences. Furthermore, under root interaction conditions, barley and pea root systems can grow together, occupying different ecological niches in the same space. Although increased density intensifies interspecific competition, the overall effect shows that promotion exceeds competition. This demonstrates that belowground root interaction is an effective way to balance competition and complementarity between intercropped species. As the planting density of the competitively superior species (barley) increases, its competitive advantage becomes stronger, particularly during vigorous growth stages (heading and grain-filling), with more significant effects. This conclusion has been confirmed by previous research. Therefore, appropriate variety combinations and planting methods can create complementarity in resource demands among intercropped crops, making interspecific facilitation greater than competition and improving resource use efficiency to increase intercropping system yield.

3.3 Correlation Between Interspecific Competitiveness and Component Crop Grain Yield

Quadratic relationships between component crop competitiveness and intercropping system grain yield have been confirmed in wheat-maize and barley-pea intercropping studies. Similarly, this study showed quadratic correlations between grain yields of intercropped barley and pea and barley's average competitiveness relative to pea throughout the growth period. Within certain competitiveness ranges (0–0.35 for barley, 0–0.13 for pea), grain yields of both crops increased with increasing barley competitive advantage. Under resource-limited growth conditions, barley and pea with similar resource demands and small sowing time differences showed smaller competitiveness differences but greater opportunities for spatial and water-fertilizer resource compensation, providing a basis for improving system productivity by moderately increasing barley' s relative competitiveness. Therefore, appropriately increasing barley' s relative competitiveness is a viable approach for achieving higher yields in barley-pea intercropping systems, with the barley grain-filling stage being a critical management period for yield improvement through competitiveness regulation, consistent with previous research findings.

This study demonstrates that belowground root interaction is key to improving intercropping yield and that dense planting is an important way to appropriately increase barley' s competitive advantage. Regulating interspecific competitiveness through increased barley planting density is an effective pathway to high yields in intercropping. Developing cereal-legume intercropping patterns can improve intercropping system productivity, and further detailed quantification of competition and complementarity in spatial and temporal ecological niches for different component crops under various root separation methods should be an important research direction.

Conclusion

In this study, intercropping with both aboveground and belowground interactions and low-density root separation increased grain yield by 8.6%–38.8% compared with monoculture. No root separation improved intercropping system grain yield with a contribution rate of 2.4%–16.2%. Intercropping system grain yield increased with barley planting density, with density contribution rates of 7.0%–10.9% under no root separation and 1.2%–2.6% under complete root separation, indicating that belowground interaction enhances the positive effects of density increases. No root separation significantly increased barley' s average competitiveness relative to pea throughout the growth period by 40.1%–89.1%, and increasing barley density further improved average competitiveness by 11.0%–49.9%. Grain yields of both intercropped barley and pea showed quadratic relationships with barley’ s average competitiveness relative to pea, with optimal competitiveness values of approximately 0.35 for barley and 0.13 for pea. The barley grain-filling stage is a critical period for regulating interspecific competitiveness to improve intercropping yield. In summary, regulating interspecific competitiveness through increased barley planting density is an effective approach for achieving high yields in intercropping systems, and complete root interaction can enhance the positive effects of density increases and intercropping advantages.

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