



Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency

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Abstract

This paper reviews recent research on the processes involved in the yield advantage in wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.), wheat/soybean [*Glycine max* (L.) Merr.], faba bean (*Vicia faba* L.)/maize, peanut (*Arachis hypogaea* L.)/maize and water convolvulus (*Ipomoea aquatica* Forsk.)/maize intercropping. In wheat/maize and wheat/soybean intercropping systems, a significant yield increase of intercropped wheat over sole wheat was observed, which resulted from positive effects of the border row and inner rows of intercropped wheat. The border row effect was due to interspecific competition for nutrients as wheat had a higher competitive ability than either maize or soybean had. There was also compensatory growth, or a recovery process, of subordinate species such as maize and soybean, offsetting the impairment of early growth of the subordinate species. Finally, both dominant and subordinate species in intercropping obtain higher yields than that in corresponding sole wheat, maize or soybean. We summarized these processes as the 'competition-recovery production principle'. We observed interspecific facilitation, where maize improves iron nutrition in intercropped peanut, faba bean enhances nitrogen and phosphorus uptake by intercropped maize, and chickpea facilitates P uptake by associated wheat from phytate-P. Furthermore, intercropping reduced the nitrate content in the soil profile as intercropping uses soil nutrients more efficiently than sole cropping.

Introduction

In China, one-third of all the cultivated land area is used for multiple cropping and half of the total grain yield is produced with multiple cropping (Tong, 1993). Intercropping, as one of the multiple cropping systems, has been practiced by farmers for many years in various ways and most areas, and has played a very important role in China. Most studies on intercropping have focused on the legume-cereal intercropping, a productive and sustainable system, its resource utilization (water, light, nutrients), and its effect on N input from symbiotic nitrogen fixation into the cropping system and reduction of negative impacts on the

environment (Jensen, 1996; Willey, 1979). However, a cereal-cereal association, e.g., wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.) intercropping where two crops grow together for about 70 to 80 days, with a yield of more than 12,000 kg ha⁻¹, has become increasingly popular in the irrigated area of the Hexi Corridor in the Gansu province, irrigated areas along the Huanghe river in Ningxia, and in Inner Mongolia Autonomous regions, China. The area under wheat/maize intercropping was 75,100 ha in Ningxia in 1995, producing 43% of the total grain yield for the area. In Gansu the area is 200,000 ha annually. Wheat/soybean [*Glycine max* (L.) Merr.] and faba bean (*Vicia faba* L.)/maize intercropping systems are popular in irrigated areas of northwest China, and peanut (*Arachis hypogaea* L.)/maize intercropping in the northern part of China. There

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have been few published research publication on interspecific interactions, especially interspecific below-ground interactions between intercropped species in wheat/maize, wheat/soybean, peanut/maize and faba bean/maize intercropping systems. In the past 10 years, many studies, including field trials in Gansu and Henan provinces and greenhouse experiments, were conducted to determine interspecific below-ground interactions between intercropped species. This paper reviews the main results and progress of our research works along with closely related work done elsewhere.

A significant contribution of below-ground interactions to border-row yields and nutrient uptake by intercropped wheat

In intercropping systems, two or more crops grow simultaneously on the same field such that the period of overlap is long enough to include the vegetative stage (Gomes and Gomez, 1983). In maize/soybean strip intercropping, West and Griffith (1992) observed a 26% increase in maize yield and a 27% reduction in soybean yield of border rows located at the outside of 8-row alternating strips in Indiana, USA. Ghaffarzadeh et al. (1994) found that strip intercropping led to 20–24% greater maize yields and 10–15% lower soybean yields in adjacent border rows in a maize/soybean intercropping system in Iowa, USA. In our study, yield advantage of intercropped wheat resulted from both the border-row and inner-row effect in wheat/maize and wheat/soybean intercropping systems (Li et al., 2001a). The yields in border rows of intercropped wheat were significantly higher than those in inner rows, both in wheat/maize and wheat/soybean intercropping systems (Figure 1). The 74% increase of grain yield in wheat intercropped with maize, 47 and 27% was attributed to above-ground and below-ground interaction, respectively. The 53% increase of grain yield in wheat intercropped with soybean, was due to a 30 and 23% above- and below-ground interaction between the two species, respectively. The contributions of above-ground and below-ground interactions to the increase of N uptake by wheat were 50 and 59%, respectively, for wheat/maize intercropping, and 23 and 19%, respectively, for wheat/soybean intercropping. Similarly, the contribution of above-ground and below-ground interactions to the increase of P uptake were 56 and 42%, respectively, for wheat/maize intercropping, and 26 and 28%, respectively, for wheat/soybean inter-

cropping (Zhang et al., 2001). Interspecific below-ground interactions and rhizosphere effects between intercropped species played an important role in yield advantage of intercropping.

Competitive – recovery production principle

Yield advantage of dominant species from interspecific competition

Interspecific competition may occur when two crops are grown together (Van der Meer, 1989). Such competition usually decreases survival, growth or reproduction of at least one species (Crawley, 1997). In the wheat/maize or wheat/soybean intercropping systems in north China, there is a 70 to 80-day overlapping growth period that causes intense interspecific interactions between the intercropped species. The interactions frequently occurred at the interface between two crop species where they were nearest in distance, and resulting in an increase or decrease of growth, development and even yields. The yield advantage in the border row of intercropped wheat probably derived from the differences in interspecific competitiveness, and wheat proved to be more competitive than maize and soybean during overlapping growth periods in the wheat/soybean and wheat/maize intercropping systems. Aggressivity measures the interspecies competition in intercropping by relating the yield changes of the two component crops (Willey and Rao, 1980).

$$A_{ab} = Y_{ia}/(Y_{sa} \times F_a) - Y_{ib}/(Y_{sb} \times F_b), \quad (1)$$

where Y_{ia} and Y_{ib} are yields of crops a and b in intercropping, Y_{sa} and Y_{sb} are yields of crops a and b in sole cropping. F_a and F_b are the proportion of the area occupied by crop a and crop b in the intercropping. When A_{ab} is greater than 0, the competitive ability of crop a exceeds that of crop b in intercropping.

In a study by Li et al. (2001a), aggressivities of wheat relative to either maize (0.26–1.63 of A_{wm}) or soybean (0.35–0.95 of A_{ws}) revealed the greater competitive ability of wheat compared with either maize or soybean. The nutrient competitive ratio, 1.09–7.54 for wheat relative to maize, and 1.2–8.3 for wheat relative to soybean, showed that wheat had a greater capability of acquiring nutrients compared with soybean and maize. However, the mechanism of the difference in competitive abilities between intercropped species is rarely analyzed. The determination of the mechanism will be helpful in controlling the interspecific

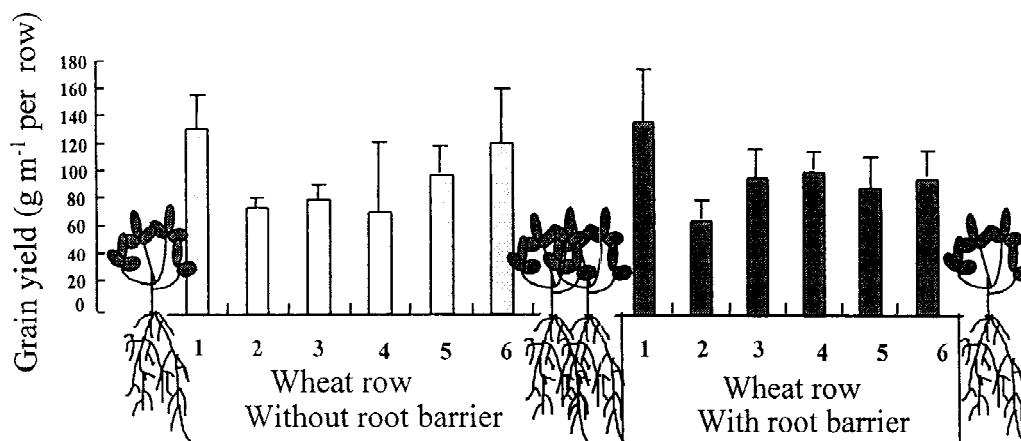


Figure 1. Effect of interspecific root interaction on border row yield of intercropped wheat in a wheat/soybean intercropping system, six rows of wheat and two rows of soybean. Row spaces for wheat and soybean were 0.12 and 0.20 m, respectively. Bars are the standard error of means. The experimental site (37°05'N, 104°40'E) is located in Jingyuan county, Gansu Province, at 1645 m above sea level. Annual mean temperature is 6.6 °C. Annual precipitation is 259 mm, and potential evaporation is 2369 mm. This site is on the edge of a loess plateau. The soils at the site are classified as Aridisol.

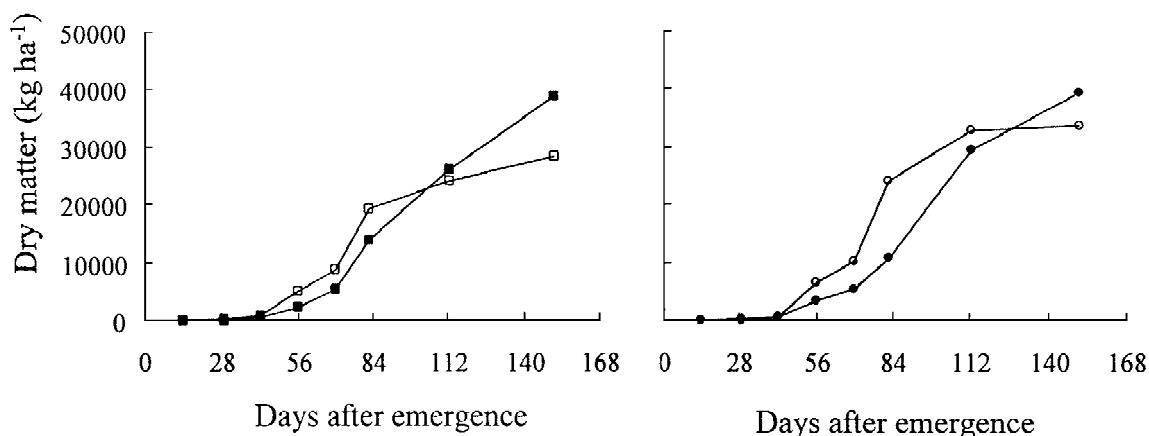


Figure 2. The difference in dry matter accumulation between intercropped maize (IM) and sole maize. (■, intercropped maize without P fertilizer, □, sole maize without P fertilizer, ●, intercropped maize receiving P fertilizer at 53 kg P ha⁻¹, and ○, sole maize receiving P fertilizer at 53 kg P ha⁻¹). The experimental site (38°37'N, 102°40'E) is located 15 km north of Wuwei City, Gansu Province at 1504 m above sea level. Annual mean temperature is 7.7 °C. Annual precipitation is 150 mm, and potential evaporation is 2021 mm. The soils at the site are classified as Aridisol.

competition and in gaining higher yield advantage of intercropping.

Recovery or compensation of subordinate species at a late growth stage

In the wheat/maize or wheat/soybean intercropping, at wheat harvesting, the growth and nutrient uptake by the subordinate species maize or soybean are reduced due to interspecific competition. There is recovery of nutrient uptake and growth after harvest of the earlier-maturing species, which made the later-maturing species compensate for impaired early growth once the earlier-maturing species was harvested. In a field trial

conducted at the Baiyun site in 1997, the rates of dry matter accumulation in the intercropped maize (10–20 g m⁻² day⁻¹) were significantly lower than those in the sole maize (17–35 g m⁻² day⁻¹) during the early stage from 7 May to 3 August, while mostly intercropped with wheat. After 3 August, however, the rates of dry matter accumulation for intercropped maize, increasing from 59 to 70 g m⁻² day⁻¹, were significantly greater than in sole maize (23–52 g m⁻² day⁻¹) (Figure 2); nutrient acquisition showed the same trend as growth. At the Jingtan site in 1998, the disadvantage of the border row of intercropped maize resulting from interspecific competition diminished

after wheat harvest, and had disappeared at maize maturity (Li et al., 2001b). However, the recovery was limited to the treatment without N and P fertilizer application (Li et al., 2001b). The recovery needs further study in understanding the mechanism involved, which will contribute to understanding yield advantage of intercropping where short-season associated with long-season species.

Interspecific below-ground facilitation – nutrients mobilized by efficient species contribute to inefficient species

Maize improved iron nutrition of peanut

Peanut (*Arachis hypogaea* L.), a major oilseed crop in China, accounts for 30% of the cropped area and 30% of the total oilseed production in the country. However, iron deficiency chlorosis frequently occurs on calcareous soils, especially in north China. Interestingly, iron deficiency chlorosis of the crop is more severe in sole cropping systems than in the intercropping system of peanut/maize on these soils. There is, therefore, considerable interest in devising practical approaches for the correction or prevention of Fe deficiency in crops in Chinese agriculture. The results demonstrated that the improvement in the Fe nutrition of peanut intercropped with maize was mainly caused by rhizosphere interactions between peanut and maize (Zuo et al., 2000).

The severity of iron deficiency chlorosis in young peanut leaves in the intercropping systems was closely related to the distance of the peanut plants from the maize roots when treatments were assessed during the peanut flowering period. In the unrestricted intercropping treatment, where neighboring roots of peanut and maize intermingled fully, the young leaves of peanut plants in rows 1–3 from the maize grew without visible symptoms of iron deficiency, while those in rows 5–10 showed variable degrees of chlorosis. In the treatment where the roots were physically separated between peanut and maize, the peanut plants in all rows were chlorotic, albeit that most of the peanut plants in the row closest to maize showed only slight signs of chlorosis (80% of young leaves were green). In contrast, in the treatment where a 400 mesh nylon mesh separation (nominal aperture 37 μm) was inserted into the ground between the two crop species to prevent direct root contact but allow interactions through mass flow and diffusion, the plants in rows 1

and 2 remained completely green, while those in rows 3–10 were chlorotic to varying extents. In the monocropping treatment, about 90% of the peanut plants showed severe Fe deficiency chlorosis in the young leaves.

Peanut is a species with strategy I for iron uptake and frequently showed Fe deficiency chlorosis on calcareous soil, whereas maize with strategy II is an Fe efficient species (Marschner, 1995). When peanut and maize grow together, phytosiderophore released from maize roots may mobilize Fe(III) and benefit the iron nutrition of peanut plant. However, there is no direct evidence to support this contention.

Maize benefits from associated faba bean

Interspecific root interactions between intercropped faba bean and maize played an important role in the yield advantage and nitrogen and phosphorus acquisition by the intercropping system (Li et al., 1999, 2002a). When the roots of two species intermingled, the land equivalent ratio (Wiley, 1979), N uptake and P uptake were 1.21, 38.4 g N m⁻² and 4.2 g P m⁻², respectively. However, when the roots of the two species were separated completely, they were reduced to 1.06, 31.8 g N m⁻² and 3.3 mg P m⁻², respectively (Li et al., 2002a). This study, however, does not provide information on the mechanism of increased N and P uptake. Possible mechanisms for interspecific facilitation are: (1) the phosphorus that is mobilized by faba bean may have been made available for maize; (2) nitrogen that was fixed by faba beans may have been transferred to maize. More research, such as on the difference in root distribution, in the ability to mobilize sparingly soil P between faba bean and maize, needs to be done.

Chickpea-facilitated P nutrition in associated wheat

In a pot experiment with no root barrier, a nylon mesh root barrier, and a solid root barrier, biomass of wheat was significantly increased by the root intermingling of intercropped wheat and chickpea (*Cicer arietinum* L.) compared with the treatments with either the solid root barrier or the nylon mesh, regardless of whether P was supplied as phytate or FePO₄.

Where phytate was applied, the root intermingling of wheat and chickpea increased the P concentration in wheat and P uptake by wheat, compared with the treatment in which the roots were separated by nylon mesh or a solid barrier. In addition, P uptake by chickpea

in the treatment with the root barrier and an organic P source was greater than that in the treatment without root barrier, suggesting that organic P mobilized by chickpea probably contributed to P uptake by wheat. In another study, Rao et al. (1999) found that acquisition of P by the legume was markedly greater than that by the grass, regardless of the P form being inorganic or organic. The results indicate that wheat is less able to use organic P than inorganic P, whereas chickpea is able to use both P sources equally effectively. When wheat and chickpea were grown together, the following may have happened. Firstly, chickpea can mobilize and absorb some organic P by releasing phosphatase into soil, and also leave some inorganic P for wheat. Secondly, wheat with a greater competitive ability acquires more P from the root zone of both wheat and chickpea, resulting in P depletion in the chickpea rhizosphere (Li et al., 2002b). The P depletion in the chickpea rhizosphere then induces the release of substance that mobilizes organic P. Therefore, further study should focus on the difference in phytase and phosphatase between chickpea and wheat.

Intercropping reduced nitrate accumulation in soil profile

Wheat/maize and faba bean/maize intercropping

There has been a rapid increase of fertilizer application in recent years to achieve high yields, especially in the wheat/maize intercropping systems. The average rate of N application in China is 180 kg N ha⁻¹ year⁻¹. In the irrigated area of Northwest China, application rates of N fertilizers average 450 kg N ha⁻¹ year⁻¹ for wheat/maize intercropping, which increases the risk of ground-water nitrate pollution. Applying N up to the economic optimum rate (estimated from yield and N rate data from individual trials) was associated with small increases in soil nitrate-N after harvest (the mean increase was 4 kg N ha⁻¹ year⁻¹). Where the optimum N rate was exceeded, soil nitrate-N levels increased to a greater extent (Richards et al., 1996). Intercropping faba bean with oats or spring wheat could reduce the nitrate accumulation in soil profiles (Stuelpnagel, 1993). Intercropping maize with ryegrass was also an effective way for increasing N uptake under conditions of high N application (Zhou et al., 2000). Nitrogen uptake by intercropping of wheat and maize was greater than that by corresponding sole cropping under same N supply (Li et al., 2001a). Therefore, we propose that wheat and maize intercropping could reduce the nitrate accumulation

in soil compared with sole maize and wheat. In an irrigated area of Hexi corridor, northwest China, the amounts of NO₃⁻ in the soil profile after wheat harvest was greater for sole wheat than for wheat intercropped with maize, and was greater for sole faba bean than for faba bean intercropped with maize supplied with 200 and 400 kg N ha⁻¹ of application. The decrease was about 0–41% for wheat and 0–31% for faba bean. Amounts of NO₃⁻ in soil after maize harvest was in the order of sole wheat and faba bean, intercropping wheat and faba bean, maize intercropped with faba bean and wheat. The results indicate that intercropping decreases the accumulation of nitrate in soil profiles.

Water convolvulus/maize intercropping

A field study was conducted in Beijing, China to test the hypothesis that intercropping could reduce nitrate in the soil profile. There were three treatments: (1) sole maize with 0.40 m row space, (2) sole water convolvulus (*Ipomoea aquatica* Forsk.) with 0.20 m row space, and (3) water convolvulus/maize intercropping with 2 rows of vegetable with 0.20 m row space and 2 rows of maize with 0.40 m row space. The results demonstrated that nitrate in the soil profile (0–1 m) where grew both vegetable and maize was reduced by intercropping (Figure 3).

Interspecific competition and facilitation are two aspects of the same interaction

Geno and Geno (2001) concluded that interspecific competition and facilitation occurs at the same time. Van der Meer (1989) noted that both competition and facilitation take place in many intercropping systems, and that it is possible to obtain the net result of land equivalent ratio (LER), an indicator of intercropping advantage, >1 where the complementary facilitation is contributing more to the interaction than the competitive interference. Thus, an LER>1 could result from low interspecific competition or strong facilitation. A pot experiment was conducted to investigate the interspecific competition and facilitation in a wheat/soybean association. The pots were separated into two compartments either by a plastic sheet to eliminate root contact and any solute movement, or by a nylon mesh (30 μm) to prevent root contact but permitting solute exchange between the compartments. In addition, there was a control treatment without any separation. Phosphorus was added at 0, 150, and 300 μg P g⁻¹ soil as KH₂PO₄. Wheat

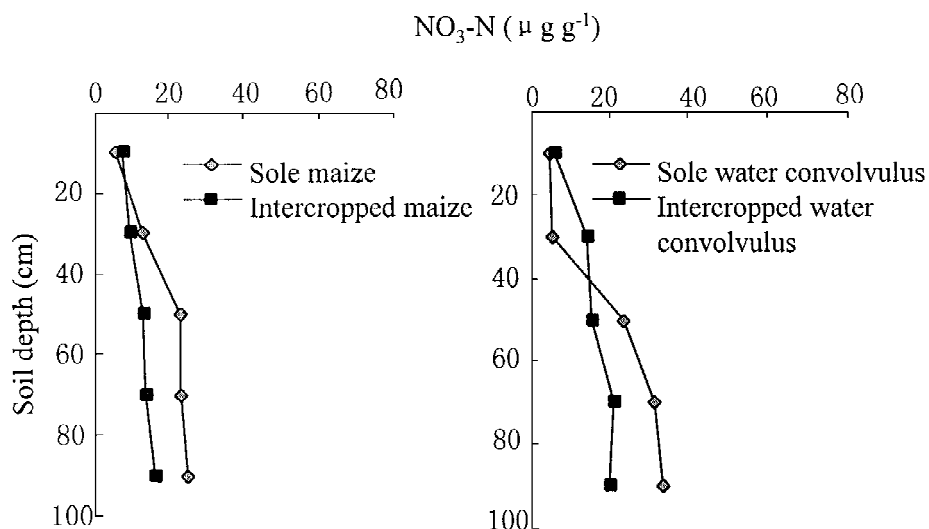


Figure 3. Nitrate concentrations in the soil profile after water convolvulus and maize harvesting (October 10, 2001) in an intercropping system and a corresponding sole cropping system. Experimental site (39°56'N, 116°17'E), located in the campus of China Agricultural University, Beijing at 54 m above sea level. Annual mean temperature is 11.8 °C. Annual precipitation is 577 mm.

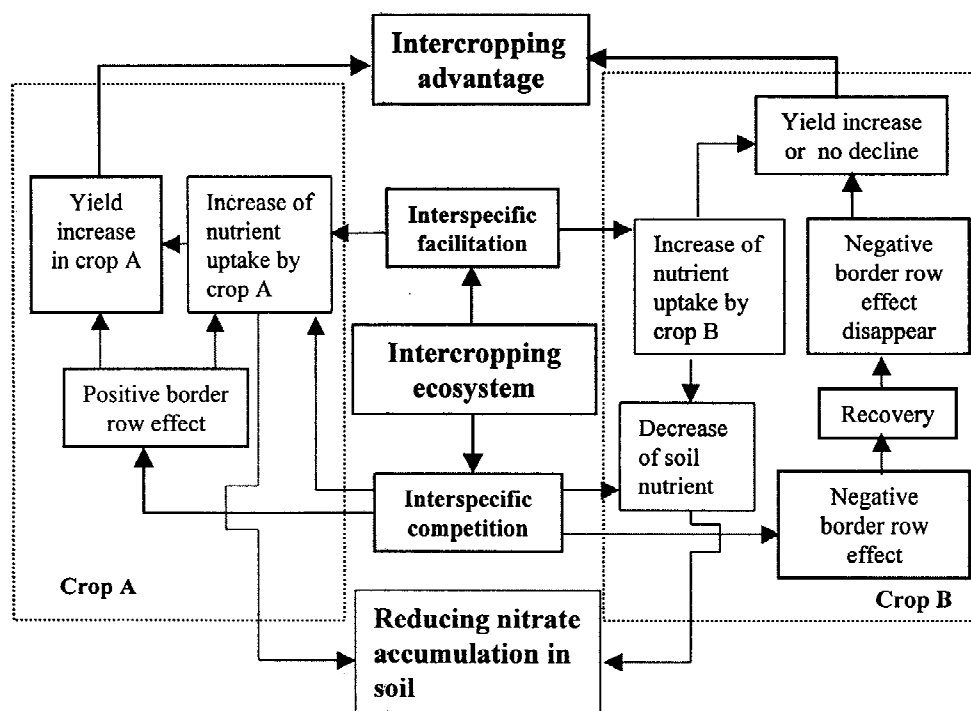


Figure 4. The relationship between yield advantage of intercropping and interspecific competition, facilitation, recovery and soil nitrate content (modified from Li et al., 2001b).

plants were grown in one compartment and soybean in the other. The obvious facilitation of wheat to phosphorus uptake by soybean was observed in the pot with the mesh separation, where competition of wheat for phosphorus was eliminated. The biomass and P uptake

of wheat in the absence of a separation were increased by 25 and 7% compared with those with the plastic sheet partition. The biomass and phosphorus uptake of soybean at the nylon mesh separation treatment were 150 and 134% higher, respectively, than those with

the plastic sheet separation. In the pots with the nylon net separation, more roots of soybean were distributed near the nylon mesh on which wheat formed a dense root mat at the other side. In contrast, soybean roots were distributed more or less evenly in the whole compartment in the treatment with the plastic sheet. It is suggested that the beneficial effect of soybean resulted from a rhizosphere effect. At the same time, biomass and P uptake of soybean were significantly reduced by the intermingling of roots of the two species, indicating that there was an interspecific competition between wheat and soybean P. This study also proved that interspecific competition and facilitation existed together in the wheat/soybean association.

Conclusion

A 'competition-recovery production principle' is proposed based on several years of studies on intercropping. It means interspecific interaction increases growth, nutrient uptake and yield of dominant species, but decreases growth and nutrient uptake of the subordinate species during the co-existence stage of two crop species. After the dominant species is harvested, the subordinate species has a recovery or complementary process so that the final yields remain unchanged or even increase compared with corresponding sole species. The principle is suitable to intercropping of short-season/long-season species. Interspecific competition and facilitation exist simultaneously. Interspecific facilitation has been observed in some intercropping systems. These include maize improving iron nutrition in peanut, faba bean enhancing nitrogen and phosphorus uptake by maize, and chickpea-facilitated P uptake by associated wheat. Yield advantage of intercropping and its relationship to interspecific interactions are summarized in Figure 4.

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