Establishment of a Logistic Equation for Crop Biomass and Analysis of Interspecific Interaction in Wheat and Faba Bean Intercropping

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Abstract

Competition between intercropped species is important for yield advantage, but little attention has been given to interspecific competitive dynamics in intercropping. Two factors involving in planting patterns (wheat monocropped, faba bean monocropped, and wheat and faba bean intercropping) and P rates (P0, 0 kg P ha^{-1} (the control); P1, 45 kg P ha^{-1}; P2, 90 kg P ha^{-1}, respecively) were investigated. Wheat and faba bean were sampled at 10 and 11 times during the growing season each of two years, respectively and data were fitted to a logistic growth model. The results showed that the growth curve of wheat and faba bean almost overlapped for the different phosphorus levels, and there was no difference between monocropping and intercropping in the early growth stage of wheat and faba bean. Interspecific competition was dominant in wheat and faba bean intercropping, and intercropping did not result in biomass advantage (LER<1, K<1). Wheat growth rate was frequently stimulated and the intraspecific competition pressure of wheat was decreased after faba bean had attained its maximum growth rate (Tmax) at all P rates. Intercropping showed biomass and yield dominance (LER>1, K>1). In conclusion, because of the different competitive pressures of wheat and faba bean at different growth stages, the final crop growth performance was also different. Phosphorus level can maximize system productivity by regulating crop interspecific interactions.

Key words: wheat and faba bean intercropping; growth pattern; species interaction; P fertilizer

Introduction

Diversity within planting patterns can improve soil biodiversity and ecosystem services, such as rotation, intercropping and mixing [1,2]. Therefore, traditional intercropping patterns have attracted considerable attention in recent years [3]. Intercropping patterns involving leguminous crops are widely distributed around the world, because of legume crops can reduce greenhouse gas emissions by biological mechanisms [4,5]. Li and other researchers described the yield and nutrient absorption and utilization advantages of legume and cereal intercropping systems [6,7], but the formation of intercropping advantages was regulated by many factors, such as the density of sowing, the relative sowing time, the amount of fertilizer and the characteristics of the crops [8].

In a legume/cereal intercropping systems, nitrogen fixed by legumes can be transferred to the gramineous crops, thus increasing the nitrogen use efficiency of intercropping [9,10]. Therefore, research on legume/cereal intercropping has been carried out in depth and systematically, in terms of examining nitrogen uptake, utilization and transformation, for many years. Consequently, many studies have shown that the interspecific interaction between legumes and cereals promotes the activation of hard soluble phosphorus in soil, and improves the absorption of phosphorus. This activation can be regulated by the application level of phosphate fertilizer. However, it is not clear as to how the level of phosphate fertilizer can regulate the interspecific interactions of legumes How is it possible to optimize the application level of phosphate fertilizer, to promote inter species complementarity and improve the yield effect of an intercropping population. These question has not attracted widespread attention.

Wheat/faba bean intercropping is a traditional cropping pattern in the Southwest of China, and it is widely adopted in many other regions [11,12]. Dong Yan [13] and other studies showed that wheat/faba bean intercropping could inhibit the occurrence of faba bean wilt, thereby significantly increasing the yield of wheat [14], also improving the mineral nutrient status of the soil and the nutrient environment of the rhizosphere [15]. A number of recent studies on wheat/faba bean intercropping have been carried out [16,17], but few have systematically explored the crop growth patterns of wheat/faba bean intercropping under different phosphorus levels. It is not clear how phosphorus level regulates interspecific interactions between wheat and faba bean. To investigate these factors, field experiments of wheat and faba bean intercropping at different P levels were conducted to identify growth parameters, species interaction indices, and the optimal P dose for maximising intercropping system productivity. The results of this study could be helpful to further understand crop performance as related to interspecific competition and to provide guidance for optimal P management in legume-based intercropping.

Materials and methods

Experiment site

The field site was established at the Yunnan Agricultural University research station in 2014 at Xundian (N 23°32′, E 103°13′, altitude 1953m), located 75 km to the northeast of Kunming City, Yunnan Province, China. The average temperature at the site is14.7°C, with annually rainfall being approximately 1040 mm. Corn was planted in the field from May to September in the previous year before the establishment of this experiment. The average monthly temperature and rainfall during the trial period are presented in Table1. The soil at the 0–30 cm depth has a clay content of 34%, a silt content of 52%, and a sand content of 14%, with soil bulk density of 1.38 g cm^{-3}. The soil at this site is a cultivated red soil of pH 7.2 with an organic C content of 20.6 g kg^{-1}. The available N (NaOH hydrolyzed), P (Olsen-P), and K (NH_4OAc-exchangeable) were 80 mg kg^{-1}, 17 mg kg^{-1}, and 146 mg kg^{-1}, respectively.

Experimental design and crop management

The field experiment design was completely randomized. The design included three kinds of planting patterns (wheat single cropping, broad bean single cropping, wheat and broad bean intercropping) and three phosphorus application levels (P0, P1, P2 respectively; P0 was no phosphorus application, P1 indicates that phosphorus application (P_2O_5) was 45 kg ha^{-1}; P2 indicates a phosphorus application (P_2O_5) of 90 kg ha^{-1}). A total of nine treatments were included, and three replications were used for each treatment. There were 27 test plots, each with an area of 5.4 × 6 = 32.4 m^2. The wheat variety was Yun Mai -52 and the faba bean variety was Yuxi big grain bean.

Table 1. The monthly average temperature and rainfall during the field experimentation of 2016 and 2017

Month	Temperature (℃)		Rainfall (mm)	
	2015-2016	2016-2017	2015-2016	2016-2017
Oct	16.9	17.1	106.2	88.6
Nov	14.1	13.2	19.3	53
Dec	9.2	10.5	26.3	6.4
Jan	9.4	9.5	54.2	8.9
Feb	11.5	10.5	18.7	18.8
Mar	17.1	12.5	39.8	27
Apr	18.7	15.5	48.9	61.6

Sample collection

All the plots are divided into three bands, and the wheat and faba bean in the middle strip was used to determine crop yield during the harvest period; the other two strips of wheat and faba bean were used for sampling at different growth stages. During the whole growth period, 11 and 10 sampling times for wheat and faba bean, respectively, were used each year. All the samples were desiccated for 30 min at 105℃, and then dried in a 70 °C to determine dry weight.

Data collection

Simulation of crop growth

The shoot biomass for the whole growing season was fitted to a logistic growth curve using Nonlinear Least Square Function [18,19].

$$y = \frac{A}{1+exp(r\times(Tmax-t))} \quad (1)$$

where y (kg ha^{-1}) was the shoot biomass produced at t days after emergence during the growing season. A (kg ha^{-1}) represented the maximum shoot biomass production, r (d^{-1}) was the initial growth rate, and Tmax (d) was the time needed for the crop to attain the maximum instantaneous growth rate in Eq. (1). All these parameters were estimated using the Slogistic1 procedure of the OriginPro8 software.

Assessment of species interaction

(1) Land equivalent ratio (LER)

Land equivalent ratio (LER) was used to measure the intercropping advantage in this study. It was calculated using the following equation:

$$LER = RYw+RYb = \frac{Yintw}{Ymonow} + \frac{Yintb}{Ymonob} \quad (2)$$

where RYw and RYb represented the relative yield of the intercropping wheat and faba bean, respectively. A value of LER higher than 1.0 indicated an intercropping yield or biomass advantage over the corresponding monocropping, and vice versa [20].

(2) Relative interspecific competitiveness (RC)

Relative interspecific competitiveness (RC) was used to determine the resource competitiveness for a given crop combination in intercropping, which was calculated according to grain yield and biomass production using the following equation:

$$RC = \frac{Yintw}{Ymonow \times Pw} - \frac{Yintb}{Ymonob \times Pb} \qquad (3)$$

In Eq. (3), if the value of RC >0, it indicates that the competitiveness of intercropped wheat was greater than that of intercropped faba bean, and vice versa [20].

(3) Relative competition intensity（RCI）

Relative competition intensity (RCI) indicates the competitive ability of a given crop combination. It could be calculated according to grain yield or biomass production under a given crop combination. RCI was calculated as follows:

$$RCIw = \frac{Pw \times Ymonow - Yintw}{Pw \times Ymomow} \qquad (4)$$

$$RCIb = \frac{Pb \times Ymonob - Yintb}{Pb \times Ymonob} \qquad (5)$$

In Eqs. (4)-(5), a value of RCI = 0 indicated that the interspecific competition equaled the intraspecific competition, while the value of RCI>0 indicated that the interspecific competition was higher, and a value of RCI <0 indicated that the intraspecific competition was higher [21].

Statistical analysis

Data were analyzed using Statistical Analysis Software (SPSS Inc., Chicago, IL, USA) with the two-factor design analytical method to test for the significance of treatments. Planting pattern and P levels were considered as fixed factors and replication as a random factor. Independent sample T test (P=0.05) was performed on the dynamic growth rate between inter- and mono-cropped wheat or faba bean at the same P application rate.

Results

Dynamic growth rate

During the two years of the experiment, the times for wheat and faba bean to reach peak of growth were different at P1 and at P2 with the growth peaks of faba bean and wheat occuring at 60 days and 75 days, respectively (Fig.1 (b), (c), (e), (f)). The time that both wheat and faba bean reached a peak of growth was at about 75 days at P0 (Fig. 1 (a), (d)). The growth curve of wheat and faba bean almost overlapped in the early growth stage (from sowing to 45-60 days after emergence) at different P levels (Fig. 1). However, the growth rate of intercropped wheat was inhibited (Fig. 1) compared with that of monocropped wheat at 15-45 days after emergence, while the growth rate of intercropped faba bean was significantly lower than monocropping faba bean in the early stages of growth at the P2 level (Fig. 1 (c), (f)).

The growth of inter- and mono-cropped faba bean was substantially slowed down, approximately 60 days after faba bean emerged, but no differences were found in the growth rates between IB and MB from then till harvest in the two years of experiments under P0 .In contrast, the growth rate of intercropped faba bean was significantly higher than that of monocropping faba bean at 60p and 75 days under the P1 treatment. The growth rate of intercropped faba bean under P2 treatment was significantly higher than that of monoculture bean in the 60-105 day period. In contrast, the growth rate of wheat greatly exceeded that of faba bean once faba bean attained its Rmax through until harvest (Fig. 1). The growth rate of IW was constantly stimulated ($P<0.05$) ranging from 60 to 105 days after the time of wheat emergence at all P levels.

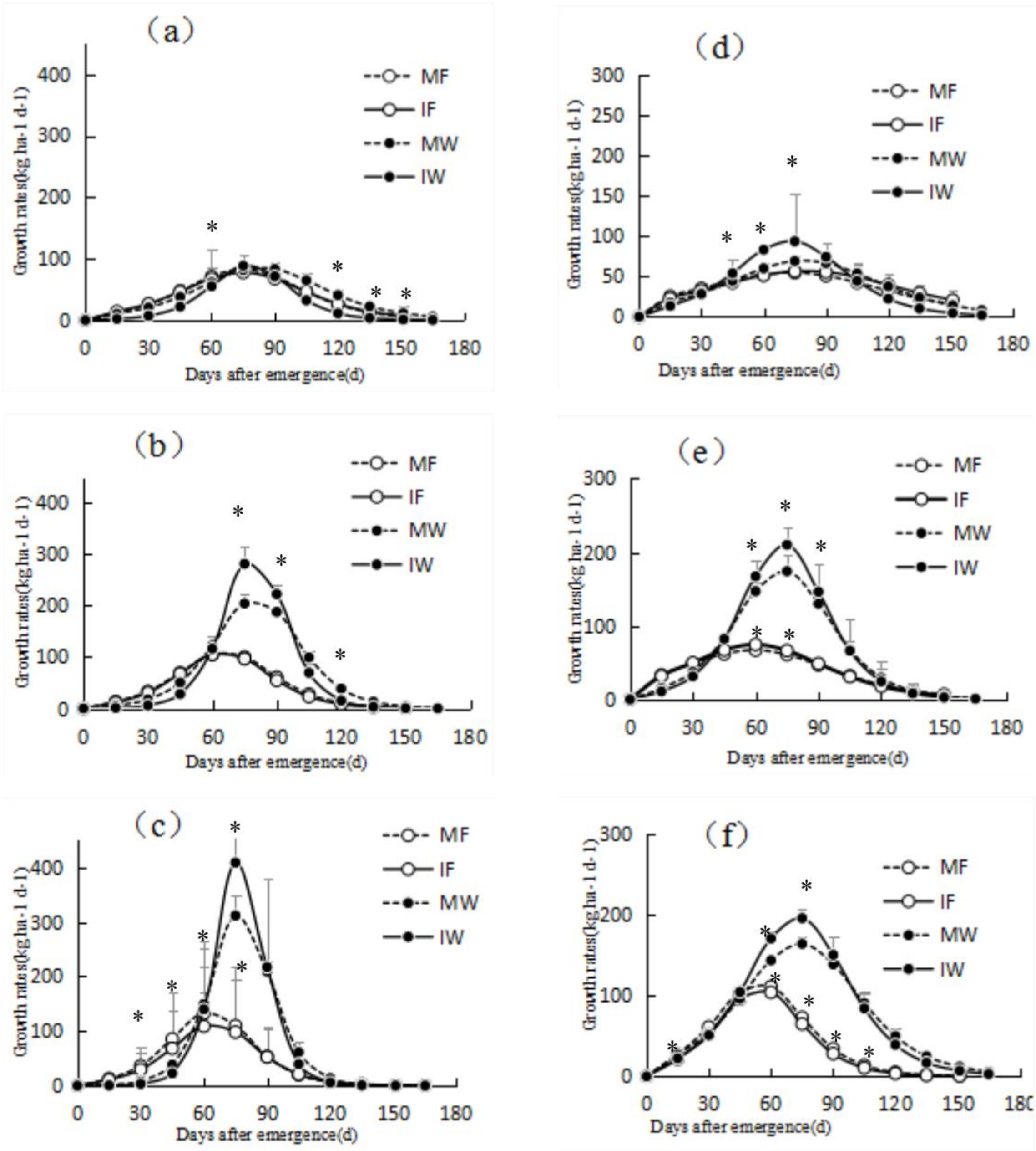

Fig. 1. Dynamic growth rate of wheat and faba bean during their co-growing season under different P levels in the experiments of 2016 and 2017..MW and MF respectively represented monoculture wheat and faba bean, and IW and IF respectively represented intercropping wheat and faba bean. (a), (b), (c), dynamic growth rate of wheat and faba bean during their co-growing season at P0, P1and P2 levels in the experiment of 2016, respectively; (d), (e), (f), dynamic growth rate of wheat and faba bean during their co-growing season at P0, P1and P2 levels in the experiment of 2017, respectively. * means significant difference between inter- and mono- cropped wheat or faba bean at the same sampling date at P<0.05.

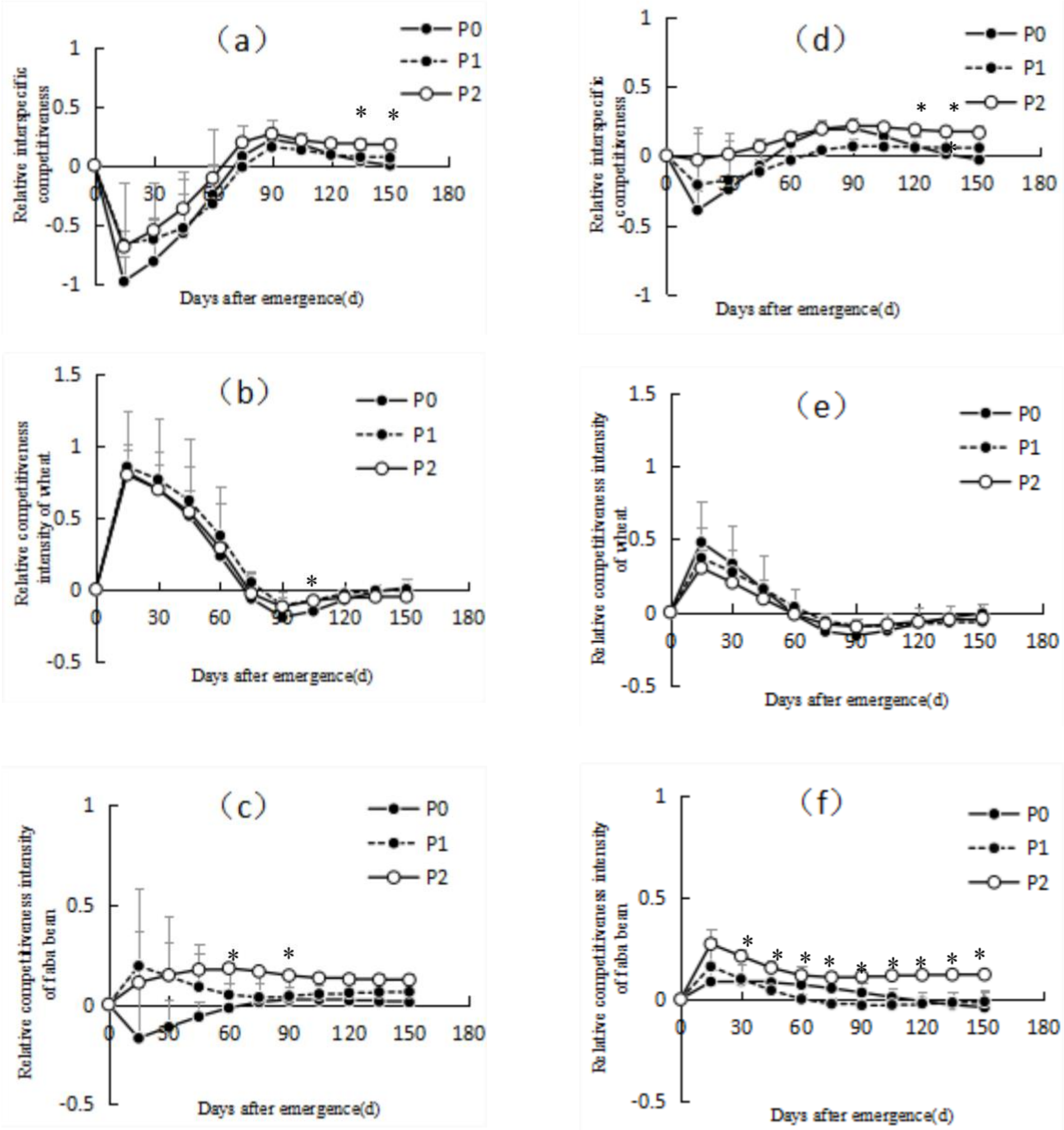

Fig. 2. Dynamic relative competition of wheat to faba bean, and relative competition intensity of wheat and faba bean under different P levels in intercropping based on per capital biomass production during their co-growing season in the experiments of 2016 and 2017.(a), (d), Relative competition of wheat to faba bean under different P levels in intercropping based on per capital biomass production during their co-growing season in the experiments of 2016 and 2017, respectively; (b), (e), Relative competition intensity of wheat under different P levels in intercropping based on per capital biomass production during their co-growing season in the experiments of 2016 and 2017, respectively; (c), (f), Relative competition intensity of faba bean under different P levels in intercropping based on per capital biomass production during their co-growing season in the experiments of 2016 and 2017, respectively. * means significant difference among different P levels at the same sampling date at P<0.05.

Species competition

The relative interspecific competitiveness (RC) between wheat and faba bean in the intercropping system changed during the co-growing season. In 2016, the competitive ability of intercropping wheat at three phosphorus levels after emergence to 60 days was lower than that of intercropping faba bean (RC<0). The competition between wheat and faba bean increased from 60 to 90 days, but slowed down during the period from 90 days after wheat and faba bean emergence till harvest (RC>0). The RC of wheat and faba bean at P2 was significantly higher than that of P0 and P1 at days 135 and 150 (Fig. 2 (a)). In 2017, the competitive ability of intercropping wheat at P0 and P1was lower than that of faba bean (RC<0) after emergence to 45 days. The competition of wheat and faba bean increased from 45 to 90 days after wheat and faba bean emergence, while competition slowed down during the period from 90 days until harvest (RC>0). Phosphorus levels had a significant effect on the relative interspecific competitiveness of wheat and faba bean at 75 and 90 days (Fig. 2 (d)).

Two years of experiments showed that the RCIw of wheat decreased with the growth of wheat (Fig. 2 (b), (e)). Obviously, the interspecific competition of wheat was higher than that of intraspecific competition (RCIw>0) at the early stage of growth.Intraspecific competition of intercropping wheat was higher than that of interspecific competition (RCIw<0) from 75days after emergence till harvest except for the sampling date 135days and 150days under P0 and P2, respectively, in 2016.

The RCIb of the intercropped faba bean also changed during growth. The interspecific competition intensity of faba bean was higher than that of intraspecific competition (RCIb>0) except for some individual sampling periods (Fig. 2 (c), (f)). RCIb was regulated by phosphorus level. The RCIb of faba bean at P2 was higher than that of P0 and P1. In 2016, the value of RCIb increased with the increase of the application amount of phosphate fertilizer from sowing until 30 days. At 60, 90 and 135 days, the RCIb at P2 was significantly higher than that of P0 and P1 (Fig. 2 (c)). In the early and late growth stages of the growth of wheat and faba bean in 2017, the value of RCIb increased with an increase in the application amount of phosphate fertilizer from sowing to 30 days and from 120-150 days. The RCIb was significantly higher in P2 than in either the P0 or the P1 treatment (Fig. 2. (f)).

Discussion

In this study, the logistic equation closely estimated the key growth parameters of the two crops. Although there was a similar growth period between wheat and faba bean, the growth curve of the crop was separated in the middle and late growth stages of both wheat and faba bean because of the difference of Tmax and the growth peak (Fig.1). Zhang indicated that when a crop interacts with another crop, its Tmax should be different [18]. Therefore, wheat and faba bean have clear intercropping patterns. Intercropping significantly increased wheat Rmax, and phosphorus application significantly increased wheat A and Rmax (Fig.1), indicating that intercropping and application of phosphate fertilizer could help to increase wheat biomass [22]. This study showed that wheat reached Rmax 75 days after emergence, while faba bean reached it 60 days after emergence (Fig.1), indicating that in intercropping, the Tmax of intercropped crops was different [22]. The utilization of nutrient resources in intercropping crops was separated in time, so this time niche differentiation reduced interspecific competition and increased the uptake of nutrient resources by the intercropping crops [23]. This may be the main factor in the wheat/faba bean intercropping that provides a yield advantage. The temperature and rainfall during the experiment period (Table 1) showed that the monthly mean temperature between November 2015 and September 2016 was higher than that between November 2016 and September 2017. Katerji indicated that faba bean is highly sensitive to temperature [24]. When wheat and faba bean are intercropped, the root growth and nodule formation in faba bean will change with rainfall [25]. Therefore, different climatic conditions may be the reason for the differences that occurred in the two years of this study. Of course, other environmental factors such as moisture, radiation or crop management measures may also influence the results that were obtained. The effects of phosphorus level, planting pattern, and their interaction on the growth parameters of intercropping wheat and faba bean should be further studied.

In this study, wheat was dominant in the middle and later stages of growth, which is consistent with results found in previous studies [26]. In the early stage of growth, interspecific competition was the main type of wheat/faba bean intercrop interaction (RCIw>0),(RCIb>0) (except for the P1 treatment in 2016) (Fig. 2), so there was no intercropping advantage (LER<1, K<1) ,which is in accordance with the results of Xiao's study [27]. By contrast, intraspecific competition was higher than interspecific competition during the mid and later periods of wheat growth (RCIw<0) (Fig. 2), except for the 135-150 day period at P0 and P1 levels in 2016. Hu found that an improvement of interspecies competition coordination could improve the productivity in a maize/pea intercropping system [28]. However, our results show that there is always a high interspecific competition in faba bean and that the growth rate is low in the early growth stage (Figs.1&2). Intercropping can reduce intraspecific competition in wheat, which makes the growth rate of wheat was higher in the middle and late stages of growth (Figs. 1&2). These results indicate that crops performance were related to interaction between legume and cereal.

Interspecific competition for nutrient resources has been the subject of previous studies [6,29]. The application of phosphorus in a wheat/faba bean intercropping system has been shown to increase the competitive ability of wheat [30]. In this study, wheat had a growth advantage in the middle and late growth stages of intercropped wheat and faba bean. In the early growth of wheat and faba bean, the competitiveness of the intercropped faba bean under P0 was higher than that of P1 and P2, which indicated that the application of phosphate fertilizer reduced the competitive ability of the faba bean. However, as the amount of phosphorus increased, the competitiveness of wheat was stronger than that of faba bean (Fig2 (a)(d)). Our results, therefore, confirm that the performance of legume and cereal is closely related to phosphate fertilizer in the intercropping system. Our research also found that there were interspecific interactions between wheat and faba bean during symbiosis. The responses of interspecies interactions to phosphorus were different depending on the growth period. The values of RCIw and RCIb were almost 0 from 60-75 days after emergence and biomass advantages of intercropping were found (Fig. 2). In the critical growing stage of intercropped wheat and faba bean, it is feasible to regulate the interactions between species and improve the advantage of intercropping populations. The dynamic growth curve of wheat and broad bean under different phosphorus levels simulated by the logistic equation showed that the competitiveness of wheat and faba bean at different growth stages was different. The growth curve was different and LER and K were different at different growth stages. Therefore, optimizing the application of phosphate fertilizer with intercropping can regulate interspecific interactions. These results show that due to interspecific interaction, phosphorus reduction does not reduce the yield of wheat or faba bean, indicating that the application of phosphate fertilizer in the intercropping population of wheat/faba bean has an optimized space.

Conclusions

The relative competition intensity of faba bean was higher during the early stage of wheat and faba bean development. Wheat and faba bean were mainly affected by interspecific competition and there was no significant difference in growth rate between mono- and inter-cropping for either wheat or faba bean. The relative competitive intensity of wheat was higher than that of faba bean in the middle and later growth stages. The intraspecific competition of wheat was dominant and the growth rate was significantly improved. However, interspecific competition of faba bean was dominant and the growth rate of faba bean decreased.

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