

## Effects of Nitrogen Application on Yield and Nitrogen Utilization Characteristics of Wheat in Sole Cropping and Relay Intercropping Systems: Postprint

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### Abstract

Wheat/corn intercropping is the principal dryland farming system in Sichuan. Investigating nitrogen uptake and utilization efficiency of wheat and the effects of intercropped corn on wheat can help further elucidate the yield advantages of intercropped wheat, efficient nutrient utilization, and the interaction mechanisms between corn and wheat. This study examined through field experiments the yield, nitrogen uptake and utilization characteristics of wheat, and the effects of corn on wheat under different nitrogen levels [ $0 \text{ kg(N)} \cdot \text{hm}^{-2}$ ,  $60 \text{ kg(N)} \cdot \text{hm}^{-2}$ ,  $120 \text{ kg(N)} \cdot \text{hm}^{-2}$ , and  $180 \text{ kg(N)} \cdot \text{hm}^{-2}$ , denoted as N1, N2, N3, and N4, respectively] in three cropping patterns: wheat monoculture, wheat/fallow strip, and wheat/corn intercropping. The results showed that under different nitrogen treatments, wheat in wheat-corn intercropping consistently exhibited significant yield advantages compared to monoculture wheat, with biomass and grain yield increasing by 15.7% and 17.8% on average, respectively; the border row advantage of intercropped wheat was pronounced, with aboveground biomass, yield, nitrogen uptake, and partial factor productivity of nitrogen fertilizer in border rows increasing by 23.8%, 27.3%, 48.9%, and 19.1%, respectively, compared to monoculture rows, indicating that intercropped wheat had higher nitrogen utilization efficiency than monoculture wheat. Under no nitrogen (N1) and low nitrogen (N2) treatments, wheat biomass and yield in wheat/corn intercropping were on average 6.5% and 5.7% lower than in wheat/fallow strip pattern; however, at medium nitrogen level (N3), wheat yield, aboveground biomass, aboveground nitrogen uptake, and partial factor productivity of nitrogen fertilizer in wheat/corn intercropping were 14.1%, 5.0%, 6.8%, and 4.5% higher than in wheat/fallow strip pattern, respectively. This indicates that in wheat/corn intercropping, intercropping corn suppressed wheat growth when nitrogen application was insufficient, but promoted wheat growth when nitrogen application

was adequate. Therefore, intercropped wheat possesses border row advantage and yield advantage, and intercropping corn between wheat rows requires appropriate nitrogen fertilizer application to eliminate nitrogen competition between wheat and corn, thereby promoting wheat growth.

## Full Text

### Wheat Grain Yield and Nitrogen Use Characteristics under Monoculture and Intercropping with Different Nitrogen Fertilization Rates

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#### Abstract

Wheat/maize relay-intercropping system is an important rainfed planting pattern in Sichuan Province, China. Investigating rational nitrogen management strategies is crucial for improving productivity and nutrient use efficiency while exploring the yield advantage mechanisms of interactions between intercropped wheat and maize. A field experiment was conducted in 2014 involving four nitrogen application rates [ $0 \text{ kg} \cdot \text{hm}^{-2}$ ,  $60 \text{ kg} \cdot \text{hm}^{-2}$ ,  $120 \text{ kg} \cdot \text{hm}^{-2}$  and  $180 \text{ kg} \cdot \text{hm}^{-2}$ , denoted by N1, N2, N3 and N4, respectively] under three planting patterns at an experimental research base in Chongzhou, Sichuan. The planting patterns included wheat monoculture (W), wheat/maize strip relay-intercropping (W/M) and wheat/empty strip (W/E). Grain yield, biomass, nitrogen uptake, nitrogen use efficiency and partial factor productivity of nitrogen (PFP-N) of wheat were calculated.

The results showed that: (1) Intercropped wheat exhibited yield advantages over monoculture wheat under all nitrogen application rates, with aboveground biomass and grain yield averaging 15.7% and 17.8% higher than monoculture wheat, respectively. (2) Border row wheat demonstrated advantages in productivity, nitrogen uptake and nutrient use efficiency, with aboveground biomass, yield, nitrogen uptake and PFP-N 23.8%, 27.3%, 48.9% and 19.1% higher than monoculture wheat, respectively, suggesting that intercropped wheat achieved higher nitrogen use efficiency with greater grain yield compared to monoculture wheat. (3) Compared to the W/E pattern, aboveground biomass and grain yield of wheat under W/M pattern decreased by 6.5% and 5.7% under zero and  $60 \text{ kg} \cdot \text{hm}^{-2}$  nitrogen application treatments, respectively. However, under the medium nitrogen application rate (N3,  $120 \text{ kg} \cdot \text{hm}^{-2}$ ), grain yield, aboveground biomass, shoot nitrogen uptake and PFP-N of wheat under W/M were 14.1%, 5.0%, 6.8% and 4.5% higher than those under W/E, respectively. These results indicated that intercropped wheat may be inhibited by intercropped maize under low nitrogen application rates ( $<60 \text{ kg} \cdot \text{hm}^{-2}$ ), whereas wheat development

in intercropping could be promoted by sufficient nitrogen application. Furthermore, intercropped wheat exhibited advantages in grain yield and nutrient use efficiency, especially for border row plants. Although maize-wheat interactions enhanced this process, sufficient nitrogen fertilizer application was critical for promoting growth of relay-intercropped wheat.

**Keywords:** Wheat/maize relay-intercropping; Nitrogen management; Yield advantage; Border row advantage; Nitrogen uptake; Partial factor productivity of nitrogen

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Nitrogen is an essential nutrient element for plant growth and plays an irreplaceable role in ensuring stable food production. However, due to its high mobility, poor soil adsorption, susceptibility to leaching and transformation losses, and irrational application practices, nitrogen use efficiency in China is only about 30% [?], which adversely affects sustainable agricultural development [?, ?]. Therefore, rational nitrogen application and improving nitrogen use efficiency have become major scientific issues concerning national food security and environmental quality [?, ?]. Crop intercropping and relay-intercropping systems, based on differences in spatial distribution and nutrient requirements among different crops, can effectively utilize various growth factors such as light, temperature, water and nutrients to achieve high yield and efficiency [?, ?, ?]. These systems represent both the essence of traditional agriculture and play important roles in modern agriculture for resource-efficient, environmentally friendly and sustainable development. Compared with traditional monoculture, intercropping systems demonstrate significant yield advantages [?, ?]. Previous research has identified border row advantage as one reason for yield superiority in intercropped wheat [?], with underground interactions exerting greater influence than aboveground factors [?, ?].

Most wheat in Sichuan is grown in relay-intercropping systems, with wheat/maize relay-intercropping being the predominant dryland farming system in the Sichuan-Chongqing region. Studies on nitrogen transfer and utilization [?], effects of different phosphorus levels on leaf area index, dry matter accumulation dynamics and phosphorus use efficiency in maize [?], and nitrogen accumulation, distribution and translocation in wheat/maize/soybean annual relay-intercropping systems [?] have shown that in wheat/maize/soybean and wheat/maize/sweet potato systems, non-separated root systems increased wheat  $^{15}\text{N}$  total uptake and  $^{15}\text{N}$  crop recovery rate compared to separated root systems. Interspecific competition-promotion relationships and nitrogen transfer existed in both systems, with wheat/maize/soybean being more conducive to fertilizer nitrogen absorption than wheat/maize/sweet potato [?]. Appropriate phosphorus application in wheat/maize/soybean intercropping systems promoted maize growth, reduced wheat's impact on maize, and improved phosphorus use efficiency in maize [?]. Nitrogen accumulation in all wheat parts increased with nitrogen application rate, and the amount and contribution rate of nitrogen transferred from vegetative organs to grain

after anthesis increased with nitrogen application, though transfer efficiency did not differ significantly among nitrogen treatments. With increasing nitrogen application, the proportion of nitrogen distributed to grain gradually decreased while that to non-grain parts increased. Low nitrogen treatment significantly affected yield and nitrogen absorption in relay-intercropped wheat, maize and soybean, while high nitrogen input caused nitrogen to remain in vegetative organs, hindering its post-anthesis transfer to grain [?]. Research concluded that the annual nitrogen application rate of 255–382.5 kg · hm<sup>-2</sup> was appropriate for wheat/maize/soybean systems, including 120–180 kg · hm<sup>-2</sup> for wheat, 195–292.5 kg · hm<sup>-2</sup> for maize, and no or minimal nitrogen application for soybean based on seedling conditions [?]. However, research on yield advantage mechanisms and nitrogen regulation management in relay-intercropped wheat remains limited, particularly regarding questions such as: Does intercropped maize affect wheat, and if so, to what extent? How does this response vary under different nutritional conditions? This study investigated wheat yield and nitrogen uptake characteristics under different nitrogen levels in three planting patterns—wheat monoculture, wheat/maize relay-intercropping, and wheat/empty strip—to provide a basis for better utilizing wheat relay-intercropping advantages and improving nitrogen use efficiency for high yield and efficiency.

## 1.1 Experimental Site

The experiment was conducted from October 30, 2013 to May 6, 2014 at the Chongzhou Modern Agricultural Experiment and Demonstration Base of Sichuan Agricultural University (103.6°E, 30.6°N). Chongzhou has a subtropical humid monsoon climate of the Sichuan Basin, characterized by distinct seasons, abundant rainfall, low sunshine and a long frost-free period. The annual average temperature is 15.9°C, with the hottest month (July) averaging 25°C and the coldest month (January) averaging 5.4°C, giving a temperature difference of 19.7°C. Annual average sunshine hours are 1,161.5 h and annual average precipitation is 1,012.4 mm, with both rainy days and rainfall being more frequent in summer than winter (spring: 176.1 mm, summer: 588.0 mm, autumn: 218.4 mm, winter: 29.9 mm). The experimental soil was a paddy soil with loam texture. Before cultivation, the topsoil (0–20 cm) had a pH of 6.3, organic matter content of 37.6 g · kg<sup>-1</sup>, total nitrogen of 2.03 g · kg<sup>-1</sup>, alkaline hydrolyzable nitrogen of 136 mg · kg<sup>-1</sup>, available phosphorus of 20.4 mg · kg<sup>-1</sup>, and available potassium of 101 mg · kg<sup>-1</sup>.

## 1.2 Experimental Materials

The wheat cultivar used was ‘Shumai 969’, a high-quality and disease-resistant variety bred by the Wheat Research Institute of Sichuan Agricultural University. Maize cultivar ‘Chuandan 418’, a recommended excellent variety in Sichuan Province and by the Ministry of Agriculture, was bred by the Maize Research Institute of Sichuan Agricultural University. Fertilizers used were urea (46%

N), calcium superphosphate (12%  $P_2O_5$ ) and potassium chloride (60%  $K_2O$ ), all purchased from local agricultural suppliers.

### 1.3 Experimental Design

A two-factor split-plot design was employed, with nitrogen application level as the main plot factor and planting pattern as the subplot factor. Wheat received four nitrogen (N) levels:  $0 \text{ kg} \cdot \text{hm}^{-2}$  (N1),  $60 \text{ kg} \cdot \text{hm}^{-2}$  (N2),  $120 \text{ kg} \cdot \text{hm}^{-2}$  (N3) and  $180 \text{ kg} \cdot \text{hm}^{-2}$  (N4). Maize received four nitrogen (N) levels:  $0 \text{ kg} \cdot \text{hm}^{-2}$  (MN1),  $90 \text{ kg} \cdot \text{hm}^{-2}$  (MN2),  $180 \text{ kg} \cdot \text{hm}^{-2}$  (MN3) and  $270 \text{ kg} \cdot \text{hm}^{-2}$  (MN4). Phosphorus and potassium were applied at consistent and adequate rates across all treatments.

Three planting patterns were established: wheat monoculture (W), wheat/maize relay-intercropping (W/M), and wheat/empty strip (W/E), arranged randomly in the field with three replications per treatment. Wheat planting specifications were identical in W/M and W/E patterns.

Each plot measured  $5 \text{ m} \times 6 \text{ m}$  ( $30 \text{ m}^2$ ) with a width of 6 m. Wheat was drill-seeded on October 30, 2013 at a seeding rate of  $180 \text{ kg} \cdot \text{hm}^{-2}$  with 20 cm row spacing. Monoculture wheat plots contained 30 rows [Figure 1: see original paper]A. In relay-intercropping plots, both wheat and maize strips were 1 m wide, with each wheat strip containing 5 wheat rows and a 1 m interval reserved for relay-intercropped maize (gap). This created a 1 m/1 m field configuration, with three wheat strips per plot. Maize was planted in the reserved gaps during wheat heading and flowering stage (March 25, 2014) using seedling lumps. Maize seedlings were transplanted at the two-leaf and one-heart stage (April 8, 2014) with 50 cm row spacing and 38 cm hill spacing, with two plants per hill, giving a planting density of  $52,500 \text{ plants} \cdot \text{hm}^{-2}$  [Figure 1: see original paper]B. In wheat/empty strip patterns, no maize was planted in the reserved gaps [Figure 1: see original paper]C.

For wheat, 60% of nitrogen and all phosphorus and potassium fertilizers were applied in 5 cm deep furrows at sowing, followed by seeding and soil covering; the remaining 40% of nitrogen was topdressed at the tillering stage using a modified sprayer, followed by irrigation to facilitate nitrogen uptake. For maize, 30% of nitrogen and all phosphorus and potassium were applied in holes at transplanting, covered with soil before seedling placement; additional nitrogen was topdressed at the jointing and tasseling stages (30% and 40%, respectively), dissolved in water and applied near plants. Wheat was harvested on May 6, 2014 for yield measurement.

### 1.4 Measurements and Calculations

#### 1.4.1 Dry Matter Accumulation and Nutrient Content

At harvest, representative wheat plants with uniform growth were selected from sampling areas. A 40 cm plant sample was collected: monoculture wheat from

the middle two rows [Figure 1: see original paper]A, and relay-intercropped wheat (both W/M and W/E) from all rows in the planting strip, which were then combined into border row, inner row and middle row samples [Figure 1: see original paper]B, C. Samples were separated into aboveground straw (including stems, leaves and glumes) and grain, oven-dried and weighed to calculate dry matter weight. Samples were ground to pass a 60-mesh sieve, and nitrogen content was determined using the Kjeldahl semi-micro distillation method [?].

#### 1.4.2 Yield Measurement

For yield determination, the middle four rows were harvested in monoculture wheat plots, while the middle planting strip (5 rows) was harvested in relay-intercropped wheat (W/M and W/E), separating border, inner and middle rows. Grain was threshed using a thresher, sun-dried and weighed to obtain actual grain yield.

#### 1.4.3 Index Calculations

Plant aboveground nitrogen uptake ( $\text{kg} \cdot \text{hm}^{-2}$ ) =  $\Sigma(\text{aboveground organ biomass at harvest} (\text{kg} \cdot \text{hm}^{-2}) \times \text{organ nitrogen content} (\text{g} \cdot \text{kg}^{-1}))$  (1)

Nitrogen harvest index (%) =  $(\text{grain nitrogen uptake} / \text{plant aboveground nitrogen uptake}) \times 100\%$  (2)

Nitrogen physiological use efficiency ( $\text{kg} \cdot \text{kg}^{-1}$ ) =  $(\text{grain yield in nitrogen-applied area} - \text{grain yield in no-nitrogen area}) / (\text{aboveground nitrogen uptake in nitrogen-applied area} - \text{aboveground nitrogen uptake in no-nitrogen area})$  (3)

Nitrogen agronomic use efficiency ( $\text{kg} \cdot \text{kg}^{-1}$ ) =  $(\text{grain yield in nitrogen-applied area} - \text{grain yield in no-nitrogen area}) / \text{nitrogen application rate}$  (4)

Partial factor productivity of nitrogen fertilizer ( $\text{kg} \cdot \text{kg}^{-1}$ ) =  $\text{grain yield} / \text{nitrogen application rate}$  (5)

### 1.5 Data Processing

For convenient comparison, biomass and yield indices of monoculture and relay-intercropped wheat in this study were calculated based on the actual occupied area of planting strips. All data were processed using Microsoft Excel 2010 and analyzed statistically using SPSS 13.0 software.

### 2.1 Changes in Wheat Biomass under Different Nitrogen Application Rates

As shown in Table 1, nitrogen application rate and planting pattern had extremely significant effects on wheat biomass ( $P < 0.01$ ), but no significant interaction effect was observed between nitrogen level and planting pattern ( $P > 0.05$ ).

With increasing nitrogen application, aboveground biomass of both monoculture and relay-intercropped wheat showed a trend of increasing first then decreasing, reaching maximum values at N3 treatment. Biomass did not increase further when nitrogen application exceeded  $120 \text{ kg} \cdot \text{hm}^{-2}$ . Under different nitrogen treatments, aboveground dry matter accumulation of relay-intercropped wheat was higher than that of monoculture wheat, increasing by 11.9%, 17.7%, 19.8% and 13.6% at N1-N4, respectively.

Biomass of different rows in relay-intercropped wheat showed a clear pattern: border row > inner row > middle row. Middle row biomass was essentially equal to that of monoculture rows, while border row biomass was 9.6% and 22.0% higher than inner and middle rows, respectively, and 18.4%-34.6% higher than monoculture rows. This indicates that the biomass advantage of relay-intercropped wheat primarily originated from border rows. Comparison between wheat/maize and wheat/empty strip patterns showed different responses under various nitrogen treatments: at N1, N2 and N4, wheat/maize reduced wheat biomass by 7.6%, 5.3% and 12.2% compared to wheat/empty strip, but at N3, wheat/maize increased biomass by 5.0% compared to wheat/empty strip.

## 2.2 Changes in Wheat Grain Yield under Different Nitrogen Application Rates

As shown in Table 2, nitrogen application and planting pattern had extremely significant effects on wheat grain yield ( $P < 0.01$ ), with no significant interaction effect between nitrogen level and planting pattern ( $P > 0.05$ ). Grain yield trends were generally consistent with biomass trends, increasing first then decreasing with nitrogen application, reaching maximum values at N3 for monoculture and relay-intercropped wheat. Grain yield did not increase further when nitrogen application exceeded  $120 \text{ kg} \cdot \text{hm}^{-2}$ . However, grain yield of wheat/empty strip treatment showed an increasing trend with nitrogen application, reaching maximum at N4. Under different nitrogen treatments, relay-intercropped wheat showed obvious yield advantages over corresponding monoculture wheat, increasing by 14.06%, 20.66%, 21.29% and 15.24% at N1-N4, respectively.

Grain yield of different rows in relay-intercropped wheat followed the pattern: border row > inner row > middle row. Middle row grain yield was essentially equal to monoculture rows, while border row grain yield was 12.38% and 18.80% higher than inner and middle rows, respectively, and 20.03%-35.00% higher than monoculture rows. This demonstrates that relay-intercropped wheat had clear yield advantages primarily derived from border row advantages. Comparison between wheat/maize and wheat/empty strip patterns showed varied responses: at N1, N2 and N4, wheat/maize reduced grain yield by 8.33%, 3.13% and 4.51% compared to wheat/empty strip, but at N3, wheat/maize increased grain yield by 14.13% compared to wheat/empty strip.

Table 3 shows that harvest index of both monoculture and relay-intercropped wheat was highest at N1 and decreased with increasing nitrogen application.

Under different nitrogen treatments, harvest index of relay-intercropped wheat in wheat/maize treatment was 6.41%, 5.47%, 3.60% and 1.22% higher than monoculture wheat, respectively.

### 2.3 Nitrogen Accumulation and Use Efficiency in Wheat under Different Nitrogen Application Rates

As shown in Table 4, nitrogen application rate and planting pattern had extremely significant effects on wheat nitrogen accumulation ( $P < 0.01$ ), with no significant interaction effect between nitrogen level and planting pattern ( $P > 0.05$ ). Nitrogen accumulation in monoculture and relay-intercropped wheat increased first then decreased with nitrogen application, reaching maximum at N3 and not increasing further when nitrogen application exceeded  $120 \text{ kg} \cdot \text{hm}^{-2}$ . However, nitrogen accumulation in wheat/empty strip treatment showed an increasing trend with nitrogen application, reaching maximum at N4. Under different nitrogen conditions, nitrogen accumulation in relay-intercropped wheat increased by 22.04%, 32.11%, 37.55% and 25.47% compared to monoculture wheat. Nitrogen accumulation in different rows of relay-intercropped wheat also showed border row  $>$  inner row  $>$  middle row trends. Middle row nitrogen accumulation was essentially equal to or slightly higher than monoculture rows, while border row nitrogen accumulation was 20.66% and 36.65% higher than inner and middle rows, respectively, and 39.00%-63.61% higher than monoculture rows. Comparison between wheat/maize and wheat/empty strip patterns showed different responses: at N1, N2 and N4, wheat/maize reduced nitrogen accumulation by 15.66%, 11.05% and 16.14% compared to wheat/empty strip, but at N3, wheat/maize increased nitrogen accumulation by 6.77%.

Table 5 shows that nitrogen harvest index of both monoculture and relay-intercropped wheat decreased with increasing nitrogen application, being highest at N1. Compared to monoculture wheat, nitrogen harvest index of relay-intercropped wheat in wheat/maize treatment was 2.17% and 5.56% higher at N1 and N2, but lower at N3 and N4. Comparison between wheat/maize and wheat/empty strip patterns showed varied responses: at N1, wheat/maize reduced nitrogen harvest index by 3.29% compared to wheat/empty strip, but at N3, wheat/maize increased nitrogen harvest index by 2.33%.

Wheat nitrogen use efficiency is presented in Table 6. Nitrogen application rate had extremely significant effects on nitrogen physiological efficiency and partial factor productivity ( $P < 0.01$ ), but no significant effect on nitrogen agronomic use efficiency ( $P > 0.05$ ). Planting pattern had no significant effects on nitrogen physiological efficiency or agronomic use efficiency ( $P > 0.05$ ), but had extremely significant effects on partial factor productivity ( $P < 0.01$ ). No significant interaction effects were observed between nitrogen level and planting pattern ( $P > 0.05$ ). From N2 to N4, nitrogen physiological efficiency, agronomic efficiency and partial factor productivity of both monoculture and relay-intercropped wheat decreased with increasing nitrogen application, indicating that increased nitrogen application significantly reduced nitrogen use efficiency. Except for the high

nitrogen N4 treatment, nitrogen agronomic efficiency and partial factor productivity at N2 and N3 followed the order  $W/M > W/E > W$ . Overall, nitrogen physiological efficiency, agronomic efficiency and partial factor productivity of relay-intercropped wheat were significantly higher than those of monoculture wheat, with nitrogen physiological efficiency of W/M and W/E being 9.09% and 2.87% higher than W, nitrogen agronomic efficiency of W/M and W/E being 56.18% and 19.10% higher than W, and partial factor productivity of W/M and W/E being 19.91% and 23.71% higher than W, respectively. No significant differences were observed between W/M and W/E in nitrogen physiological efficiency, agronomic efficiency or partial factor productivity, indicating that nitrogen use efficiency of relay-intercropped wheat was significantly higher than that of monoculture wheat.

### 3 Discussion and Conclusion

Crop intercropping represents both the essence of traditional agriculture and a primary measure for high yield and efficiency in modern agriculture. Numerous studies have demonstrated that intercropping benefits crop yield stability and increase while improving resource use efficiency, showing obvious yield advantages [?, ?, ?]. Qi et al. [?] and Fan et al. [?] also found that relay-intercropped wheat in Sichuan showed yield and border row advantages over monoculture wheat. In this study, border row biomass and grain yield of relay-intercropped wheat were 23.81% and 27.27% higher than monoculture rows on average, while yield, biomass and harvest index of relay-intercropped wheat increased by 17.81%, 15.74% and 4.18% compared to monoculture wheat, respectively. Additionally, under different nitrogen treatments, aboveground nitrogen accumulation, grain nitrogen accumulation and partial factor productivity of nitrogen in wheat/maize systems were significantly higher than in monoculture wheat, increasing by 48.91%, 32.63% and 19.08% on average, respectively. These advantages in yield and nutrient efficiency resulted from higher biomass, nitrogen uptake and nitrogen use efficiency in border rows compared to inner and middle rows.

In the Sichuan wheat/maize relay-intercropping system, maize is planted into wheat rows during wheat heading and flowering stage. Although the co-growth period is only about 40 days and maize is planted between wheat rows, with maize at the jointing stage (6-8 leaf stage) when wheat is harvested, what impact does the intercropped maize have on wheat? This study explored the effects of intercropped maize on wheat under different nitrogen application rates. The results revealed both interspecific competition between wheat and maize and intraspecific competition among wheat plants. In wheat/empty strip systems, only intraspecific competition occurred. Previous reports indicated that wheat had stronger competitiveness for soil and fertilizer nitrogen than maize in wheat/maize intercropping systems, giving wheat a competitive advantage while maize was at a disadvantage [?, ?, ?]. This study confirmed these findings. At medium nitrogen level (N3), relay-intercropping advantages showed

wheat/maize > wheat/empty strip, with wheat yield and aboveground biomass in wheat/maize increasing by 14.13% and 5.03% compared to wheat/empty strip, and aboveground nitrogen uptake, grain nitrogen uptake and partial factor productivity increasing by 6.77%, 7.50% and 4.51% on average, respectively. These advantages occurred because intercropping changed root morphology, increasing fresh weight, volume and number of wheat roots while decreasing maize root length [?, ?], enabling intercropped wheat to absorb more nutrients. Additionally, root distribution patterns changed after intercropping. Field studies by Li et al. [?] and Liu et al. [?] found that maize intercropped with wheat experienced inhibited horizontal root growth during the co-growth period, while wheat roots could extend into maize root zones, but maize roots could not extend into wheat root zones, leading to yield and nutrient uptake advantages at wheat harvest. Furthermore, during the co-growth period, wheat and maize were at different growth stages—wheat from heading to harvest and maize from transplanting to jointing—with peak nutrient demand periods staggered, allowing wheat to benefit from intercropped maize [?].

However, the interspecific relationship between wheat and maize varied under different nitrogen application rates. Under zero (N1) and low nitrogen (N2) conditions, wheat yield and aboveground biomass in wheat/empty strip systems averaged 6.16% and 6.91% higher than in wheat/maize relay-intercropping, while at high nitrogen (N4), wheat yield and biomass in wheat/maize relay-intercropping were 4.51% and 12.24% lower than in wheat/empty strip. This likely occurred because under nitrogen-deficient conditions, wheat and maize competed intensely for nutrients in wheat/maize relay-intercropping systems, inhibiting wheat growth. In wheat/empty strip patterns, wheat had greater development space, allowing border rows to absorb more soil nutrients and promoting border row advantages, resulting in nitrogen uptake, grain nitrogen uptake and partial factor productivity averaging 15.50%, 16.65% and 16.46% higher than in wheat/maize patterns. At medium nitrogen (N3), wheat nutrients were sufficient in wheat/maize relay-intercropping systems, eliminating the need to obtain nutrients from maize rows and reducing maize's impact. Excessive nitrogen application would further decrease wheat yield and biomass, indicating that excessive nitrogen is also detrimental to wheat growth in wheat/maize systems.

In summary, relay-intercropped wheat in this study demonstrated obvious yield advantages, border row advantages and stronger nitrogen absorption capacity, enabling better nitrogen fertilizer utilization. In wheat/maize relay-intercropping systems, interspecific relationships varied with nitrogen application rate. Under nitrogen-deficient conditions, intercropped maize exerted obvious competitive inhibition on wheat, but increasing nitrogen application to appropriate levels reduced competition from intercropped maize and even promoted wheat growth through maize fertilization. Therefore, adequate nitrogen application is essential in wheat/maize relay-intercropping systems to eliminate nitrogen competition between wheat and maize and promote wheat growth.

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