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Abstract

In the arid regions of northern Xinjiang Uygur Autonomous Region (hereafter referred to as northern Xinjiang), China, developing intensive and sustainable cropping patterns is crucial for ensuring food security and promoting green agricultural development. As a typical cereal and legume intercropping system, maize and peanut intercropping demonstrates significant potential to enhance yield and resource use efficiency. However, the effects of nitrogen management and row configuration on crop productivity and inter-specific interactions under the unique ecological conditions of northern Xinjiang remain unclear. This study employed a field experiment with four planting patterns (maize monoculture (MM), peanut monoculture (MP), four rows of maize intercropped with four rows of peanuts (4M4P), and six rows of maize intercropped with six rows of peanuts (6M6P)) and five nitrogen application levels (0 (N0), 100 (N100), 200 (N200), 300 (N300), and 400 (N400) kg/hm^2). The results showed that under the 6M6P intercropping pattern combined with the N200 application level, maize morphological parameters were significantly improved, with plant height increasing by 10.48%, stem base circumference by 13.64%, and root length density (RLD) by 47.63%. Additionally, adaptive root morphological responses of maize were promoted in deeper soil depths, with RLD increasing by 15.48%–54.76% in the 0–60 cm soil depth. Intercropping significantly inhibited peanut growth and root development, as reflected by reductions of 12.37% in main stem height, 27.01% in dry matter weight, and 15.73%–25.23% in RLD in the 0–20 cm soil depth. However, nitrogen application at the N200 level effectively alleviated this inhibition, increasing peanut aboveground nitrogen accumulation by 80.12%–92.93% compared with the N0 level. Although the peanut nitrogen harvest index (NHI) decreased by 6.21%–7.06% relative to MM, it remained at a relatively high level. This planting configuration also significantly enhanced maize dry matter accumulation (increased by 28.50%) and nitrogen uptake (increased by 38.65%–55.21%) compared with MM. The nitrogen use efficiency (NUE) of both crops was the highest at the N100 and N200 levels, whereas N300 and N400 levels suppressed the aforementioned indicators. A positive correlation was observed between dry matter accumulation and nitrogen accumulation. Nitrogen translocation was enhanced in maize and allocation to grains was improved through improved morphological plasticity and root system adaptation, as reflected by its NHI, remaining at a high level of 79.54%–83.00%. This configuration achieved the highest land equivalent ratio (1.30) and maize grain yield under the experimental conditions. Together, these findings elucidate how nitrogen management and row configuration regulate crop growth and competitive dynamics in intercropping systems, providing a scientific basis for optimizing cereal and legume intercropping management in arid regions.

Full Text

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Effects of nitrogen fertilizer and intercropping patterns on crop root growth, nitrogen uptake, and yield

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Abstract: In the arid regions of northern Xinjiang Uygur Autonomous Region (hereafter referred to as northern Xinjiang), China developing intensive and sustainable cropping patterns is crucial for ensuring food security and promoting green agricultural development. As a typical cereal and legume intercropping system, maize and peanut intercropping demonstrates significant potential to enhance yield and resource use efficiency. However, the effects of nitrogen management and row configuration on crop productivity and inter-specific interactions under the unique ecological conditions of in northern Xinjiang remain unclear. This study employed a field experiment with four planting patterns (maize monoculture (MM), peanut monoculture (MP), four rows of maize intercropped with four rows of peanuts (4M4P), and six rows of maize intercropped with six rows of peanuts (6M6P)) and five nitrogen application levels (0 (N_0), 100 (N_{100}), 200 (N_{200}), 300 (N_{300}), and 400 (N_{400}) kg/hm^2). The results showed that under the 6M6P intercropping pattern combined with the N_{200} application level, maize morphological parameters were significantly improved, with plant height increasing by 10.48%, stem base circumference by 13.64%, and root length density (RLD) by 47.63%. Additionally, adaptive root morphological responses of maize were promoted in deeper soil depths, with RLD increasing by 15.48%-54.76% in the 0-60 cm soil depth. Intercropping significantly inhibited peanut growth and root development, as reflected by reductions of 12.37% in main stem height, 27.01% in dry matter weight, and 15.73%-25.23% in RLD in the 0-20 cm soil dept. However, nitrogen application at the N_{200} level effectively alleviated this inhibition, increasing peanut aboveground nitrogen accumulation by 80.12%-92.93% compared with the N_0 level. Although the peanut nitrogen harvest index (NHI) decreased by 6.21%-7.06% relative to MM, it remained at a relatively high level. This planting configuration also significantly enhanced maize dry matter accumulation (increased by 28.50%) and nitrogen uptake (increased by 38.65%-55.21%) compared with MM. The nitrogen use efficiency (NUE) of both crops was the highest at the N_{100} and N_{200} levels, whereas N_{300} and N_{400} levels suppressed the aforementioned indicators. A positive correlation was observed between dry matter accumulation and nitrogen accumulation. Nitrogen translocation was enhanced in maize and allocation to grains was improved through improved morphological plasticity and root system adaptation, as reflected by its NHI, remaining at a high level of 79.54%-83.00%. This configuration achieved the highest land equivalent ratio (1.30) and maize grain yield under the experimental conditions. Together, these findings elucidate how nitrogen management and row configuration regulate crop growth and competitive

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Keywords: intercropping; nitrogen level; root length density; specific root length; nitrogen uptake; land equivalent ratio

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1 Introduction

Intensive agriculture, designed to maximize yields, relies predominantly on monoculture and is characterized by heavy inputs of chemical fertilizers and pesticides. This approach leads to a range of adverse environmental consequences, including soil erosion and degradation, which ultimately undermine the sustainability of land use (Pavlidis et al., 2020; Sun et al., 2022). Intercropping offers a promising alternative by enabling agricultural intensification across both temporal and spatial dimensions. This practice not only alleviates the deterioration of soil physical-chemical properties associated with long-term monoculture but also increases land productivity per unit area, thereby helping to mitigate land-use competition between grain and oil crops in China (Zhang and Li, 2003). Defined as the cultivation of two or more crop species in specific row arrangements within the same field, intercropping capitalizes on spatial complementarity within plant communities to maximize the use of light, space, and time, ultimately enhancing crop yields (Jacquelyn et al., 2022). Numerous studies have confirmed the yield advantages of cereal and legume intercropping, such as maize with soybean, maize with peanut (Zheng et al., 2022; Dong et al., 2024b), and sorghum with soybean (Wang et al., 2021).

Nitrogen (N) fertilizer is a critical driver of crop growth and agricultural ecosystem productivity, accounting for more than 60.00% of global yield increases and playing an indispensable role in food security (Tilman et al., 2002). Early researches primarily examined the effects of varying N application rates on the yield of intercropped crops (Yuan et al., 2015; Jiao et al., 2016). Subsequent studies began to explore the mechanisms of interspecific competition and facilitation mediated by N availability, revealing that cereal and legume intercropping can enhance N use efficiency through complementary resource use (Jiao et al., 2021a; Roco et al., 2024). Recently, research has shifted toward optimizing N application rates and timing in conjunction with planting configurations to balance crop productivity with resource use efficiency (Xu et al., 2017; Zhao et al., 2024). While moderate N application can improve the yield and resource use efficiency of intercropping systems, excessive N use not only raises production costs but also leads to environmental pollution (Ouyang et al., 2018). Therefore, identifying optimal N application rates and improving N management practices are essential for achieving sustainable agricultural resource use in maize and peanut intercropping systems.

Crop growth and final yield in intercropping systems are closely tied to root proliferation (Dong et al., 2024b). As the primary interface between plants and soil environment, roots are highly sensitive to changes in their surroundings and are continuously influenced by soil nutrient availability, particularly N (Tang et al., 2025). Studies have shown that N fertilization often enhances root morphological traits, such as root length density (RLD), root surface area, and root volume, and plants strategies such as localized stimulation of lateral root branching and elongation to increase N uptake efficiency (Jia and Wirén, 2020). Maize and peanut intercropping, a typical cereal and legume intercropping system, effectively leverages the complementary N nutrition of the two species. Legumes, capable of symbiotic N fixation create distinct N niches across spatial and temporal dimensions, thereby promoting efficient resource partitioning (Sun et al., 2025). Previous research has demonstrated that root interactions between maize and peanut improve soil N use efficiency, with maize in border rows exhibiting a competitive advantage in N uptake (Dong et al., 2022). For instance, Zhang et al. (2024) reported that although N accumulation in border and inner rows of peanuts tended to decline at maturity, their N fixation capacity was enhanced. This enhancement was attributed to a positive border row effect from maize, which alleviates the "N inhibition" commonly observed in peanut.

Despite these advances, N management in maize and peanut intercropping systems continues to face several key challenges. First, the N requirements of maize and peanut differ markedly: maize, a cereal crop, demands relatively high N inputs to achieve high yields, whereas peanut, a legume, can meet much of its N demand through symbiotic N fixation, and excessive N application can suppress nodulation and N fixation capacity (Feng et al., 2021; Zheng et al., 2022). Second, the optimal N application rate for intercropping systems remains inconsistent across studies, likely owing to interactions among planting configuration, soil properties, and climatic conditions (Feng et al., 2021). Third, existing research has largely focused on aboveground responses and traditional agronomic indicators (e.g., row spacing, light use efficiency, and border effects), while insufficient attention has been given to root morphological plasticity and its role in N uptake and interspecific competition (Jiao et al., 2021b). Therefore, there is an urgent need to identify N application thresholds that simultaneously optimize maize yield, sustain peanut N fixation, and minimize N losses (Zhang et al., 2024). The results might to elucidate how planting configuration regulates interspecific competition through root interactions, and to develop integrated management strategies that account for the spatiotemporal dynamics of N demand (Xia et al., 2023). However, research on the effects of intercropping ratios and reduced N application on root growth, N uptake, and yield in northern China remains limited. To address this knowledge gap, we conducted a field experiment in northern China to systematically investigate the effects of different N application rates and planting patterns on root spatiotemporal distribution, N uptake and utilization, and yield in a maize and peanut intercropping system.

This study made core contributions in three aspects including root morphological plasticity, integration of planting pattern optimization with N reduction, and extension to arid regions, thereby filling critical knowledge gaps in root mediated interspecific interactions and configuration-based N management. This research aims to address three key questions: (1) the regulatory patterns of root spatial distribution in maize and peanut under intercropping conditions and their relationship with resource competition; (2) the land equivalent ratio (LER) advantage of intercropping systems and their response characteristics to N input; and (3) the effects of different N levels on systemic N use efficiency and their physiological and ecological mechanisms.

2 Materials and methods

2.1 Study area

From May 2024 to September 2025, an experiment was undertaken at the Shuangquan Town, Shihezi City, northern Xinjiang Uygur Autonomous Region (hereafter referred to as northern Xinjiang), China (44°18′N, 85°59′E; 412 m a.s.l.). The study area belongs to temperate continental climate, with annual mean temperature of 6.6°C, mean annual precipitation of 277.3 mm, annual mean sunshine of 2784 h, and a mean frost-free period of 166 d. The test soil, classified as sandy loam, had a bulk density of 1.34 g/cm^3. Pre-experimental soil analysis of the 0–40 cm soil depth indicated an organic matter content of 20.26 g/kg, total N of 1.10 g/kg, alkaline N of 58.37 mg/kg, available phosphorus of 21.76 mg/kg, available potassium of 184.43 mg/kg, and pH value of 7.3. The monthly climatic conditions throughout the growing seasons (1 April–20 September) of both years are illustrated in Figure 1.

2.2 Experimental design and crop management

Maize (*Zea mays* L.) cultivar "Zhendan 958" and peanut (*Arachis hypogaea* L.) cultivar "Silihong" (commercial cultivars grown in this area) were used for monoculture and intercropping in the field. The experiment was arranged in a two-factor randomized complete block design. Four planting patterns were

Daily mean temperature and precipitation during the whole crop period in 2024 (a) and 2025 (b)

Figure 1: Daily mean temperature and precipitation during the whole crop period in 2024 (a) and 2025 (b)

Schematic diagram of planting patterns and sampling points

Figure 2: Schematic diagram of planting patterns and sampling points

established: monoculture maize (MM), monoculture peanut (MP), four rows of maize intercropped with four rows of peanuts (4M4P), and six rows of maize intercropped with six rows of peanuts (6M6P). Five N levels (0 (N_0), 100 (N_{100}), 200 (N_{200}), 300 (N_{300}), and 400 kg/hm^2 (N_{400})), creating 20 treatments with 3 replicates each (total 60 plots). The area of the plot is 10 m(×)5 m. The specific planting pattern was shown in Figure 2, using uniform

row spacing. The distance between maize and peanut rows is 40 cm, while the row spacing within maize is also 40 cm with a hill spacing of 20 cm. For peanut, the row spacing is 20 cm with a hill spacing of 10 cm. The experiment utilized planting density of 1.25×10^5 plants/hm^2 for maize and 5.00×10^5 plants/hm^2 for peanut, with a plastic mulch applied pre-sowing across all treatments. Sowing for both crops was conducted simultaneously on 7 May, 2024, and 11 May, 2025.

Fig. 1 Daily mean temperature and precipitation during the whole crop period in 2024 (a) and 2025 (b)

Fig. 2 Schematic diagram of planting patterns and sampling points. MM, monoculture maize; MP, monoculture peanut; 4M4P, four rows of maize intercropped with four rows of peanuts; 6M6P, six rows of maize intercropped with six rows of peanuts.

Base fertilizer was uniformly applied across all plots, accounting for 40.00% of the total fertilizer application during the entire growth period. The base fertilizer consisted of potassium dihydrogen phosphate (containing 52.00% P_2O_5 and 34.00% K_2O) at 157 kg/hm^2 and potassium

sulfate (containing 52% K_2O) at 4 kg/hm^2. Five nitrogen levels were applied as base treatments: 0, 40, 80, 120, and 160 kg/hm^2 of pure N. Topdressing was conducted three times during the growing season, at the maize large trumpet stage, tasseling stage, and grain-filling stage. Urea (46.00%), along with the remaining amounts of potassium dihydrogen phosphate and potassium sulfate, was applied in proportions of 60.00%, 25.00%, and 15.00% at the three stages, respectively. The fertilization method for intercropped peanuts is the same as that for intercropped maize, with three topdressing periods: full bloom stage, peg penetration stage, and pod formation stage. The topdressing ratio follows the same pattern as above. The fertilization method for monoculture is identical to that of intercropping. The crop irrigation method was drip irrigation, with a total of 10 irrigation events throughout the growing season, each applying 450 m^3/hm^2. Prior to sowing, basal fertilizer was uniformly broadcast on the soil surface and then incorporated into the 0–20 cm topsoil depth by plowing.

2.3 Determination of agronomic traits

Soil and plant samples were collected on three times in both 2024 and 2025, corresponding to key growth stages. The first sampling occurred in mid-June, coinciding with the flowering-pegging stage of peanut and the large trumpet stage of maize. The second was in late July, during the pod-setting stage of peanut and the tasseling stage of maize. The final sampling was in early September, when both crops had reached their maturity stage. Three representative plants per treatment were measured, with three replicates. A tape measure and ruler were used to determine maize (plant height, stem base circumference (measured using a soft flexible string)) and peanut (main stem height, length of the first pair of lateral branches (measured from the base to the top of the first lateral branch)). The average values were then calculated.

2.4 Characteristics of root system distribution in space and time

2.4.1 Root sampling

Soil and root samples were collected from the maize and peanut intercropping system at different growth stages. The sampling points for root systems in each plot are shown in Figure 2. Sampling dates were 17 June, 24 July, and 4 September in 2024, and 17 June, 27 July, and 4 September in 2025, corresponding to the large trumpet stage, tasseling stage, and maturity stage of maize and flowering-pegging stage, pod-setting stage, and maturity stage of peanut, respectively. A cylindrical steel soil sampler with an inner diameter of 4.5 cm (volume of 565 cm^3) was driven into the soil using a mallet. The continuous core sampling method was used to collect root samples at predetermined points with a root auger. Sampling depths were upper (0–20 cm), middle (20–40 cm), and lower depths (40–60 cm). Root samples from the same soil depth within each plot were pooled in equal mass to obtain composite samples, which were used for subsequent root analyses to represent the overall root characteristics of the intercropping system.

2.4.2 Fine root analysis

Following collection, we individually placed each root sample in a double layer of 200-mesh nylon gauze (35 cm($\times$)35 cm) and rinsed under running water to remove soil. Living roots, identified by their brighter color and turgidity, were carefully separated with forceps. We distinguished maize and peanut roots in the intercropping plots based on morphological characteristics (color and shape) using monoculture roots as a reference; typically, maize roots are white, while peanut roots are brown. The isolated roots were scanned using a high-speed photographic apparatus at a resolution of 3836 × 2735 pixels. The resulting images were analyzed with WinRHIZO^TM software (Regent Instruments Inc., Quebec, Canada), calibrated with a "Black Width" parameter of 0.03. RLD was calculated using the known soil core volume (565 cm^3). Subsequently, the root samples were oven-dried at 105°C for 30 min, then at 85°C to constant weight for dry mass measurement, which was used to determine the specific root length (SRL).

The RLD (cm/cm^3) was calculated by Equation 1:

$$\text{RLD} = \frac{L_r}{V_s}, \qquad (1)$$

where L_r is the root length (cm); and V_s is the soil volume (cm^3).

The SRL (cm/mg) was calculated using Equation 2:

$$\text{SRL} = \frac{L_\text{r}}{W_\text{d}}, \qquad (2)$$

where W_d is the fine root dry weight (mg).

2.5 Dry matter and N accumulation

During the peanut flowering-pegging (large trumpet for maize), pod-setting (tasseling for maize), and maturity stages, plant samples were collected once each. In each treatment, three plants were randomly chosen for sampling, with three repetitions. The organs of maize (roots, stems, leaves, and ears) and peanuts (roots, stems, leaves, and pods) were separated and labeled. After processing, we dried the samples in an oven. Before drying, we preheated the oven to 105°C, blanched the samples for 30 min, then reduced the temperature to 80°C and dried until a constant weight is achieved. Once dried, we measured the weight of the samples with a balance and recorded the details.

For the mature plant samples, after drying and grinding the organs through a 60-mesh sieve, the total N content was determined using the Kjeldahl method with a fully automated Kjeldahl nitrogen analyzer (Kjeltec 8400, FOSS, Hillerød, Denmark).

The N-related parameters are calculated by the following equations (Li, 2019):

$$\text{Plant N accumulation} = \text{Plant N content} \times \text{Plant dry weight}, \qquad (3)$$

$$\text{Nitrogen harvest index (NHI)} = \frac{\text{Total N accumulation in grains}}{\text{Total N accumulation in the plant}} \times 100\%, \qquad (4)$$

$$\text{N agronomic efficiency (NAE)} = \frac{\text{Crop yield in N-fertilized plot} - \text{Crop yield in control plot}}{\text{Amount of N fertilizer applied}}, \quad (5)$$

$$\text{N use efficiency (NUE)} = \frac{\text{Total N uptake in N-fertilized plot} - \text{Total N uptake in control plot}}{\text{Amount of N fertilizer applied}} \times 100\%. \quad (6)$$

2.6 Yield and LER

At maturity stage, grain yield was determined by manually harvesting all plants within three randomly placed 1.0 m(×)1.0 m quadrats per plot. After threshing and air-drying, we measured the grain weight. The theoretical yield per plot was extrapolated from this sampled data and the total plot area. The yield advantage of the intercropping system was evaluated using the LER, calculated with the following formula:

$$\text{LER} = \frac{Y_{\text{im}}}{Y_{\text{mm}}} + \frac{Y_{\text{ip}}}{Y_{\text{mp}}}, \quad (7)$$

where Y_{im}, Y_{mm}, Y_{ip}, and Y_{mp} are the yields (kg/hm^2) of intercropped maize, monocropped maize, intercropped peanut, and monocropped peanut, respectively. If LER>1.00, it indicates that the maize and peanut intercropping system has yield advantage, whereas a value less than 1.00 signifies a lack of such an advantage.

2.7 Data analysis

Data were analyzed using a two-factor analysis of variation (ANOVA) in SPSS v.26.0 software, with mean separations performed by the least significant difference (LSD) test ($P < 0.050$). Microsoft Excel v.2020 software was used for data organization, while SigmaPlot v.15.0 and Origin v.2025 softwares were employed for creating graphs.

3 Results

3.1 Agronomic traits

3.1.1 Plant height and stem base circumference of maize

Intercropping significantly enhanced maize growth. Both plant height and stem base

circumference under the MM pattern and intercropping followed a trend of rapid initial increase followed by a slower decline (Fig. 3). Over the two-year period, at the large trumpet stage, maize under the 4M4P and 6M6P intercropping patterns exhibited significantly greater plant height and stem base circumference than the MM pattern, with the 6M6P pattern generally showing stronger growth promotion than the 4M4P pattern. Similar trends were observed at the tasseling and maturity stages. N application significantly improved maize development compared with the N_0 level. Across different N levels, plant height and stem base circumference generally followed the order: $N_{200}>N_{100}>N_{300}>N_{400}>N_0$. At the N_{200} levels, plant height and stem base circumference increased by 12.52% and 21.16%, respectively, under the 4M4P pattern, and by 15.04% and 23.47% under the 6M6P pattern, compared with the N_0 level. The growth-promoting effect of intercropping was most pronounced at the N_{200} level.

3.1.2 Plant height and length of the primary lateral branch of peanut

Intercropping significantly inhibited peanut growth. Throughout the growing season, both plant height and first lateral branch length showed an initial increase followed by a subsequent decline (Fig. 3). During the two-year trial, under average N conditions at the flowering-pegging stage, peanut plant height under the 4M4P and 6M6P intercropping patterns was significantly lower than that under the MP pattern, with reductions ranging from 2.23% to 21.54% across sampling periods. A similar inhibitory effect was observed for the first lateral branch length, where intercropped peanuts showed reductions between 1.92% and 41.46% relative to the MP pattern. Comparable patterns were recorded at the pod-setting and maturity stages. N application partially alleviated this growth inhibition. Across all cropping systems, N_{200} emerged as the optimal N level. Compared with the N_0 level, plant height increased by 53.32%-71.50% under the MP pattern and by 56.12%-56.41% under intercropping at the N_{200} level. The response of first lateral branch length to N was even more pronounced, rising by 68.38%-133.96% under the MP pattern and by 78.75%-93.55% under intercropping.

3.2 Dry matter weight

Overall, intercropping promoted continuous dry matter accumulation in all maize organs while inhibiting aboveground accumulation in peanut. At the flowering-pegging stage, root, stem, and leaf dry weights of intercropped maize were significantly higher than those of the MM pattern, following the order of 6M6P>4M4P>MM (Fig. 4). In contrast, aboveground dry weight of peanut under intercropping was consistently lower than that of the MP pattern, with stronger suppression under the 4M4P pattern compared with the 6M6P pattern. N application significantly enhanced dry matter accumulation in both crops and partially moderated the inhibitory effect of intercropping. Maize responded strongly to all N levels, with the N_{200} level showing the most pronounced promotion. Over the two-year study, total plant dry weight of intercropped maize at the N_{200} level increased by more than 62.67% compared with the N_0 level. For peanut, N fertilization, especially within the N_{100}-N_{200} levels, effectively

Fig. 3. Plant height and stem base circumference of maize and plant height and first-order lateral branch length of peanut under four planting systems

Figure 3: Fig. 3. Plant height and stem base circumference of maize and plant height and first-order lateral branch length of peanut under four planting systems

Fig. 4

Figure 4: Fig. 4

alleviated intercropping-induced suppression. At the N_0 level, total plant dry weight across planting patterns decreased by 66.00%–84.00% relative to the N_{200} level, with a more pronounced N response observed in monoculture system. The promoting effect of intercropping on maize dry matter accumulation was more evident in 2025, and the 6M6P pattern consistently outperformed 4M4P across both years. The degree of inhibition on peanut also varied systematically with year and row-ratio configuration.

3.3 RLD

The root system serves as a central organ for water and nutrient uptake in plants, with its growth and distribution directly influencing aboveground development. Temporally, RLD of both crops peaked at mid-growth stages. Intercropping induced the opposite effects: it enhanced maize RLD by 27.14%–48.57% compared with the MM pattern (Fig. 5), particularly under the 6M6P pattern. Conversely, it suppressed peanut RLD by 8.94%–35.21%, with stronger suppression under the

Fig. 3 Plant height and stem base circumference of maize (a–d) and plant height and first-order lateral branch length of peanut (e–h) under four planting systems. FS, large trumpet stage for maize and flowering-pegging stage for peanut, respectively; PS, tasseling stage for maize and pod-setting stage for peanut, respectively; MS, maturity stage; N_0-N_{400}, nitrogen application rates of 0, 100, 200, 300, and 400 kg/hm^2, respectively. N, nitrogen fertilizer level; C, cropping pattern; N×C, their interaction.

Fig. 4 Dry weight of different organs in maize (a–f) and peanut (g–l) under four planting systems. Different lowercase letters indicate significant differences between different nitrogen application level treatments under the same planting pattern and plant organ at P<0.050 level. Bars are standard errors.

4M4P pattern. This result indicates a sustained competitive advantage for maize throughout the growth period. N application significantly modulated RLD, with an optimal rate (N_{200}) maximizing RLD for both crops. The promoting effect of N was more pronounced in maize under intercropping but more evident in peanut under the MP pattern. Vertically, roots were concentrated in the topsoil

Fig. 5. Root length density (RDL) of maize and peanut under four planting systems. Panels: (a) FS in 2024; (b) PS in 2024; (c) MS in 2024; (d) FS in 2025; (e) PS in 2025; (f) MS in 2025; (g) FS in 2024; (h) PS in 2024; (i) MS in 2024; (j) FS in 2025; (k) PS in 2025; (l) MS in 2025. Axes include RLD of maize or peanut (cm/cm^3), nitrogen fertilizer (kg/hm^2), and depth (cm). Legends include MM, 4M4P, 6M6P for maize and MP, 4M4P, 6M6P for peanut.

Figure 5: Fig. 5. Root length density (RDL) of maize and peanut under four planting systems. Panels: (a) FS in 2024; (b) PS in 2024; (c) MS in 2024; (d) FS in 2025; (e) PS in 2025; (f) MS in 2025; (g) FS in 2024; (h) PS in 2024; (i) MS in 2024; (j) FS in 2025; (k) PS in 2025; (l) MS in 2025. Axes include RLD of maize or peanut (cm/cm^3), nitrogen fertilizer (kg/hm^2), and depth (cm). Legends include MM, 4M4P, 6M6P for maize and MP, 4M4P, 6M6P for peanut.

Fig. 6

Figure 6: Fig. 6

(0-40 cm for maize and 0-20 cm for peanut). Intercropping intensified this stratification: it increased maize RLD in the 0-40 cm depth by 15.48%-73.61%, while reducing peanut RLD in the top 20 cm by 8.47%-25.23%. N fertilization, especially at the N_{200} level, further promoted root proliferation in surface layers across all systems.

3.4 SRL

SRL variations revealed opposite root morphological plasticity strategies between maize and peanut in intercropping systems. Temporally, SRL of both crops followed an initial increase followed by a decline over the growing season. Intercropping resulted in significant differences: maize SRL in intercropping systems was consistently higher, especially under the 6M6P pattern

Fig. 5 Root length density (RDL) of maize (a-f) and peanut (g-l) under four planting systems. Different lowercase letters indicate significant differences among different nitrogen application level treatments under the same cultivation pattern and same soil depth at $P < 0.050$ level.

than under the MM pattern, with an increase of 2.37%-25.73% at the flowering-pegging stage (Fig. 6), indicating that intercropping promoted the formation of finer, more exploratory roots in maize. In contrast, peanut SRL was significantly lower under intercropping than under the MP pattern, with a reduction of 4.36%-20.13% at the flowering-pegging stage. The inhibitory effect was stronger under the 4M4P pattern than under the 6M6P pattern, suggesting that intercropping limited fine root investment in peanut. The effect of N application was nonlinear, with moderate N (N_{200}) favoring higher SRL. However, the enhancing effect of N on SRL was more pronounced

Fig. 7 Accumulation of N content in the aboveground parts of mature maize and peanut.

Figure 7: Fig. 7 Accumulation of N content in the aboveground parts of mature maize and peanut.

Fig. 6 Specific root length (SRL) of maize (a-f) and peanut (g-l) under four planting systems. Different lowercase letters indicate significant differences among different nitrogen application level treatments under the same cultivation pattern and same soil depth at P<0.050 level.

under the MP pattern and intercropped maize. Vertically, maize SRL increased with soil depth and was the lowest in the surface depth (0-20 cm), while peanut SRL peaked in the 20-40 cm depth. Intercropping intensified this divergence: compared with the MM pattern, intercropping significantly increased the average SRL of maize in the 0-60 cm soil depth (12.22% and 22.37% under the 4M4P and 6M6P patterns, respectively), indicating that intercropping promoted finer root formation throughout the soil profile in maize. Conversely, intercropping significantly reduced the average SRL of peanut in the 0-60 cm depth (8.71% and 16.44% under the 6M6P and

4M4P patterns, respectively), further confirming that intercropping inhibited fine root formation and vertical expansion in peanut.

3.5 Plant N accumulation

Figure 7 shows the result of plant N accumulation. N accumulation in maize was significantly enhanced under intercropping systems (Fig. 7a and b), with values following the order of 6M6P>4M4P>MM. Over the two-year study, intercropped maize exhibited N accumulation that was 16.50%-67.14% higher than that under the MM pattern, with the greatest increase observed at the N_{200} level. In contrast, N accumulation in peanut was significantly reduced under intercropping (Fig. 7c and d), with reductions ranging from 8.54% to 66.86%. The inhibitory effect was stronger under the 4M4P pattern than under the 6M6P pattern. Although N application generally promoted N accumulation in peanut, the effect was more pronounced under the MP pattern. At the N_{200} level, average N accumulation under the MP pattern exceeded those under the 6M6P and 4M4P patterns by 85.19% and 142.61%, respectively. These findings demonstrate a clear asymmetry in N acquisition between maize and peanut in intercropping systems: maize benefits substantially, while peanut experiences competitive suppression. Appropriate N application, especially at the N_{200} level, can partially mitigate this suppression, though the response remains stronger under the MP pattern.

Fig. 7 Accumulation of N content in the aboveground parts of mature maize (a and b) and peanut (c and d). Different lowercase letters indicate significant differences between different nitrogen application level treatments under the same planting pattern at P<0.050 level. Bars are standard errors.

3.6 N uptake and utilization

As shown in Tables 1 and 2, the NHI of maize was consistently and significantly higher (79.54%-83.00%) than that of peanut (56.15%-76.89%), demonstrating a stronger capacity of maize to translocate N to grains. Intercropping did not significantly affect maize NHI but

significantly reduced it in peanut, particularly in 2024, when NHI under the 4M4P and 6M6P patterns decreased by 6.21% and 7.06%, respectively, compared with the MP pattern. This result indicates that intercropping inhibited N translocation to pods in peanut. NAE declined significantly as N application increased. Maize showed the highest NAE at the N_{100} level, and maize under the MM pattern generally had higher NAE than intercropped maize. In 2024, NAE of under the MM pattern (44.90) at the N_{100} level was 2.0 and 1.4 times higher than those of 4M4P and 6M6P, respectively. Within the intercropping system, maize NAE (22.06-32.63) was substantially higher than peanut NAE (7.52-8.23), suggesting that N contributed more to yield gains in intercropped maize. NUE gradually decreased with increasing N application. At the N_{100}-N_{200} level, intercropped maize, especially under the 6M6P pattern, often exhibited higher NUE than MM maize. In contrast, intercropped peanut showed significantly lower NUE than MP peanut across all N levels, with reductions of 41.22%-66.27% at the N_{100} level.

Table 1 Effects of N application and planting patterns on N utilization of maize

Year	Nitrogen level	NHI (%)	NHI (%)	NHI (%)	NAE (kg/kg)	NAE (kg/kg)	NAE (kg/kg)	NUE (%)	NUE (%)	NUE (%)
Year	Nitrogen level	MM	4M4P	6M6P	MM	4M4P	6M6P	MM	4M4P	6M6P
2024	N_0	84.47	82.44	79.49	-	-	-	-	-	-
2024	N_{100}	77.19	77.76	80.25	44.90	22.06	32.63	19.42	25.79	32.70
2024	N_{200}	79.60	79.23	80.96	26.20	13.26	22.00	19.31	21.16	25.74
2024	N_{300}	82.93	79.49	83.93	12.40	4.65	5.31	5.16	5.77	8.70
2024	N_{400}	77.86	78.79	78.35	6.71	0.89	1.41	1.36	3.10	2.42
2024	Mean	80.41	79.54	80.60	22.55	10.22	15.34	11.31	13.95	17.39
2025	N_0	85.27	84.45	82.90	-	-	-	-	-	-
2025	N_{100}	80.94	79.31	79.49	47.54	23.22	34.58	21.49	27.54	29.18
2025	N_{200}	78.94	77.28	77.99	27.75	13.98	23.30	12.59	15.39	18.19
2025	N_{300}	84.85	80.60	80.06	13.14	4.88	5.62	4.61	5.83	7.06
2025	N_{400}	85.01	82.50	82.36	7.11	0.91	1.50	1.87	3.34	3.63
2025	Mean	83.00	80.83	80.56	23.88	10.75	16.25	10.14	13.02	14.51

Note: N_0-N_{400}, nitrogen application rates of 0, 100, 200, 300, and 400 kg/hm^2, respectively. NHI, nitrogen harvest index; NAE, nitrogen agronomic efficiency;

NUE, nitrogen use efficiency; MM, monoculture maize; 4M4P, four rows of maize intercropped with four rows of peanuts; 6M6P, six rows of maize intercropped with six rows of peanuts. "-" means no value.

Table 2 Effects of N application and planting patterns on N utilization of peanut

Year	Nitrogen level	NHI (%)	NHI (%)	NHI (%)	NAE (kg/kg)	NAE (kg/kg)	NAE (kg/kg)	NUE (%)	NUE (%)	NUE (%)
Year	Nitrogen level	MP	4M4P	6M6P	MP	4M4P	6M6P	MP	4M4P	6M6P
2024	N_0	58.46	38.10	26.19	-	-	-	-	-	-
2024	N_{100}	71.18	63.04	72.22	11.26	8.23	7.52	6.29	1.88	3.00
2024	N_{200}	57.13	61.48	69.35	13.79	6.75	6.39	4.27	1.62	1.96
2024	N_{300}	65.45	63.74	65.78	3.63	2.34	1.36	0.60	0.43	0.61
2024	N_{400}	63.41	58.25	47.22	0.72	1.66	0.82	0.25	0.15	0.17
2024	Mean	63.13	56.92	56.15	7.35	4.75	4.02	2.85	1.02	1.43
2025	N_0	75.79	67.86	69.86	-	-	-	-	-	-
2025	N_{100}	78.13	74.76	79.62	10.63	5.69	7.11	3.85	1.54	2.95
2025	N_{200}	77.76	77.57	79.23	13.03	5.33	6.04	2.56	1.04	1.59
2025	N_{300}	78.04	69.11	73.03	3.43	1.67	1.43	0.67	0.22	0.35
2025	N_{400}	74.74	67.39	69.59	0.68	0.94	0.68	0.25	0.09	0.19
2025	Mean	76.89	71.34	74.27	6.94	3.41	3.81	1.83	0.72	1.27

Note: MP, monoculture peanut. "-" means no value.

3.7 Yield and LER

Compared with the MM pattern, intercropping led to a reduction in maize grain yield as a result of lower planting density per unit area. Across N treatments over the two-year study, maize yields were 5.49%-25.38% lower under the 4M4P and 6M6P patterns than under the MM pattern (Table 3), with a more pronounced reduction under the 4M4P pattern. Peanut grain yield was the highest under the MP pattern. N application significantly increased grain yield in both crops. Yield peaked at moderate N levels and then declined with further increase in N input. For example, under the MP pattern, peanut yield was 110.75% higher at the N_{200} level than at the N_0 level. LER averaged 1.13 for the 4M4P pattern and 1.24 for the 6M6P pattern during the two-year study, indicating a clear intercropping yield advantage, especially under the 6M6P pattern. Maize contributed more to LER than peanut, and higher LER values were generally observed under lower N levels.

3.8 Correlation of traits with yield

Based on correlation analysis (Fig. 8), we found that maize yield was primarily associated with N content (r=0.51) and stem base circumference (r=0.40), forming a synergistic mechanism of "N uptake-structural support" along with root length density (r=0.31). On the other hand, peanut yield relied mainly on the efficient synergistic accumulation of biomass (r=0.70) and N (r=0.72) and supported from a dense root length density (r=0.58), while aboveground morphological traits had a weaker influence (r=0.27). The results indicate that peanut yield is characterized by a key functional module of "high N efficiency-dense roots-high biomass", highlighting distinct crop-specific strategies for yield formation.

4 Discussion

4.1 Crop growth indicators

Crop growth morphology and dry matter accumulation constitute a continuous physiological process in yield formation, both co-regulated by interspecific competition and resource availability. Maize gains a competitive advantage in light competition through a "tall and sturdy stem" morphological strategy (Zhu et al., 2014). In this study, this result was manifested as a significant increase in plant height (by 2.12% and 4.06% under the 4M4P and 6M6P patterns, respectively) along with enhanced stem base circumference. This morphological development strengthens maize' s light interception capacity and lodging resistance, laying a structural foundation for its efficient dry matter accumulation (Kou et al., 2025). Consequently, the aboveground dry matter accumulation of intercropped maize increased by 16.11% compared with the MM pattern, with a more pronounced gain under the 6M6P pattern than under the 4M4P pattern. This enhancement is attributed to the potentially improved light and ventilation conditions within the maize canopy resulting from the more optimized row arrangement, further reinforcing its morphological and yield advantages. Previous studies also indicate that intercropping promotes maize growth and enhances resource use efficiency, thereby increasing dry matter accumulation and supplying more assimilates for later grain filling, ultimately boosting yield (Li et al., 2023). In soybean and maize intercropping systems, maize dry matter accumulation can be increased by up to 52.63% (Zhao et al., 2020). In contrast, intercropped peanuts, affected by shading from the maize canopy, are at a disadvantage in light competition, leading to significant suppression of morphological growth (main stem height and lateral branch length decreased by 7.44%-17.29% and 3.65%-17.52%, respectively, compared with the MM pattern). This morphological inhibition directly restricts the synthesis of photosynthetic products, ultimately resulting in a sharp reduction of 35.93% in aboveground dry matter accumulation compared with the MM pattern. Previous research similarly confirms that intercropping significantly reduces peanut dry matter accumulation (Liu et al., 2020). The planting row ratio modulates shading intensity, thereby affecting the degree of suppression on peanuts. For instance,

Table 3 Maize yield, peanut yield, and land equivalent ratio (LER) under different treatments

Fig. 8. Correlations between yield and measured traits for maize (a) and peanut (b).

Figure 8: Fig. 8. Correlations between yield and measured traits for maize (a) and peanut (b).

Year	Nitrogen level	Maize yield (kg/hm^2) MM	Maize yield (kg/hm^2) 4M4P	Maize yield (kg/hm^2) 6M6P	Maize yield (kg/hm^2) MP	Peanut yield (kg/hm^2) 4M4P	Peanut yield (kg/hm^2) 6M6P	LER 4M4P	LER 6M6P
2024	N_0	9309.84± 454.92	8591.45± 98.52	8798.54± 86.38	2581.11± 261.69	724.26± 59.75	839.82± 89.05	1.20	1.27
2024	N_{100}	13,799.57± 112.18	10,797.02± 72.41	12,061.32± 275.47	3644.37± 313.47	1293.57± 107.98	1550.94± 140.20	1.14	1.30
2024	N_{200}	14,549.85± 178.74	11,244.00± 156.01	13,198.56± 281.42	5186.91± 405.75	1790.41± 134.11	2047.55± 156.02	1.12	1.30
2024	N_{300}	13,030.73± 148.02	9987.09± 181.17	10,390.26± 123.15	3610.31± 337.22	1224.97± 110.94	1268.84± 117.06	1.11	1.15
2024	N_{400}	11,993.40± 108.07	8949.18± 126.86	9363.71± 180.80	2852.71± 278.00	1099.80± 101.22	1111.75± 106.62	1.13	1.17
2025	N_0	9861.52± 481.41	9118.34± 94.58	9320.44± 91.87	2729.11± 277.51	545.23± 52.35	888.42± 94.37	1.12	1.27
2025	N_{100}	14,615.50± 119.10	11,440.76± 75.38	12,778.83± 290.13	3855.21± 331.10	1368.69± 114.53	1640.64± 148.47	1.14	1.30
2025	N_{200}	15,411.15± 191.45	11,914.00± 165.41	13,981.07± 297.38	5487.70± 430.38	1895.06± 142.10	2166.40± 165.07	1.12	1.30
2025	N_{300}	13,802.20± 156.72	10,582.59± 191.55	11,007.58± 130.41	3818.52± 356.12	1247.96± 115.05	1296.47± 122.88	1.09	1.14
2025	N_{400}	12,706.53± 118.69	9481.74± 133.84	9919.56± 192.47	3016.53± 293.68	1209.09± 109.22	1217.12± 114.16	1.15	1.18
ANOVA	N		***			***			
ANOVA	C		***			***			
ANOVA	Y		***			*			
ANOVA	N×C		***			***			
ANOVA	N×Y		ns			ns			
ANOVA	C×Y		ns			ns			
ANOVA	N×C×Y		ns			ns			

Note: Different lowercase letters within the same culture pattern and the same year indicate significant differences among different nitrogen levels at $P<0.050$ level. ANOVA, analysis of variance; N, nitrogen fertilizer level; Y, year; C, cropping pattern; , P*<0.050 level;* **, $P<0.001$ level; ns, no significance. Mean±SD.

Fig. 8 Correlations between yield and measured traits for maize (a) and peanut (b). PH, plant height; SBC, stem base circumference; DMA, dry matter accumulation; RLD, root length density; SRL, specific root length; NC, nitrogen content; MSH, main stem height; FBL, first branch length.

under the 2M6P pattern, peanut growth indicators may surpass those under the MP pattern (Wang et al., 2026), whereas the 6M6P pattern in this study exhibited a stronger inhibitory effect. N management plays a crucial coordinating role in this process. Appropriate N application (N_{200} level) not only supports the competitive growth of maize but also alleviates the physiological inhibition of peanuts under shading, increasing their main stem height and lateral branch length by 62.39% and 83.89%, respectively, compared with the N_0 level. This result aligns with previous conclusions that N can improve the photosynthetic status and competitiveness of intercropped peanuts (Han et al., 2023). However, excessive N application (N_{300} and N_{400} levels) may exacerbate canopy closure or lead to carbon–N metabolic imbalance, thereby inhibiting the dry matter accumulation of both crops, particularly peanuts, indicating an optimal threshold for N fertilizer supply (Gao et al., 2020).

4.2 Root architecture-based synergistic N utilization mechanisms

The spatial distribution characteristics of root systems form the structural foundation for resource competition and complementarity in intercropping systems (Hauggaard-Nielsen et al., 2001). This study demonstrates that maize and peanut exhibit significant vertical niche differentiation in intercropping systems (Zheng et al., 2022). The underlying mechanism lies in the morphological plasticity of root architecture, which optimizes resource allocation and directly influences the dynamics of N uptake and utilization efficiency (Li et al., 2025). The stratification of roots reflects a spatial partitioning strategy for limited resources. As a deep-rooted crop, maize primarily distributes its roots in the 20–60 cm soil depth, whereas peanut, as a shallow-rooted crop, concentrates its roots in the 0–30 cm topsoil (Dong et al., 2024b). This distribution pattern stems from divergent adaptive strategies during root development: maize enhances its vertical root growth to access deep soil water and nutrients, while peanut increases its topsoil root density to improve capture of surface resources. Under intercropping systems, maize significantly increased its root length density in the 0–40 cm soil depth by 14.86%–56.40% and its specific root length by 12.22%–22.37% compared with the MM pattern, reflecting an adaptive strategy of increasing fine root proportion to expand absorptive surface area (Dong et al., 2024b). The elevated fine root proportion enhances water and nutrient uptake capacity, thereby establishing a morphological foundation for efficient N utilization. The differentiation in N acquisition strategies and the improvement in utilization efficiency are direct consequences of root spatial heterogeneity. The deep-rooted architecture enables maize to efficiently absorb nitrate N from deeper soil depths,

resulting in a 37.33% increase in aboveground N accumulation compared with the MM pattern. This competitive pressure triggers a physiological compensation mechanism in peanuts: reduced soil N availability alleviates N repression, stimulating peanut to enhance nitrogenase activity to compensate for N deficit (Zhang et al., 2024). This study confirms that under appropriate N application (N_{100} and N_{200} levels), the system achieves optimal NAE and NUE. The underlying mechanisms for this efficiency improvement include: spatial root differentiation reduces competitive consumption during N uptake, allowing more absorbed N to be allocated to growth organs; and maize competitive pressure on soil N significantly enhances peanut' s biological N fixation, providing an additional N source to the system. This synergistic relationship of "spatial partitioning-functional complementarity" enhances both total N accumulation and utilization efficiency in the intercropping system (Dong et al., 2022). Management significantly regulates root development and N allocation. Appropriate N application (N_{200} level) optimizes root architecture by promoting the synthesis and transport of endogenous hormones, thereby stimulating root branching and elongation (Huang et al., 2024). Consequently, maize maintains a high NHI (78.26%-79.48%), and its deep and extensive root network ensures stable N supply during later growth stages, facilitating efficient N translocation to grains. However, excessive N application (N_{300} and N_{400} levels) disrupts the carbon-N balance in plants, inhibits the allocation of photosynthetic products to roots, reduces root-to-shoot ratio and fine root proportion, and increases N leaching and volatilization losses (Qi and Hu, 2022), leading to a sharp decline in NAE and NUE. Planting row configuration further modulates interspecific interactions. The 6M6P pattern intensifies systemic resource competition, prompting maize to deepen its root exploration while stimulating peanut to enhance physiological root activity for improved resource use efficiency (Zheng et al., 2021). This competition-driven functional differentiation of roots transforms into a synergistic effect under appropriate N application (N_{200} level). Ultimately, through multi-level regulation of "root differentiation-functional complementarity-N redistribution," the system achieves maximized overall NUE.

4.3 Productivity and LER

LER is a key indicator for measuring the land use efficiency of intercropping systems relative to monoculture, with values greater than 1.00 indicating a yield advantage for intercropping (Fu et al., 2023). In this two-year study, the LER values of the maize and peanut intercropping system exceeded 1.00 across all N application levels (1.14-1.30 for the 6M6P pattern), confirming that intercropping significantly improves land use efficiency. LER values were generally higher under low N treatments than under high N treatments, and the 6M6P pattern exhibited higher LER than the 4M4P pattern. These results suggest that optimizing N input and row configuration is key to achieving yield advantages and efficient resource utilization. These findings are consistent with previous researches (Jiao et al., 2016; Liu et al., 2023). The improvement in system productivity stems from the complementary synergy of aboveground and belowground resources, particularly root spatial distribution and N utilization. Intercropping promotes maize plant height, stem diameter, and aboveground dry matter accumulation, significantly increasing maize grain yield, which becomes the primary contributor to the overall system yield. This process is closely related to the efficient N absorption capacity of maize deep root system. In contrast, peanut growth was significantly suppressed under intercropping, with grain yield reductions ranging from 57.44% to 76.09%. This result aligns with previous studies showing yield reductions in leguminous crops when intercropped with non-leguminous crops (Tarirai et al., 2022). This phenomenon can be attributed to two mechanisms: first, during the overlapping growth period, maize' s fibrous root system exhibits stronger nutrient competition in the shallow soil depths, limiting peanut' s absorption of N, phosphorus, and other nutrients; second, atmospheric N fixed by peanut through nodulation is partially utilized by maize, forming a synergistic "N fixation-transfer" pathway (Dong et al., 2024). However, this N transfer does not fully compensate for the yield loss in peanuts due to competitive suppression. N application levels significantly regulate system productivity and interspecific competition. In this study, the yields of both crops peaked at the

N_{200} level, where intercropping advantages were most pronounced. This result indicates that appropriate N application can synergistically promote crop yields and overall system productivity. Excessive N application (N_{300} and N_{400} levels) led to excessive vegetative growth in maize, aggravated canopy closure, further deteriorated light conditions for peanuts, delayed peanut maturity, and induced foliar diseases, ultimately reducing peanut yield and total system productivity (Han et al., 2022). This result demonstrates that in maize and peanut intercropping systems, moderate N reduction can alleviate interspecific competition, optimize resource allocation, and achieve synergistic improvements in system productivity and land use efficiency. Based on the findings of this study, we recommended an application rate of 200 kg/hm^2 in combination with the 6M6P intercropping pattern for maize and peanut intercropping systems. This configuration promotes deeper root proliferation in maize (20-60 cm), with root length density increasing by 15.48%-54.76%, thereby enhancing N uptake from deeper soil depths while reducing nutrient competition with peanut in the topsoil and sustaining peanut nodulation and biological N fixation. In practice, conventional N application rates (300-400 kg/hm^2) can be reduced by 33.00%-50.00% without compromising system productivity. Future research should further validate the adaptability of this pattern under diverse soil and climatic conditions and investigate the long-term effects of N reduction on soil fertility and microbial communities.

5 Conclusions

Overall, in terms of aboveground morphology and interspecific competition, maize under the 6M6P pattern exhibited significant increases in plant height and basal stem circumference, indicating enhanced aboveground competitiveness. In contrast, peanuts demonstrated optimal morphological development under the MP pattern with appropriate N application (N_{200} level), suggesting that rational row arrangement and N management can mitigate the shading and nutrient competition exerted by maize on peanuts. Belowground, intercropped maize extended its root system into peanut rows, primarily occupying the 0–40 cm soil depth, which increased RLD. This expanded root spatial distribution improved N uptake efficiency, promoted dry matter accumulation, and maintained a higher NHI. The increase in SRL of both crops in deeper soil depths reflects their adaptive root plasticity in response to heterogeneous nutrient availability. Excessive N application reduced NUE in both maize and peanuts, whereas appropriate nitrogen level enhanced NUE while reducing environmental costs. The advantages of the intercropping system were not only reflected in the competitive superiority of maize but also in improved land productivity, as evidenced by a LER of 1.27–1.30, confirming the yield advantage of intercropping over monoculture. These findings indicate that optimizing row and N input can alleviate interspecific competition, thereby fostering complementary resource use and synergistic effects within the system.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

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