Moderation of nitrogen input and integration of legumes via intercropping enable sustainable intensification of wheat-maize double cropping in the North China Plain : A four-year rotation study

Agricultural Systems

Xia, Haiyong; Qiao, Yuetong; Li, Xiaojing; Xue, Yanhui; Wang, Na et al

https://doi.org/10.1016/j.agsy.2022.103540

Agricultural Systems 204 (2023) 103540

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Moderation of nitrogen input and integration of legumes via intercropping enable sustainable intensification of wheat-maize double cropping in the North China Plain: A four-year rotation study

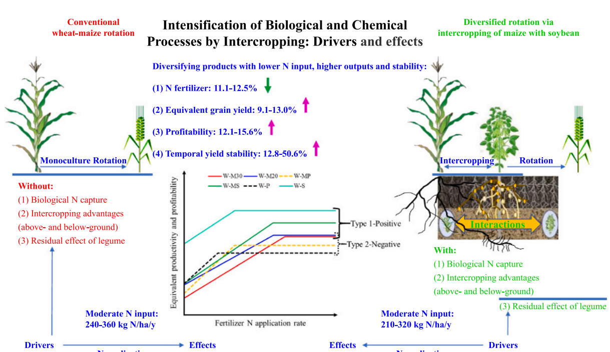
Haiyong Xia [a,b,c,f,*], Yuetong Qiao [a,b], Xiaojing Li [a,b], Yanhui Xue [a], Na Wang [a], Wei Yan [d], Yanfang Xue [d], Zhenling Cui [d,e], Wopke van der Werf [f,*]

[a] Crop Research Institute, National Engineering Laboratory for Wheat and Maize, Shandong Academy of Agricultural Sciences, Jinan 250100, China
[b] College of Life Sciences, Shandong Normal University, Jinan 250014, China
[c] College of Agronomy, Qingdao Agricultural University, Qingdao 266109, China
[d] Maize Research Institute, National Engineering Laboratory for Wheat and Maize, Shandong Academy of Agricultural Sciences, Jinan 250100, China
[e] College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant-Soil Interactions, Ministry of Education, China Agricultural University, Beijing 100193, China
[f] Center for Crop Systems Analysis, Wageningen University & Research, Wageningen 6700 AK, the Netherlands

HIGHLIGHTS

- The sustainability of wheat-maize (W-M) rotation is threatened by excessive fertilizer input and nitrogen (N) surplus.
- Integration of legumes in W-M via intercropping was proposed to lower N input with high outputs and yield stability.
- Yield, yield stability and profitability were compared among six rotations (with legumes and without) under four N levels.
- W-M with soybean intercropping (W-MS) saved N input and had higher yield, profit and yield stability than W-M.
- W-MS with moderate N application could replace conventional W-M in the North China Plain for its comprehensive performance.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Dr. Jagadish Timsina

Keywords:
Simultaneous intercropping
Land equivalent ratio
Gross margin

ABSTRACT

CONTEXT: Wheat-maize (W-M) double cropping is the dominant land use system in the North China Plain (NCP). This system has high grain output but suffers from high fertilizer input and nitrogen (N) surplus. Meanwhile, the market demands more protein and oil crops, such as soybean or peanut.
OBJECTIVE: Here, we assess whether incorporation of legumes into W-M via intercropping with maize can contribute to lower annual N input while maintaining high annual outputs and diversifying products with high yield stability.

* Corresponding authors at: Crop Research Institute, National Engineering Laboratory for Wheat and Maize, Shandong Academy of Agricultural Sciences, Jinan 250100, China; Center for Crop Systems Analysis, Wageningen University & Research, Wageningen 6700 AK, the Netherlands.
E-mail addresses: haiyongxia@cau.edu.cn (H. Xia), wopke.vanderwerf@wur.nl (W. van der Werf).

https://doi.org/10.1016/j.agsy.2022.103540
Received 16 July 2022; Received in revised form 27 September 2022; Accepted 16 October 2022
Available online 25 October 2022
0308-521X/

Temporal stability
Sustainability and resilience

METHODS: We compared yield, yield stability, and profitability of six rotation systems: W-M30 (at the maize inter-plant distance of 30 cm), the density-increased W-M20, wheat-soybean (W-S), wheat-peanut (W-P), and wheat with an intercrop of maize (at the inter-plant distance of 20 cm) and soybean (W-MS) or peanut (W-MP). Four annual N input levels were compared: N0 (no N input), N1 (reduced N input), N2 (target practice), and N3 (current high input).

RESULTS AND CONCLUSIONS: Results over four years showed that replacing maize by maize/legume intercrops had a similar wheat yield as that of W-M while the N input was intermediate between W-M and W-legume rotations. Total actual/equivalent grain yields and gross margins of W-MS or W-MP were consistently intermediate between W-M and W-legume rotations. Intercropping enhanced the yield and temporal yield stability of maize per plant, with benefits for both yield stability of the intercropping system of maize season and the annual rotation system. Averaged over six rotation systems, increasing N supply increased the annual total actual/equivalent grain yield, gross margin and yield stability to a plateau starting at N1 or N2, without a further significant increase at N3. Specifically, the response of total equivalent yield or gross margin of each annual system to increasing N supply could be fitted by the linear-plateau model. Compared to the response curve of W-M, W-MS and W-S reached the plateau with a lower N input and higher yield and profit, while W-MP and W-P reached the plateau with lower N input but decreased the yield and profit. Compared to W-M with 240–360 kg N/ha/year, W-MS used 210–320 kg N/ha/year saving 11.1–12.5% fertilizer N, while maintaining or improving production by 9.1–13.0%, and improving profitability by 12.1–15.6% and temporal yield stability by 12.8–50.6%.

SIGNIFICANCE: W-MS diversifies products with lower N input and higher outputs, profitability, and temporal yield stability than conventional W-M, thus is highly recommended towards productive and sustainable agriculture in the NCP.

1. Introduction

Double cropping of winter wheat and summer maize (W-M) is the most common agricultural production system in the North China Plain (NCP) (Zhao et al., 2022a). Approximately 45% of the national wheat and 30% of the national maize are produced in this system (Lu et al., 2021). However, the system is considered environmentally unsustainable due to overuse of nitrogen (N) fertilizer (Yin et al., 2021). Chinese farmers apply about totally 550–600 kg N/ha each year for W-M, far exceeding the annual N demand of about totally 330 kg N/ha (Zhao et al., 2015). Excessive N application reduces N-use efficiency and results in nitrate leaching to the surface water and atmospheric emissions of NH_3, N_2O and NO (Yin et al., 2021; Liu et al., 2022). A reduction in inputs is necessary to enable a cleaner production with lower N losses to the environment. Incorporation of N_2 fixing legumes offers potential to lower fertilizer use, though it should be considered that replacing maize by legumes would also result in a major reduction in grain output, as legumes have lower yields than maize (Nemecek et al., 2008; Thierfelder et al., 2012; Chen et al., 2019; Rose et al., 2019; Gao et al., 2020; Xiao et al., 2022; Xu et al., 2022).

Intercropping is the cultivation of two or more intermingled crop species on the same field (Vandermeer, 1989). A meta-analysis of drivers of yield gain showed that intercrops with maize had greater yield gains than intercrops without maize (Li et al., 2020). Strip intercropping of maize with legumes is the most common type of intercropping system in the world (Li et al., 2020). Component crop species may be grown simultaneously within the same field or partly overlapping, with different sowing or harvesting dates. As maize has a late and long growing season, it is usually harvested after a legume crop in a system known as relay strip intercropping (Li et al., 2013; Brooker et al., 2015). Intercrops of maize with legumes have lower N fertilizer input requirement than sole maize crops due to N_2 fixation by the legume (Li et al., 2020; Stomph et al., 2020; Xu et al., 2020).

At present, the Chinese self-sufficiency rate of cereal grains is >95%, but the self-sufficiency rate of edible oils is <35%, and >80% of soybean protein relies on imports (The China Agricultural Sector Development Report, 2020). The Chinese government aims to increase protein and oil crop self-sufficiency, but this target needs to be achieved on the current land area as China has little spare areas to reclaim new land for agriculture. Intercropping may, however, increase land use efficiency and achieve an increase in sufficiency of protein and oil crops without land clearing (Li et al., 2021). Therefore, for the first time during the past 30 years, the Chinese Government aims to promote strip intercropping, especially maize-based intercropping with peanut or soybean, in Northeastern China (i.e. Liaoning, Jilin and Heilongjiang provinces), Chinese Huang-Huai-Hai plain (mainly including Hebei, Shandong, Henan and Anhui provinces) and Southwestern China (e.g. Sichuan and Yunnan provinces) (General Office of the State Council of China, 2015; *China's No. 1 Central Document*, 2022).

Most of the productivity gains in intercropping are observed under conditions of relay strip intercropping with temporal niche differentiation (TND), especially in temperate climate areas with a growing season longer than necessary for growing one crop, but too short for growing two consecutive crops as in double cropping, e.g. in northwestern and southwestern China) (Li et al., 2001; Yu et al., 2015; van Oort et al., 2020; Chai et al., 2021; Li et al., 2021); and the yield advantage was increased at greater TND (Yu et al., 2015; Li et al., 2020). Relatively few studies have focused on performance of simultaneous maize/legume intercropping systems, in which the two species are sown and harvested simultaneously.

In the north of China, three cropping systems mainly exist: (1) conventional one-crop-per-year monocultures occupy most areas of northeastern China (Liaoning, Jilin, Heilongjiang); (2) two-crops-per-year relay intercropping in northwestern China (e.g. Gansu province); and (3) most areas of the North China Plain (Hebei, Shandong, Henan) are occupied by the two-crops-per-year double cropping (Li et al., 2020; Chai et al., 2021; Sun et al., 2021; Zhao et al., 2022a). Intercropping and diversified crop rotations have a strong potential to safeguard food security and counteract the severe degradation of arable land and air pollution in the North China Plain (Feike et al., 2012; Fung et al., 2019; Yang et al., 2021). A shift from cereal production in conventional W-M to a three-crops-per-year diversified rotation that includes legumes via intercropping with maize in the NCP would be beneficial to increase China's self-sufficiency for edible oils and soybean proteins. Such a shift would reduce the need for N fertilizer, irrigation water, herbicides and pesticides, and decrease the large emissions of reactive N compounds, e.g. ammonia (NH_3), into the atmosphere, where they become significant components of fine particulate matter air pollution ($PM_{2.5}$). In such a system, the winter wheat crop could be followed by a simultaneous intercrop of summer maize with peanut or soybean. However, the impacts of such a shift on total food production, resource use, farmer profits, eco-sustainability and environmental friendship of the whole year under field conditions have not been studied or evaluated, especially in the NCP, where the relay intercropping system of wheat-maize had been very popular in the past practice of intercropping (Feike et al., 2012). In addition, a three-crops-per-year diversified system that includes legumes via intercropping could also be applicable to South China and South Asia (e.g. India, Pakistan, Bangladesh and Nepal), where maize-rice (an emerging cropping system in subtropical region of China), rice-wheat, rice-maize and maize-wheat cropping systems face similar unsustainability issues and research gaps as the W-M system in the NCP (Timsina et al., 2010; Chauhan et al., 2012; Sun et al., 2019; Mehmood et al., 2020; Bhatt et al., 2021), and has a global relevance for countries with double cropping or rotation systems (Jeong et al., 2014; Barbieri et al., 2019; Zhao et al., 2022b).

Incorporation of legumes in rotations has the potential to increase subsequent crop yields and economic returns, and reduce N fertilizer requirements (Zhao et al., 2022b). However, there is still lack of information on effects of intercropping of maize with legumes on subsequent wheat performance and their effects on the annual yield stability, especially lack of long-term study (Liang, 2022). Whether the yield of annual double cropping systems could be maintained with the increase of experimental year under different N application rates, especially regarding the comparison of annual systems with legumes (intercropping or monoculture) and without legumes under low N supply, are emerging questions worthy to be addressed (Liang, 2022). Intercropping has been found to stabilize crop yields under contrasting climatic conditions (Koskey et al., 2022). Increasing the planting density of maize in monoculture may decrease yield stability due to lodging (Winans et al., 2021). Studies on responses of the year-to-year temporal yield stability or yield retention ability of annual double cropping systems with legume intercropping to climatic and soil N changes will provide new knowledge on sustainable intensification of cropping systems towards more resilient to management (e.g. increasing the planting density), and climatic and environmental changes.

Here we report on a 4-year field experiment with permanent plots comparing different rotation systems with wheat and maize, peanut or soybean, with or without maize intercropping with legumes at different annual N input levels to study agronomic and economic performance of a more diversified cropping system. We test whether increases in crop diversity via the integration of intercropping with rotation improve productivity, yield stability, and profitability, with lower N fertilizer input. Specific hypotheses are: (1) Replacing maize by maize/legume intercropping in wheat-maize rotation lowers annual N input and maintains wheat yield. (2) Productivity and profitability of diversified rotations with intercropping are intermediate between conventional wheat-maize and wheat-legume rotation; therefore intercropping plays a buffering role in satisfying demands of different crops while providing considerable farmer profits. (3) Moderation of N inputs below current high level does not result in yield penalties. (4) Intercropping facilitates the growth of dominant species maize, thus increases the year-to-year yield stability of maize, the stability of intercropping system and the annual diversified rotation system as a whole. (5) Integration of appropriate intercropping and moderate N input has better overall performance than the conventional wheat-maize double cropping, enabling sustainable intensification.

2. Materials and methods

2.1. Study site

A four-year field experiment was conducted from mid-June 2017 to mid-June 2021 at Jiyang Experimental Station (36°58°Ji 116Jiyan) of Shandong Academy of Agricultural Sciences, Jinan, China. The area has a continental and warm-temperate monsoon climate with hot and rainy summer and a cold and dry spring and winter. The annual mean temperature is 12.0–13.6 °C. The cumulative temperature above 10 °C is 4000–4500 °Cd, and above 0 °C is 4500–5000 °Cd. The frost-free period is 195–210 days, and the area has 2400–2700 h of sunshine annually. The annual precipitation is 500–700 mm and potential evaporation is 1800–2100 mm. Weather data of the study site for the 4 years were obtained from the Shandong Meteorological Bureau (Fig. 1). Soil of this experimental site is a calcareous yellow fluvo-aquic sandy loam, with a bulk density of 1.49 g/cm^3 and a pH of 7.6 (1:2.5 *w/v* in water). It contains 13.3 g/kg organic matter, total N of 0.95 g/kg, alkaline hydrolyzable N of 82.6 mg/kg, Olsen-phosphorus (P) is 15.4 mg/kg, and NH_4OAc-exchangeable potassium (K) is 107.1 mg/kg in the top 30 cm.

2.2. Experimental design and crop management

For the summer maize season from mid-June to mid-October, the experiment was a split-plot design with four N input levels as main plot factor and six cropping systems as sub-plot factor. The main plots had four basal application rates of N (0, 60, 80, 100 kg/ha) given to all cropping systems before sowing (broadcast fertilization) (Table 1). A second application of N fertilizer, equal to the basal fertilizer, was top-dressed by broadcasting at pre-tasseling to maize monoculture plots and to the area between adjacent maize rows in intercrop plots, but not to the legumes and the area between maize and legume rows. N fertilizer was given as urea. We used maize (*Zea mays* L.) variety “Xianyu no. 335”, peanut (*Arachis hypogaea* L.) variety “Huayu no. 25” and soybean (*Glycine* max L.) variety “Qihuang no. 34”. In each year, maize, peanut and soybean were sown around 25 June and harvested around 10 October.

The sub-plot treatments comprised six cropping systems for the summer crops, including conventional sole maize with a plant distance in the row of 30 cm, labeled M30, a density-increased sole maize with a plant distance in the row of 20 cm, labeled M20, sole peanut, labeled P, sole soybean, labeled S, maize/peanut intercropping, labeled MP, and maize/soybean intercropping, labeled MS. Intercrops had maize at a plant distance in the row of 20 cm, like M20. Across the two factors of N input and cropping system, there were $4 \times 6 = 24$ treatments, each with three replicates. All plots were permanent over 4 years to observe possible cumulative treatment effects.

Conventional sole maize was grown at a row distance of 50 cm (Fig. 2), resulting in a density of 6.7 plants/m^2 in M30, consistent with local farmers’ practice. Density-increased sole maize M20 had the same row distance and a density of 10 plants/m^2. Sole peanut and soybean were planted by hole sowing at a row distance of 50 cm, with an inter-hole distance in the row of 20 cm, resulting a density of 10 holes/m^2 and 20 plants/m^2 (each hole with two seedlings). Row and inter-plant distances of maize in intercropping were the same as in the density-increased sole maize (M20) while row and inter-hole distances of peanut or soybean in intercropping were the same as in the sole crops. Intercrops were grown in species strips comprising two rows. The gap between neighboring maize and legume rows in intercropping was 50 cm (Fig. 2). Maize and the legume thus occupied each half of the intercropped area. Compared to M20 and sole legume, the relative densities of intercropped maize and peanut or soybean were all 0.5, indicating a replacement intercrop; compared to M30, the relative density of intercropped maize was 0.75, which was higher than would have been the case in a replacement intercropping. Here, the relative density is defined as the plant density of a species in intercropping divided by plant density in the sole cropping, and density is expressed as the number of plants per unit area of the whole cropping system (Zhang et al., 2007).

Each plot (mono- or intercropped) had an area of 40 m^2 (8.0 m width $\times$ 5.0 m length), with rows oriented north to south. A sole crop plot comprised 16 rows of maize, peanut or soybean while an intercropped plot consisted of 8 maize rows and 8 peanut or soybean rows, planted in alternating strips each comprising two rows of the same species. Maize and legume strips in the intercrop plots were kept in the same position year after year.

Each year, wheat (*Triticum aestivum* L.) variety “Jimai no. 22” was sown in the autumn at a row distance of 20 cm (Fig. 2), around 25 October, and harvested around 10 June in the following year. A basal

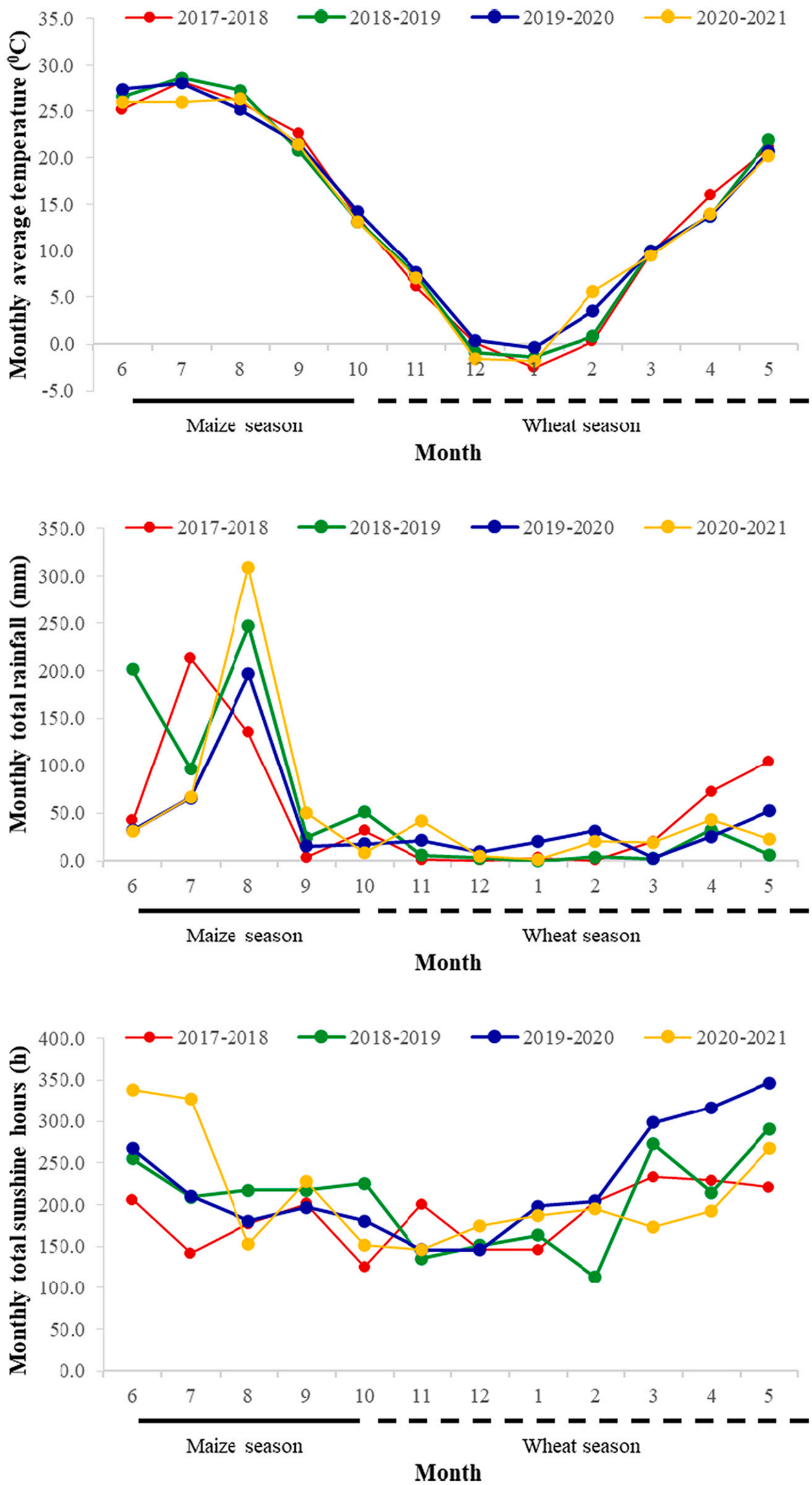


Fig. 1. Monthly average temperature, total rainfall and total sunshine hours of Jiyang, Shandong Province, China, over June 2017–May 2021.

application of N in wheat of 0, 60, 100 and 120 kg/ha was given before sowing (broadcast fertilization) (Table 1). A topdressing with the same dose of N was given by broadcasting at wheat regreening in spring. N was given as urea.

N input was labeled as N0, N1, N2 and N3; where N0 is no N supply, leading to N deficiency, N1 is below the recommended or standard rate for maize and wheat, N2 is considered standard or adequate for maize and wheat in the study area, and N3 is considered high for maize and wheat. There were three types of double cropping systems: (1) conventional winter wheat-summer maize (two-crops-per-year); (2) conventional winter wheat-legume (peanut or soybean) (two-crops-per-year); and (3) the double cropping system of winter wheat-maize/legume intercropping (three-crops-per-year). Across these three double cropping systems, N1, N2 and N3 ranged 180–240, 280–360 and 340–440 kg/ha, respectively (Table 1).

P fertilizer (150 kg P_2O_5/ha, supplied as calcium superphosphate)

Table 1
Detailed N application strategy for maize, legume and wheat across the 4 years from mid-June 2017 to mid-June 2021.

Cropping system	Summer/autumn (maize, soybean, peanut)		Winter/spring (wheat)		Total fertilizer (kg/ha)
	Basal fertilization (kg/ha)	Topdressing at maize pre-tasseling stage[1] (kg/ha)	Basal fertilization (kg/ha)	Topdressing at wheat regreening stage (kg/ha)	
Wheat-Maize	0	0	0	0	0
	60	60	60	60	240
	80	80	100	100	360
	100	100	120	120	440
Wheat-Maize/Legume intercropping	0	0	0	0	0
	60	30	60	60	210
	80	40	100	100	320
	100	50	120	120	390
Wheat-Legume	0	0	0	0	0
	60	0	60	60	180
	80	0	100	100	280
	100	0	120	120	340

[1] Evenly applied in mono-cropped plots and in the area between maize rows in intercrop plots.

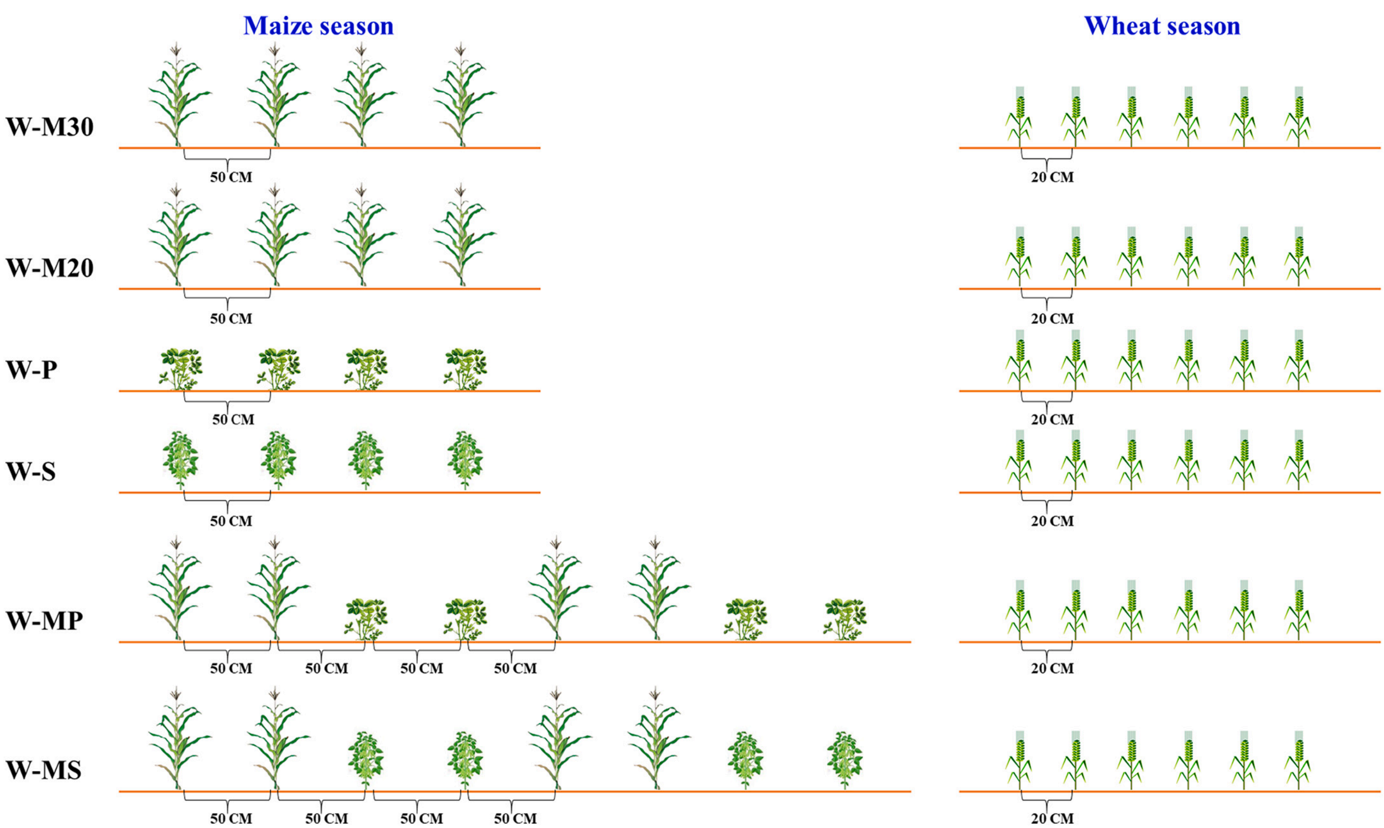


Fig. 2. Schematic diagram of six different double cropping systems with wheat (W) as a winter crop and maize (M), peanut (P), soybean (S), maize/peanut intercropping (MP), or maize/soybean intercropping (MS) during summer. The inter-plant distance of maize is 30 cm in M30, and 20 cm in M20 and intercropping.

and K fertilizer (120 kg K_2O/ha, supplied as potassium sulfate) were evenly broadcast and incorporated into the upper 20 cm of the soil as basal fertilizers before sowing of each crop. All plots received the same amount of P or K fertilizer in the summer maize growing season or in the winter wheat growing season. No organic manure was applied. Maize and wheat straw was returned to the field, while peanut and soybean straw was removed. Irrigation, weeds, pests, and diseases were managed according to farmers' practice.

2.3. Plant sampling

Grain yields of maize and legumes were determined by harvesting two adjacent rows (5 m length × 2 rows) per each mono- or intercropped plot. Grain yields of wheat were measured in a 1 m^2 area (1 m × 1 m) in the center of each plot. Maize ears and soybean pods were air-dried to standard moisture content (−14.0% and − 13.5%, respectively) and then threshed to calculate final grain yields. Peanut pods were air-dried to standard moisture content (−10.0%) to assess pod yield. Wheat grain yields were calculated when air-dried to standard moisture content (−13.0%).

We also collected additional aboveground plant samples from a smaller area in each plot to determine the harvest index and total biomass, excluding roots. The biomass sampling area was 0.6 m length × 1.0 m width in maize and legumes, and 0.5 m length × 0.4 m width in wheat. The number of plants was counted, and samples were manually separated into grain and straw and oven-dried at 65–70 °C (48 h) to constant mass.

2.4. Calculations

2.4.1. Land equivalent ratio (LER)

The land equivalent ratio (LER) of summer crops is calculated as the sum of partial LERs (relative yields) per species ($pLER_m$ and $pLER_l$):

$$LER = pLER_m + pLER_l = Y_m/M_m + Y_l/M_l \quad (1)$$

where "m" and "l" indicate maize and legume (peanut or soybean), respectively, Y is the yield (per unit of total area of the intercrop) in intercropping, and M is the yield in monoculture. An LER > 1.0 indicates that intercropping saves land, while LER = 1.0 or < 1.0 indicate non-advantage or a disadvantage, respectively. LER and pLER were calculated for both grain yields and biomass yields at the same N application level in the same year. Thus, the LER was used to assess intercropping effects, given the level of N input. The sole crop yield in M20 was used to calculate the pLER of maize.

2.4.2. Temporal yield stability (i.e. the year-to-year stability)

The inverse of the coefficient of variation was used as a measure of temporal stability. It was calculated for each plot as μ/σ, where μ is the temporal mean of grain/pod yield and σ is its temporal standard deviation during the study period of four years (Mehrabi and Ramankutty, 2019; Renard and Tilman, 2019; Egli et al., 2021).

2.4.3. Equivalent grain yield

To compare grain yields of different crop species or cropping systems, grain/pod yields of maize, peanut and soybean were converted into wheat equivalent economic yield (WEEY, kg/ha) (Pradhan et al., 2018; Sun et al., 2021):

$$WEEY = Y_{nw} \times P_{nw}/P_w \quad (2)$$

where "nw" and "w" indicate non-wheat crop and wheat, respectively; Y is the grain/pod yield; P is the grain/pod price.

2.4.4. Gross margin

Economic incentive is the main driver of N fertilization by farmers. Partial budgets were therefore calculated that included only the revenue from yield and the costs of seeds and fertilizer. These budgets are simple and relevant because other budget components do not depend on the input of fertilizer. Thus the gross margin (G) was calculated as the product of yield and price minus the costs of fertilizer and seeds (Huang et al., 2015; Gao et al., 2020).

$$G = Y \times P - C \quad (3)$$

where Y is the crop yield, P is the market price, and C indicates fertilizer and seed costs. For intercropping systems, G was calculated as:

$$G = Y_m \times P_m + Y_l \times P_l - C \quad (4)$$

where "m", "l" represent maize, legume (peanut or soybean), respectively.

The average price for urea in Chinese market was 0.28 $/kg over the period 2017–2021. Calcium superphosphate and potassium sulfate cost 0.12 and 0.59 $/kg, respectively. On average, seeds of wheat, maize, peanut and soybean cost 0.65, 6.26, 2.78 and 2.02 $/kg, respectively. The farm gate prices for wheat, maize, peanut and soybean, and prices of inputs were obtained through our interviews with local dealers. The average prices for wheat, maize and soybean grains were 0.34, 0.28 and 0.85 $/kg, respectively, and for peanut pods was 0.93 $/kg.

2.5. Statistical analysis

We carried out a two-factor split-plot analysis of variance (ANOVA) in SAS 9.4 (SAS Institute, Cary, NC, USA), with N level and cropping system as factors, and a one-way ANOVA for the interaction effect of N level and cropping system, to analyze the data within the same experimental year or aggregated over years. The data of the year-to-year temporal yield stability was analyzed by the two-factor split-plot ANOVA. A three-way ANOVA with N level, cropping system and year as factors was used to analyze the pooled data of each index/parameter from the four years' experiment. Differences were compared by Fisher's protected least significant difference (LSD) at the 0.05 probability (*P*) level. Yield and profit response curves to the N application rate in the different annual cropping systems were generated using the linear-plateau model according to the NLIN procedure in SAS (Yan et al., 2014).

3. Results

3.1. Grain yield and biomass

Maize biomass and grain yield were significantly affected by year, N level and cropping system but little affected by the interaction of these three factors (Table 2). The pLERs for biomass and grain yield of maize in intercropping with soybean or peanut were significantly affected by year and N level but not by the companion crop species (Fig. 3). Compared with N0, maize grain yields increased by 17.1% at N1, 15.9% at N2 and 15.9% at N3, and grain yield pLERs of maize increased from 0.66 at N0 to 0.76 at N1, 0.74 at N2 and 0.78 at N3, averaged over years and cropping systems. Increasing the plant density from 67,000 (M30) to 100,000 plants/ha (M20) significantly increased the average maize grain yield from 10.1 to 10.9 t/ha by 7.9%. Maize grain yields were significantly lower in intercropping than in sole cropping. Similar results were obtained for maize biomass and biomass yield pLERs. The grain/biomass yield pLERs for intercropped maize ranged from 0.60 to 0.80, which is much higher than 0.5 (the area ratio occupied by only maize in the intercropping system), demonstrating substantial yield increase, i.e. the intercrop reached 60–80% of the sole maize yield using only 50% land area of sole maize. No significant differences in yield pLER were found between maize intercropped with peanut and soybean.

On average over years and N levels, intercropping reduced grain or pod/biomass yields of peanut and soybean and their harvest indexes significantly (Table 3). Compared with the significant reduction of the average harvest index of soybean from 0.54 in sole cropping to 0.52 in intercropping, the average harvest index of peanut was much more reduced from 0.46 in sole cropping to 0.33 in intercropping (Table 3). The average grain yield pLER of peanut was 0.21, which was significantly lower than that of soybean 0.29, but not for the biomass yield pLER (Fig. 3). On average over years and cropping systems, compared with N0, the averaged grain/biomass yields of soybean at N2 and N3, and the harvest index of peanut at N3 were all decreased, while the harvest indexes of soybean at N2 and N3 were significantly increased. N addition decreased the pLERs of the legumes from 0.23 to 0.33 to 0.17–0.30, indicating the suppression effect of intercropping on legume growth was increased. The pLERs of intercropped peanut and soybean ranged from 0.17 to 0.33, and were much lower than 0.5 (the area ratio occupied by the legume in the intercropping system), indicating a huge yield penalty at plant level.

N level, cropping system, and experimental year significantly affected grain yield LERs of the maize/legume intercrops (Fig. 3). With greater N input, the LER was significantly increased from 0.94 at N0 to 1.04 at N3 for grain yield, and from 0.96 at N0 to 1.05 at N3 for biomass yield, averaged over years and mixture with soybean or peanut. On average, the LER for grain yield (not biomass yield) of maize intercropping with peanut was smaller than one (0.95, indicating a disadvantage in land use), which was significantly lower than that of maize

Table 2
Effects of nitrogen (N) input and cropping system (C) on yield and economic parameters of summer maize averaged across four years (Y), 2017–2020.

Parameters	N application gradient	Maize					ANOVA			
		M30	M20	MP-M	MS-M	Mean	Variable	*P*	Variable	*P*
	N0	8.7b	10.5a	7.1c	6.5c	8.2B	Y	< 0.0001	Y × N	0.2957
	N1	10.3a	11.3a	8.7b	8.2b	9.6A	N	< 0.0001	Y × C	0.1297
Grain yield (t/ha)	**N2**	10.6a	11.1a	7.9b	8.5b	9.5A	C	< 0.0001	N × C	0.6027
	N3	10.7a	10.9a	8.4b	8.1b	9.5A			Y × N × C	0.6004
	Mean	10.1B	10.9A	8.0C	7.8C	9.2				
	N0	18.8b	21.9a	15.0c	13.0c	17.1B	Y	< 0.0001	Y × N	0.8004
	N1	21.4a	23.8a	17.4b	16.5b	19.8A	N	< 0.0001	Y × C	0.0048
Biomass (t/ha)	**N2**	21.4ab	23.5a	16.4c	18.3bc	19.9A	C	< 0.0001	N × C	0.6263
	N3	22.1a	22.8a	17.0b	16.3b	19.6A			Y × N × C	0.4060
	Mean	20.9B	23.0A	16.4C	16.0C	19.1				
	N0	0.48a	0.49a	0.49a	0.51a	0.50A	Y	< 0.0001	Y × N	0.2036
	N1	0.50a	0.50a	0.51a	0.51a	0.51A	N	0.2909	Y × C	0.5213
Harvest index	**N2**	0.52a	0.48b	0.49ab	0.48b	0.49A	C	0.6259	N × C	0.3574
	N3	0.50a	0.50a	0.51a	0.51a	0.51A			Y × N × C	0.5475
	Mean	0.50A	0.49A	0.50A	0.50A	0.50				
	N0	7.1a	4.9a	6.5a	8.2a	6.7A	N	0.5678		
	N1	10.6a	6.0a	6.4a	10.8a	8.4A	C	0.0406		
	N2	5.6a	8.5a	7.3a	13.9a	8.8A	N × C	0.5548		
	N3	6.6ab	5.3b	11.3ab	11.6a	8.7A				
Grain yield stability	**Mean**	7.5B	6.1B	7.9AB	11.1A	8.2				
	N0	2072b	2509a	1780bc	1607c	1992B	Y	< 0.0001	Y × N	0.2957
	N1	2438ab	2648a	2179bc	2033c	2324A	N	0.0002	Y × C	0.1297
Gross margin ($/ha)	**N2**	2509ab	2589a	1960c	2105bc	2291A	C	< 0.0001	N × C	0.5561
	N3	2511a	2488a	2084b	1987b	2267A			Y × N × C	0.6004
	Mean	2382B	2559A	2001C	1933C	2219				

Values followed by the same lowercase letters are not significantly different among different cropping treatments at the 5% level, as judged by Fisher's protected LSD (horizontal comparison); means followed by the same capital letters are not significantly different among different N levels (vertical comparison) or among different cropping treatments (horizontal comparison). M30, M20, MP-M and MS-M indicated sole maize at an inter-plant distance of 30 cm (M30) or 20 cm (M20), and maize in the intercropping system of maize and peanut (MP-M) or soybean (MS-M), respectively.

intercropping with soybean (1.02).

N level, cropping system, and experimental year significantly affected total equivalent/actual grain yields of six cropping systems of maize season (Table S1; Fig. 4). On average over years and cropping systems, the average total equivalent grain yield reached a peak at N1 and declined when the fertilizer input was increased from N1 to N3. Sole soybean had the highest average total equivalent grain yield, while sole peanut had the lowest. Increasing the planting density of sole maize significantly enhanced the average total equivalent grain yield by 7.2%. Compared with sole maize, MS significantly increased the average total equivalent grain yield by 11.2–19.3%, while MP decreased by 4.8–11.2%.

Wheat grain yield and biomass were significantly affected by N level, cropping system and experimental year (Table 4; Fig. 4). The grain yield of wheat, averaged over the six cropping systems and four years, was dramatically increased from 3.1 t/ha at N0 to 7.8 t/ha at N1, 8.5 t/ha at N2, and 8.7 t/ha at N3. Biomass yield showed a similar response to N input. Wheat yields were higher in cropping systems with soybean or peanut, than in systems in which maize was included as a sole crop or an intercrop with one of the legumes, especially at zero and/or low N input conditions. At N0, the wheat grain yield was 3.8–4.5 t/ha when rotated with peanut or soybean, compared to 2.4–2.9 t/ha when rotated with maize monoculture or intercropping. This effect of cropping system was masked at higher N input, with no significant differences observed at N2 and N3. Wheat harvest index was similar across treatments, ranging between 0.54 and 0.57. Wheat had relatively lower harvest index in M30 than in other cropping systems, especially at higher N input; the harvest index was higher at N2 and N3 than at N0, especially in the treatments MS, P and S, averaged across four years.

The total equivalent/actual grain yield achieved in a year (June to June next year) was significantly affected by N level, cropping system and experimental year (Tables S1 and S2; Fig. 4). Averaged across cropping systems and years, the total equivalent grain yield was dramatically increased from 11.8 t/ha at N0 to 17.4 t/ha at N1, 17.6 t/ha at N2 and 17.6 t/ha at N3, by 47.5%–49.2%, reaching a plateau at N1 with no significant differences among N1, N2 and N3. The total wheat-equivalent grain yield response of each annual cropping system to N application rate is shown in Fig. 5, and a linear-with-plateau model fitted the data well. The plateau was reached at input levels between N1 and N2 in W-M30, W-M20 and W-MS, and before N1 for W-MP, W-P and W-S. The calculated maximum grain yields based on these yield response curves ranged from 15.3 to 20.6 t/ha in the order W-S > W-MS > W-M20 > W-M30 > W-MP > W-P (Fig. 5). Averaged across N levels and years, compared with W-M30, increasing the maize planting density in W-M20 increased the total equivalent grain yield from 15.1 to 15.8 t/ha. W-S had the highest equivalent grain yield among systems with an average of 19.6 t/ha, while W-P had the lowest with an average of 14.8 t/ha; the averaged total equivalent grain yield of W-MS was 6.3–11.3% significantly higher than that of W-M, while W-MP had lower equivalent grain yield than W-M. The total equivalent/actual grain yield of W-MP was generally intermediate between W-M and W-P, and that of W-MS was intermediate between W-M and W-S (Tables S1 and S2; Fig. 4).

With the increase of experimental years, different N application rates would lead to greater yield gaps, at N0, the total equivalent grain yield could not be maintained (Table S2). Yield levels of W-MS, W-MP and W-P in N1 were similar to those in N2 and N3 in each year. On the other hand, in year 4, the yields of W-M30, W-M20 or W-S in N1 were significantly lower than in N3 though similar to those in N2. In all cropping systems, except W-M30 in the fourth year, yields were similar in N2 and N3 in each year (Table S2).

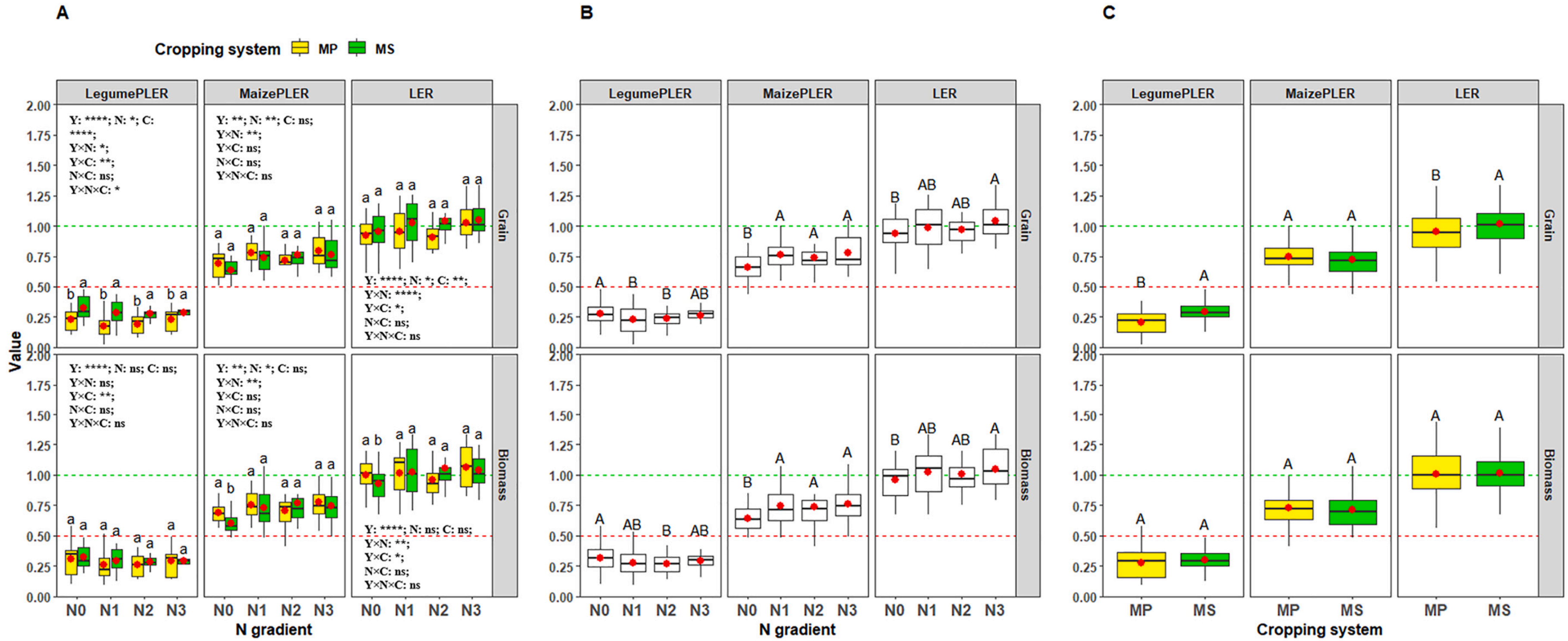


Fig. 3. Partial and total land equivalent ratios for grain and biomass yield (PLER, LER) of legumes and maize in intercropping as affected by nitrogen (N) application rates and cropping systems (C) across four experimental years (Y). MP and MS indicate maize intercropping with peanut and with soybean, respectively. N0, N1, N2 and N3 indicate no N supply, below the recommended or standard N rate for maize, standard or adequate N rate for maize, and high N rate for maize, respectively. Boxplots in A show data across four years ($n = 12$), in B show data across four years without distinguishing peanut or soybean ($n = 24$), and in C show data across four years without distinguishing N application rates ($n = 48$). Boxplot elements are defined as follows: the center line represents the median, box limits represent the upper and lower quartiles, whiskers represent 1.5 times interquartile range and the red point represent the mean. The same lowercase letters above boxes indicate no significant differences among different cropping systems separately for each N application rate at the 5% level by Fisher's protected LSD (A); the same capital letters above boxes indicate no significant differences among different N levels (B) or among different cropping systems (C) at the 5% level by Fisher's protected LSD. ANOVA results which indicate the probabilities (*P* values) of the source of variation were shown in A. *, **, ***, **** and ns indicate $P \leq 0.05$, 0.01, 0.001, 0.0001 and no significance, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Effects of nitrogen (N) input and cropping system (C) on yield and economic parameters of peanut and soybean averaged across four years (Y), 2017–2020.

Parameters	N application gradient	Peanut			ANOVA				Soybean			ANOVA			
		Monoculture	Intercropping	Mean	Variable	*P*	Variable	*P*	Monoculture	Intercropping	Mean	Variable	*P*	Variable	*P*
Pod/grain yield (t/ha)	**N0**	2.58a	0.57b	1.57A	Y	< 0.0001	Y × N	0.9893	5.1a	1.5b	3.3AB	Y	< 0.0001	Y × N	0.0132
	N1	2.70a	0.42b	1.56A	N	0.5607	Y × C	0.0004	5.8a	1.3b	3.5A	N	0.1775	Y × C	0.0001
	N2	2.48a	0.47b	1.47A	C	< 0.0001	N × C	0.4157	4.4a	1.6b	3.0AB	C	< 0.0001	N × C	0.0752
	N3	2.27a	0.50b	1.38A			Y × N × C	0.9966	4.4a	1.3b	2.8B			Y × N × C	0.0006
	Mean	2.51A	0.49B	1.50					4.9A	1.4B	3.2				
Biomass (t/ha)	**N0**	5.57a	1.62b	3.60A	Y	< 0.0001	Y × N	0.9556	10.3a	3.0b	6.6A	Y	< 0.0001	Y × N	< 0.0001
	N1	5.53a	1.30b	3.41A	N	0.7485	Y × C	< 0.0001	11.2a	2.7b	7.0A	N	0.0046	Y × C	< 0.0001
	N2	5.34a	1.31b	3.33A	C	< 0.0001	N × C	0.9639	8.0a	3.1b	5.5B	C	< 0.0001	N × C	0.0066
	N3	5.66a	1.52b	3.59A			Y × N × C	0.9652	8.0a	2.4b	5.2B			Y × N × C	< 0.0001
	Mean	5.52A	1.44B	3.48					9.4A	2.8B	6.1				
Harvest index	**N0**	0.47a	0.36b	0.41A	Y	< 0.0001	Y × N	0.0596	0.52a	0.51a	0.52B	Y	< 0.0001	Y × N	< 0.0001
	N1	0.50a	0.31b	0.41A	N	0.0345	Y × C	0.0606	0.52a	0.49a	0.50B	N	< 0.0001	Y × C	0.0117
	N2	0.46a	0.34b	0.40A	C	< 0.0001	N × C	0.0069	0.56a	0.52b	0.54A	C	0.0005	N × C	0.2814
	N3	0.41a	0.33b	0.37B			Y × N × C	0.0407	0.55a	0.54a	0.55A			Y × N × C	0.0821
	Mean	0.46A	0.33B	0.40					0.54A	0.52B	0.53				
Pod/grain yield stability	**N0**	4.5a	2.6a	3.5A	N	0.4271			2.5a	8.4a	5.5A	N	0.6726		
	N1	3.7a	1.8b	2.7A	C	0.0330			2.1b	7.4a	4.8A	C	0.3894		
	N2	4.3a	2.1a	3.2A	N × C	0.7943			3.4a	4.7a	4.1A	N × C	0.0423		
	N3	8.1a	2.8a	5.5A					10.2a	3.9a	7.0A				
	Mean	5.2A	2.3B	3.7					4.6A	6.1A	5.3				
Gross margin ($/ha)	**N0**	1721a	187b	954A	Y	< 0.0001	Y × N	0.9893	3951a	1084b	2517AB	Y	< 0.0001	Y × N	0.0132
	N1	1792a	35b	913A	N	0.3953	Y × C	0.0004	4506a	884b	2695A	N	0.1462	Y × C	0.0001
	N2	1580a	72b	826A	C	< 0.0001	N × C	0.3918	3354a	1138b	2246AB	C	< 0.0001	N × C	0.0720
	N3	1369a	95b	732A			Y × N × C	0.9966	3327a	868b	2097B			Y × N × C	0.0006
	Mean	1616A	97B	856					3784A	993B	2389				

Values followed by the same lowercase letters are not significantly different among different cropping treatments at the 5% level, as judged by Fisher's protected LSD (horizontal comparison); means followed by the same capital letters are not significantly different among different N levels (vertical comparison) or among different cropping treatments (horizontal comparison).

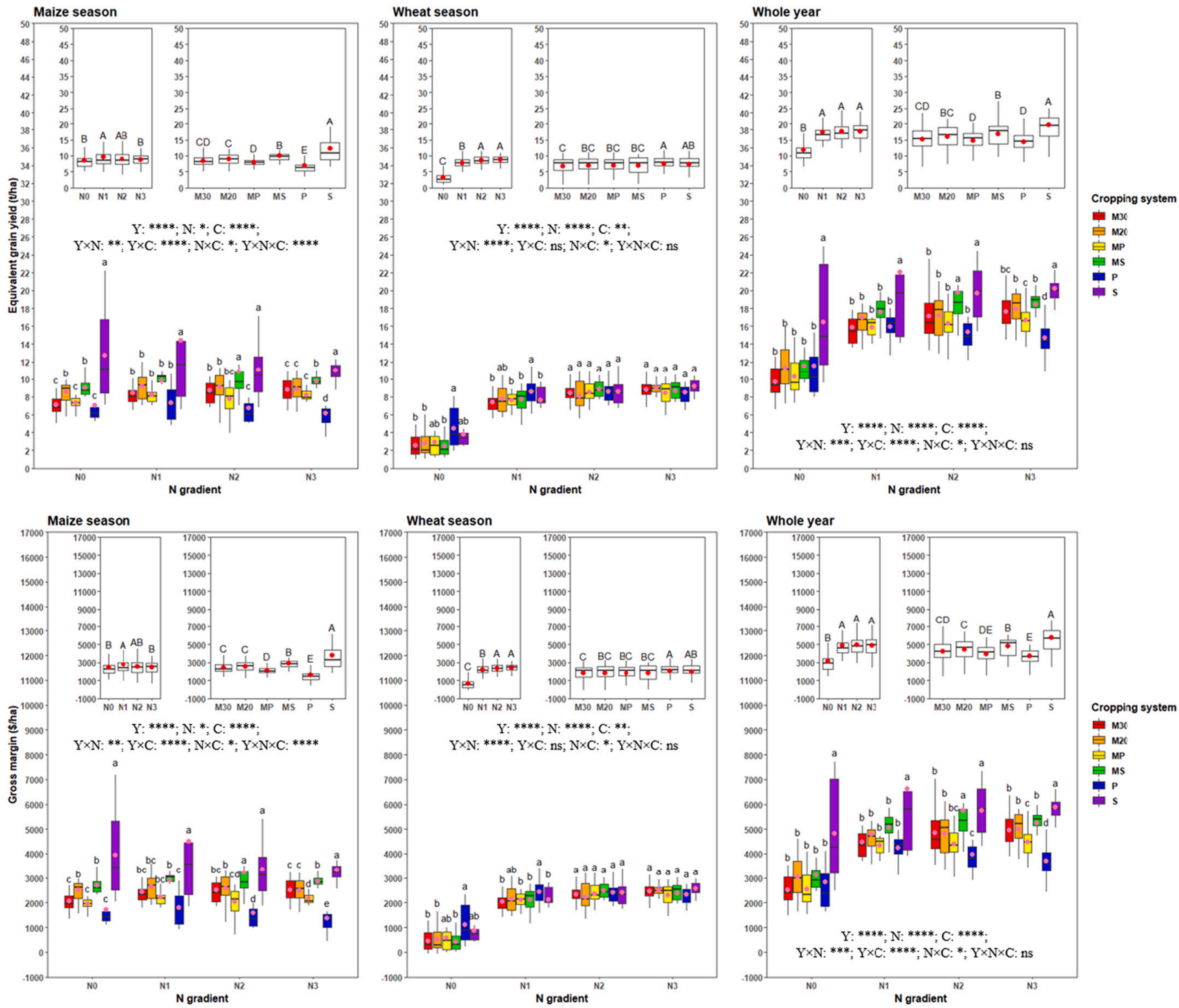


Fig. 4. Wheat-equivalent grain yields and gross margins as affected by nitrogen (N) application rates and cropping systems (C) across four experimental years (Y). M30, M20, MP, MS, P and S indicate sole maize at an inter-plant distance of 30 cm (M30) or 20 cm (M20), intercropping of maize and peanut (MP) or soybean (MS), sole peanut (P) and soybean (S), respectively. N0, N1, N2 and N3 indicate no N supply, below the recommended or standard rate for maize and wheat, standard or adequate rate for maize and wheat, and high rate for maize and wheat, respectively. Main boxplots show data across four years (n = 12), inserted boxplots show data across four years without distinguishing cropping systems (left, $n = 72$) or N levels (right, n = 48). Boxplot elements are defined as follows: the center line represents the median, box limits represent the upper and lower quartiles, whiskers represent 1.5 times interquartile range and the pink or red point represent the mean value. The same lowercase letters above boxes indicate no significant differences among different cropping systems separately for each N application rate at the 5% level by Fisher's protected LSD; the same capital letters above boxes indicate not significant differences among different N gradients or among different cropping systems at the 5% level by Fisher's protected LSD. ANOVA results which indicate the probabilities (*P* values) of the source of variation were shown in out boxplots. *, **, ***, **** and ns indicate $P \leq 0.05$, 0.01, 0.001, 0.0001 and no significance, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Year-to-year temporal stability of grain yield

Nitrogen addition didn't significantly affect the temporal yield stability of maize, peanut and soybean, when averaged over treatments of monoculture and intercropping (Tables 2 and 3). However, it significantly increased the temporal stability of total grain yield of maize season on average across six cropping systems, from 6.0 at N0 to 10.0 at N3 supply (Table 5). For winter wheat, averaged over six cropping systems, increasing N supply from N0 to N3 increased the temporal stability of grain yield gradually from 2.8 to 9.0 (Table 5). Averaged over all six cropping systems, the temporal stability of annual total grain yield and equivalent grain yield increased significantly from 5.1 to 5.2 without N addition to 8.7–9.7 with N supply (Table 5).

Across all N levels, increasing maize density in monoculture generally decreased the temporal stability, while intercropping increased the temporal stability of maize from an average 6.1–7.5 to 7.9–11.1, and intercropping with soybean had significantly greater yield stability than sole maize (Table 2). However, intercropping significantly reduced the temporal stability of peanut pod yield from an average of 5.2 to 2.3 (Table 3). On average, the temporal stability of observed total grain yield was higher in mixtures of maize and peanut or soybean, with values ranging 9.7–11.0, than in sole crops, with values from 4.6 to 7.5

Table 4
Effects of nitrogen (N) input and preceding cropping (C) system on the biomass yield and harvest index of winter wheat averaged across four years (Y) with sowing in October 2017–2020 and harvest in June 2018–2021.

Parameters	N application gradient	Preceding cropping treatment							ANOVA			
		M30	M20	MP	MS	P	S	Mean	Variable	*P*	Variable	*P*
Biomass (t/ha)	**N0**	4.7b	5.1b	5.4b	4.5b	8.5a	7.1ab	5.9C	Y	< 0.0001	Y × N	< 0.0001
	N1	13.6a	14.3a	13.7a	13.7a	15.0a	14.1a	14.1B	N	< 0.0001	Y × C	0.5255
	N2	15.7a	14.3a	15.5a	15.6a	15.5a	15.3a	15.3A	C	0.0458	N × C	0.0189
	N3	16.3a	15.9a	15.2a	15.5a	15.0a	16.3a	15.7A			Y × N × C	0.2935
	Mean	12.6B	12.4B	12.4B	12.3B	13.5A	13.2AB	12.7				
Harvest index	**N0**	0.55a	0.56a	0.56a	0.55a	0.54a	0.54a	0.55B	Y	< 0.0001	Y × N	0.0071
	N1	0.55ab	0.55b	0.56ab	0.56ab	0.57a	0.54b	0.56AB	N	0.0205	Y × C	0.1113
	N2	0.54b	0.56ab	0.56ab	0.57a	0.56ab	0.57a	0.56A	C	0.0554	N × C	0.0489
	N3	0.55b	0.57a	0.56ab	0.56ab	0.57a	0.57a	0.56A			Y × N × C	0.7148
	Mean	0.55B	0.56A	0.56A	0.56A	0.56A	0.56AB	0.56				

Values followed by the same lowercase letters are not significantly different among different preceding cropping treatments at the 5% level, as judged by Fisher's protected LSD (horizontal comparison); means followed by the same capital letters are not significantly different among different N levels (vertical comparison) or among different preceding cropping treatments (horizontal comparison). M30, M20, MP, MS, P and S indicated sole maize at an inter-plant distance of 30 cm (M30) or 20 cm (M20), the intercropping system of maize and peanut (MP) or soybean (MS), and sole peanut (P) or soybean (S), respectively.

(Table 5). Significant differences were observed between treatments of M20 and MS, and between MP or MS and P or S. Averaged over different N application rates, there were no significant differences in the temporal stability of wheat grain yields among six cropping systems (Table 5). Increasing the density of sole maize decreased the temporal annual production stability, averaged over N levels, both for total grain yield and economically equivalent total grain yield, from an average 8.1–8.3 in M30 to 6.7–6.8 in M20, and the integration of intercropping with rotation increased the temporal annual production stability from 5.6 to 8.6 in M, P and S to 8.9–10.2 in MP and MS (Table 5). There were significant differences in temporal stability of annual total actual/equivalent grain yields between MS and M20 or S, and between MP and S.

3.3. Gross margin

The gross margin of wheat and maize responded positively to higher N input, but the responses of peanut and soybean were less strong or even negative (Tables 2 and 3; Fig. 4). A starter fertilizer (N1) increased the gross margin of sole legumes, but higher N input (N2 and N3) decreased the gross margin as compared to N0 and N1 (Table 3). Low N application (N1) significantly increased the average gross margin of maize from 1992 $/ha without N addition to 2324 $/ha (Table 2). However, compared with N1, N2 and N3 did not lead to a further significant increase in the gross margin of maize, and even resulted in some decline. Similar results were found for the average gross margins over the six cropping systems, where a low N supply significantly increased the average gross margin from 2485 to 2752 $/ha (Fig. 4). The gross margin of wheat increased from 662 $/ha at N0 to 2428 $/ha at N3, with no significant difference between N2 and N3 (Fig. 4). Averaged over cropping systems and years, the total gross margin over the whole year increased from 3147 $/ha without N addition to a plateau at around 4900 $/ha with a low N supply (Table S3; Fig. 4). The total gross margin response of each annual cropping system to N application rate was similar to that of total equivalent grain yield (Fig. 5).

On average across N levels and years, compared with M30, the gross margin of maize was increased by M20 from 2382 to 2559 $/ha, but decreased by intercropping with peanut or soybean (Table 2). Intercropping dramatically reduced gross margin of peanut and soybean (Table 3). Among six cropping systems of summer maize season, sole soybean had the highest gross margin, while sole peanut had the lowest (Fig. 4). MS intercropping significantly increased the average gross margin from 2382 to 2559 $/ha in sole maize to 2926 $/ha in the intercropping system, while MP significantly reduced the average gross margin to 2098 $/ha. The gross margin of wheat was higher when the preceding crop was sole peanut or soybean than when the preceding crop was maize or maize/legume intercropping, especially at low N supply (Fig. 4). Throughout the whole year, sole soybean had the highest gross margin ($5771/ha, on average across years and N levels), while sole peanut had the lowest ($3688/ha) among the six systems (Table S3; Fig. 4). MS had a significantly higher gross margin than maize monoculture, but MP had a lower gross margin. The gross margin of MS/MP was intermediate between sole maize and legume. The gross margin of M20 was slightly (5.0%) higher than that of M30.

3.4. Overall performance

Overall analysis revealed the double cropping system of W-MS had a better comprehensive performance in equivalent grain yield, stability and gross margin than W-MP and also than W-M and W-P or W-S; increasing N supply increased total grain yield and gross margin to a plateau starting at N1 or N2, the further increase of N led to slightly changed productivity and profitability, but with lower yield stability (Fig. 6).

4. Discussion

4.1. Findings on N input requirements of different crop systems: moderation is possible without yield penalty

Different crop species responded differently to N input. We found a plateau for maize average grain yield and gross margin starting at the N1 supply, exhibiting no significant differences between low and higher N supply, regardless of cropping systems and years (Table 2). This result indicated a total of 120 kg N/ha for sole maize and 90 kg N/ha for intercropped maize was sufficient to maintain high productivity and profitability without yield penalty. Such a low N at around 100 kg/ha for optimized N management in maize production has been also reported by Liu et al. (2022). The maize cultivar "Xianyu no. 335" used in the current study is more tolerant to low N supply than the variety "Zhengdan no. 958" which is commonly used in NCP (Hao et al., 2020). The experiment started with a high level of soil initial N due to farmers' conventional high fertilization levels over the last decades, and the high atmospheric N deposition (e.g. in Huantai, near to our experimental site, from 28 to 85 kg/ha, during 1985–2015) may also decrease the fertilizer N requirement (Bellarby et al., 2018; Gao et al., 2020). In addition, an adequate precipitation amount during the maize growth season, e.g. a total of 432.5 mm on average of 4 years from June to September in the region of this study (Fig. 1), would decrease the dependence sensitivity of maize yield on fertilizer N input and be conducive to sustain high maize yields (Liang et al., 2022). Tailoring N fertilizer application to

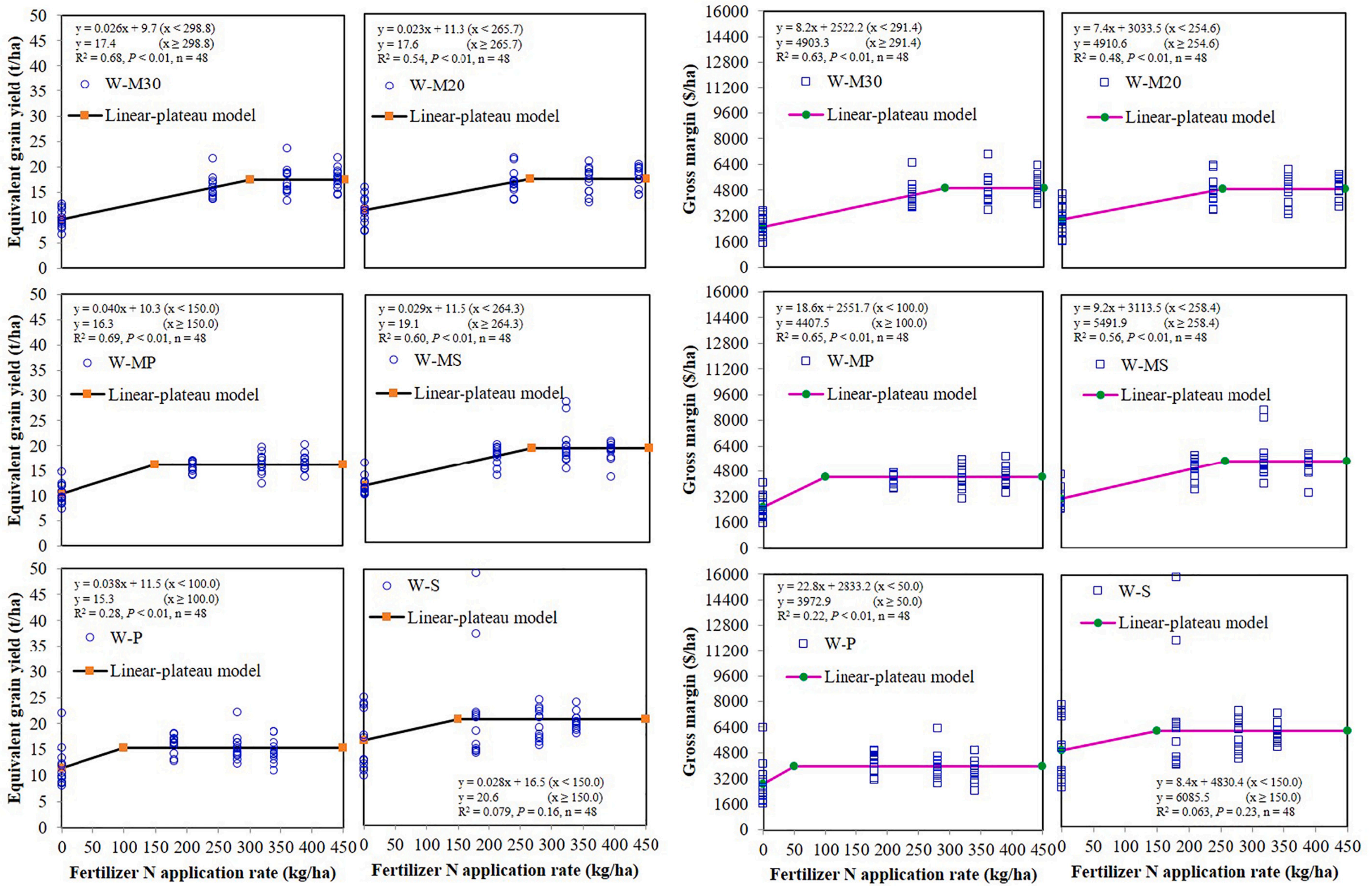


Fig. 5. Wheat-equivalent grain yield and gross margin as a function of fertilizer N application rate in six double cropping systems with wheat (W) as a winter crop and maize (M), peanut (P), soybean (S), maize/peanut intercropping (MP), or maize/soybean intercropping (MS) during summer. The inter-plant distance of maize is 30 cm in M30, and 20 cm in M20 and intercropping.

Table 5
Effects of nitrogen (N) input and cropping (C) system on the year-to-year temporal stability of grain yield.

Season and crop species related	Parameters	Nitrogen gradient	M30	M20	MP	MS	P	S	Mean	Variable	*P*
Summer maize season	**Grain yield**	**N0**	7.1ab	4.9ab	8.7a	8.5a	4.5ab	2.5b	6.0B	N	0.0456
		N1	10.6ab	6.0abc	7.4abc	12.7a	3.7bc	2.1c	7.1AB	C	0.0051
		N2	5.6a	8.5a	8.2a	7.6a	4.3a	3.4a	6.3B	N × C	0.6900
		N3	6.6a	5.3a	14.6a	15.3a	8.1a	10.2a	10.0A		
		Mean	7.5ABC	6.1BC	9.7AB	11.0A	5.2C	4.6C	7.3		
Winter wheat season	**Grain yield**	**N0**	2.3a	2.9a	2.4a	2.1a	3.6a	3.2a	2.8C	N	0.0125
		N1	6.7a	4.9a	9.2a	5.2a	6.0a	5.7a	6.3B	C	0.4405
		N2	7.5a	4.8a	7.0a	8.9a	9.1a	7.3a	7.4AB	N × C	0.0256
		N3	9.5ab	10.5ab	6.9b	6.2b	6.8b	13.9a	9.0A		
		Mean	6.5A	5.8A	6.4A	5.6A	6.4A	7.5A	6.4		
Double cropping of the whole year	**Grain yield**	**N0**	6.8a	4.3bc	6.9a	6.5ab	4.0c	2.7c	5.2B	N	0.0045
		N1	11.1ab	7.7ab	11.2ab	12.9a	8.4ab	3.0b	9.1A	C	0.0243
		N2	7.5a	7.9a	9.0a	10.6a	8.4a	8.5a	8.7A	N × C	0.4178
		N3	7.6b	7.3b	8.3ab	10.6ab	8.9ab	13.4a	9.3A		
		Mean	8.3AB	6.8B	8.9AB	10.2A	7.4AB	6.9B	8.1		
	Wheat-equivalent economic grain yield	**N0**	6.8a	4.2abc	6.5ab	6.8a	3.9bc	2.6c	5.1B	N	0.0069
		N1	10.2ab	7.4ab	13.6a	10.9ab	13.3a	2.9b	9.7A	C	0.0464
		N2	7.7a	7.6a	11.0a	9.3a	10.2a	6.5a	8.7A	N × C	0.6337
		N3	7.7a	7.6a	9.2a	13.7a	7.2a	10.3a	9.3A		
		Mean	8.1ABC	6.7BC	10.1AB	10.2A	8.6ABC	5.6C	8.2		

Values followed by the same lowercase letters are not significantly different among different cropping systems/species at the 5% level by Fisher's protected LSD (horizontal comparison); means followed by the same capital letters are not significantly different among different N input levels (vertical comparison) or among different cropping systems/species (horizontal comparison). M30, M20, MP, MS, P and S indicated sole maize at the inter-plant distance of 30 cm (M30) or 20 cm (M20), the observed intercropping system of maize and peanut (MP) or soybean (MS), and sole peanut (P) or soybean (S), respectively. Wheat-equivalent economic grain yield indicates the grain/pod yields of peanut, soybean and maize, converted into wheat equivalent economic yields.

precipitation could save N input (Cao et al., 2017; Dai et al., 2022). Consequently, the average grain yield of nonfertilized sole maize reached 8.7 t/ha in M30 and 10.5 t/ha in M20.

For wheat, the plateau of average grain yield and gross margin started at N2, i.e. 200 kg/ha, with no further significant increase from 200 to 240 kg/ha (Fig. 4). This result is consistent with previous studies (Liu et al., 2016; Wang et al., 2017; Liu et al., 2022), in which, the recommended N rate for wheat is around 225 kg/ha. The average grain yield of nonfertilized wheat was low to 3.1 t/ha, much lower than the 7.8 t/ha fertilized at N1, showing a dramatic yield gap. Therefore, in the present study, wheat was more sensitive to moderation of N input than maize. An inadequate and much lower precipitation amount of wheat season (170.1 mm on average, mainly from October to May) than that of maize season (432.5 mm on average, mainly from June to September) may be in part responsible for this difference (Fig. 1). Synthesis of climate, soil factors, and N management practices affect the responses of wheat productivity to N fertilizer (Wang et al., 2018). Moreover, our study confirmed the grain yield and gross margin of the N_2-fixing legume was less-dependent on external fertilizer N, and even declined at higher N levels (N2,N3), suggesting the fertilizer N could be waived or only applied as a starter at a low rate (Table 3).

The average grain yield LER of intercrops was well above one if N input was at N3 for maize/peanut intercropping or at least N1 for maize/soybean intercropping, showing overall yield advantage (Fig. 3). The average LER with N addition increased compared to no N supply, mainly due to a stronger performance of maize and a relatively small change of legume yield. Maize tends to have greater leaf area index at higher N input (Liu et al., 2017; Gao et al., 2020), thus resulting in higher pLER for grain and biomass yield in our study (Fig. 3). However, Gao et al. (2020) found that the LER decreased at higher N input due to greater shading by maize on peanut and lower peanut yield. Such inconsistency may be attributed to different strip configurations (e.g. strip width) and environmental conditions, which determine the strength of competition and complementarity, and comprehensive benefits of intercropping (Raza et al., 2020; van Oort et al., 2020). On average over intercropping systems and years, a plateau of LER occurred at N1 (Fig. 3), and on average over six summer cropping systems and years, the plateau or peak of actual/equivalent grain yield and gross margin occurred at N1 (Table S1; Fig. 4). This result indicated an optimal rate of 90 kg N/ha for the maize-based intercropping system to attain comparable productivity and profitability. A low N input of 120 kg/ha in the rotation system of alfalfa and alfalfa/silage maize intercropping has been recently reported to provide comparable productivity and profitability with lower environmental impacts than a total of 396 kg/ha in the winter wheat-summer maize rotation system in NCP (Xu et al., 2022).

Our results indicated a total N supply ranging from N1 to N2 (i.e. 240–360 kg/ha for W-M, 210–320 kg/ha for W-M/legume intercropping and 180–280 kg/ha for W-legume rotation) was suitable to achieve high productivity and profitability of all annual cropping systems while avoiding high N waste or surplus, and the optimal N application rate for wheat-legume rotations was even lower than the N1 level (Figs. 4 and 5). These findings were consistent with other previous studies. Zhao et al. (2015) reported the annual fertilizer N demand for winter wheat and summer maize was totally around 330 kg/ha. Yin et al. (2021) developed a steady-state N balance approach for sustainable small holder farming, and a total of average 319–342 kg N/ha input for the two crops of wheat and maize was estimated. Liu et al. (2022) demonstrated a total of 225 kg N/ha in combination with urease and nitrification inhibitors for wheat and maize as optimized N management.

A growing number of empirical results showed the nitrogen or nutrient enrichment may often destabilize ecosystem productivity of grassland (Hautier et al., 2015; Liu et al., 2019; Jungers et al., 2021). Uniquely, in our agricultural field experiment, N addition enhanced the average temporal yield stability of wheat, and higher N corresponded to higher stability (Table 5). However, there was a plateau (starting at N1) for the increase of the temporal production stability of maize season or the whole year, averaged over six cropping systems. Here, N addition didn't significantly alter stability of maize, peanut and soybean on

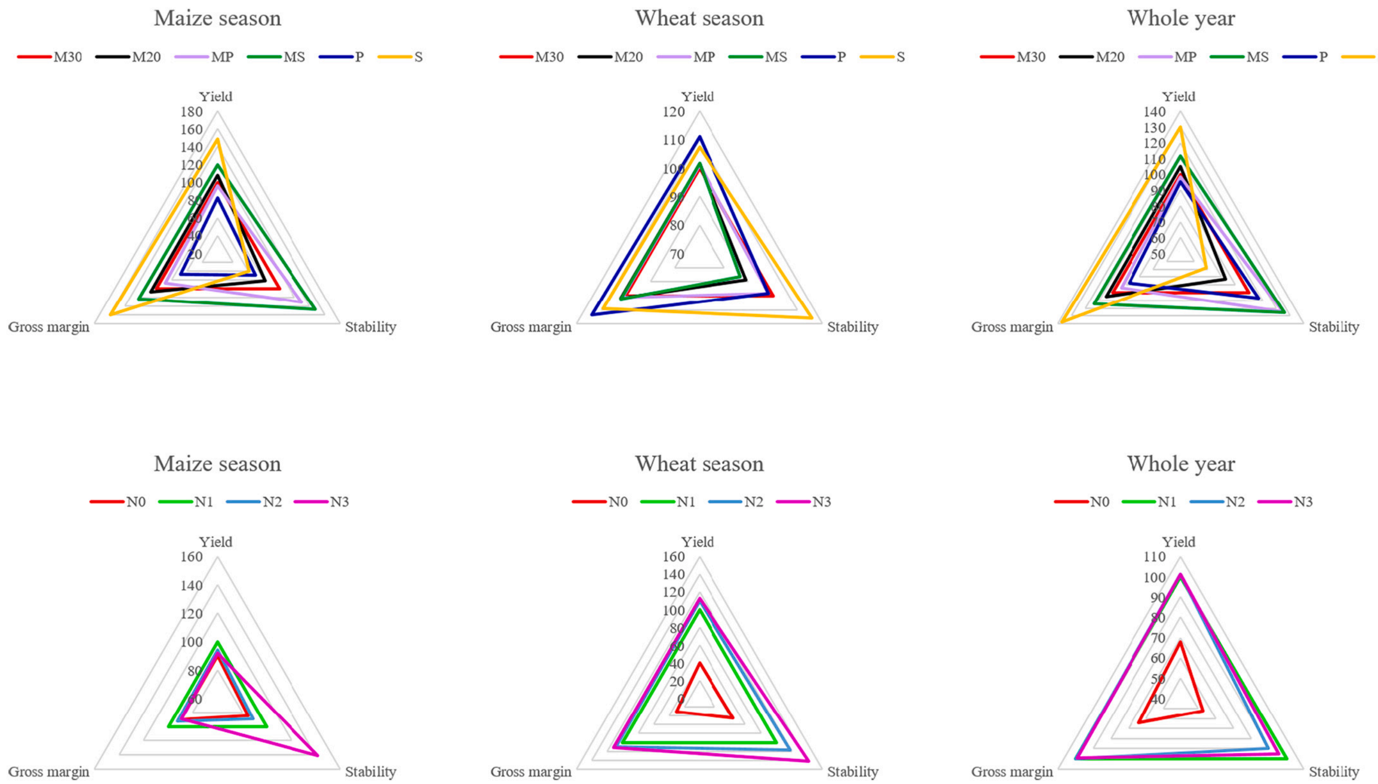


Fig. 6. Multicriteria assessment of different cropping systems and nitrogen (N) application rates during different growing seasons and the whole year. The top three panels compare criteria for six different cropping systems, averaged over N input levels, during the maize season (left), the wheat season (middle) and the whole year. The bottom panels compare criteria for four different levels of N input, averaged over cropping systems. M30, M20, MP, MS, P and S indicate sole maize at an inter-plant distance of 30 cm (M30) or 20 cm (M20), the observed intercropping system of maize and peanut (MP) or soybean (MS), sole peanut (P) and soybean (S), respectively. N0, N1, N2 and N3 indicate no N supply, below the recommended or standard rate for maize and wheat (N1), standard or adequate rate for maize and wheat (N2), and high rate for maize and wheat (N3), respectively. Data of each metric value for each cropping species/system or N rate were the four-year average relative change ratio (%) in comparison with the treatment of M30 (upper graphs), or in comparison with the treatment of N1 (lower graphs). Yield indicates wheat-equivalent economic grain yield.

average (Tables 2 and 3). Some other studies on grassland also have found either a neutral or positive effect of fertilization on ecosystem stability (Grman et al., 2010; Yang et al., 2011). Most recently, a global meta-analysis synthesizing 467 N application studies with duration $\geq$5 years in croplands across the world suggests that long-term N fertilization can contribute to mitigate global food insecurity by not only enhancing cereal yield but also promoting its stability (Liang et al., 2022).

In general, as suggested by others (Zhao et al., 2015; Sun et al., 2018; Raji and Dörsch, 2020; Long et al., 2021), our study confirms that an appropriate or even a precise (determined by model simulation) N application rate is required to not only boost high productivity and profitability, but also increase the temporal stability. As different crops responded differently to N input, it is recommended to optimize the fertilization regime from a systematic view throughout the whole year to tailor total N input for better comprehensive performance (Zhao et al., 2015; Silva et al., 2021; Liu et al., 2022).

4.2. Benefits of intercropping in a rotation context

Many studies have reported intercropping had great over-yielding advantage (Xu et al., 2020; Feng et al., 2021; Li et al., 2021). Our study showed that the grain yield LER of maize/peanut intercropping was <1.00 and that of maize/soybean was slightly >1.00 in most situations (Fig. 3). These results are in accordance with several previous studies (Ren et al., 2017; Gao et al., 2020; Sun et al., 2021). Gao et al. (2020) observed the grain yield LER of maize/peanut intercropping was above 1.00 only if N input was <180 kg/ha, and decreased to <1.00 at higher N supply rates. Ren et al. (2017) and Sun et al. (2021) reported the maize/soybean intercropping had an average grain yield LER from 1.05 to 1.07. However, the grain yield LER as high as 1.85–2.20 was achieved in the maize/soybean intercropping as observed by Chen et al. (2019). These huge differences might be mainly due to different situations of temporal niche differentiation in intercropping. Longer co-growth period of intercropped crop species may decrease the temporal niche complementarity and increase the competition for resources (Zhang and Li, 2003). In our study, maize and peanut/soybean were sown and harvested at the same time, i.e. simultaneous intercropping, the same as Ren et al. (2017), Gao et al. (2020) and Sun et al. (2021), thus limited the intercropping yield advantage. These results are consistent with findings that the yield advantage was increased at greater TND (Yu et al., 2015; Li et al., 2020).

Our results showed the grain yield LER of maize/soybean intercropping (1.02 on average) was significantly higher than that of maize/peanut (0.95 on average), indicating the maize/soybean intercropping is more ecologically suitable than maize/peanut. However, such difference didn't exist in LER of biomass yield. This phenomenon could be associated with the large reduction in harvest index of peanut from an average of 0.46 in monoculture to 0.33 in intercropping (Table 3), where the long-term shading induced by maize limited photosynthesis and decreased the long-distance translocation of above-ground photosynthates to belowground peanut pods. Similar results were found in our previous study (Xia et al., 2019). However, the harvest index of soybean was relatively less affected by intercropping, possibly because the pod of soybean is located above-ground while that of peanut is below-ground. We have noted that shaded peanut plants may lack the vigour for the young pods ("pegs") to penetrate the soil, resulting in sink limitation.

The equivalent grain yield and gross margin of maize/soybean intercropping was higher than that of sole maize, but lower than that of sole soybean (Fig. 4), primarily due to the higher market price of soybean than maize (Sun et al., 2021). A similar trend was reported in maize/peanut intercropping (Gao et al., 2020). However, this didn't occur in the maize/peanut intercropping in our study because the high price of peanut could not fully compensate for its low yield in intercropping. The equivalent grain yield and gross margin of maize/peanut intercropping was higher than sole peanut, but lower than sole maize. Although the market price of peanut is higher than maize, the low productivity of peanut, due to the cultivation practice with no ridge-furrow and no plastic film mulching in this study, limited its gross margin in monoculture and intercropping. In both cases above-mentioned, the equivalent grain yield and gross margin of intercropping was intermediate between sole maize and sole legume, providing considerable productivity and profitability and balanced advantages of profitability and diversity of crop outputs.

Rotating wheat with peanut or soybean increased the grain and biomass yield, and gross margin of wheat as compared to maize-wheat rotation, especially at zero or low N input, but not at adequate and high N supply (Table 4; Fig. 4). This is consistent with most other studies, and mainly due to the residual effect of legume, which can fix N_2 from the atmosphere (Guinet et al., 2020; Muschietti-Piana et al., 2020). However, intercropping of peanut/soybean with maize had no such strong residual effect as sole legume. Actually, it has been proved the intercropped legume is beneficial for N acquisition of neighboring cereal crop (Hauggaard-Nielsen et al., 2009b; Li et al., 2011; Jensen et al., 2020; Rodriguez et al., 2020), thus we can speculate that the residual effect of intercropped legume on subsequent wheat may be weakened to a large extent due to the simultaneous presence of maize, which would earn "the first pot of gold" from legume. Therefore, our present results confirmed this hypothesis. Similarly, Hauggaard-Nielsen et al. (2009a) demonstrated the depletion of soil mineral N of subsequent wheat was independent of preceding cropping strategy of pea and barley intercropping. Although increasing the planting density of sole maize enhanced maize productivity and profitability, which suggested it might pre-empt N acquisition by subsequent wheat, it had no significant effect on wheat performance in the current study.

Our current study found that maize/soybean intercropping in rotation with wheat increased the equivalent grain yield and gross margin by 6.3–11.3% and 8.4–13.9% on average, respectively, compared with the conventional maize-wheat rotation. Unfortunately, a disadvantage was observed in the maize/peanut intercropping and rotation with wheat (Fig. 4). As above-mentioned, the extremely low productivity of peanut was the main reason for this. Therefore, we recommend the maize/soybean intercropping and rotation with wheat rather than the W-MP to substitute the conventional rotation of W-M for better productivity and profitability. Considering all six double cropping systems, our results proved the total equivalent grain yield and gross margin of the diversified rotation system with intercropping (W-MS or W-MP) was consistently intermediate between conventional wheat-maize and wheat-legume rotation. It is thus preferable to adopt intercropping in the rotation system to alleviate the competition and conflict over land on production of food, oils and feed. Therefore, the integration of intercropping with crop rotation can play a buffering role in satisfying demands of different crops while providing considerable farmer profits (Li et al., 2021).

4.3. Inclusion of intercropping increased temporal yield stability

The temporal stability of maize yield was decreased when the density of maize was increased by reducing the inter-plant distance from 30 to 20 cm (Tables 2 and 5). This may have been due to the increased risk of lodging and decreased resistance to abiotic/biotic stress. Our results further confirm that crop diversification by intercropping of maize with legume crops improved the year-to-year yield stability of maize (with a narrow inter-plant distance of 20 cm) and the intercropping system as compared to monoculture, implying great potential to mitigate adverse effects of weather variability, particularly in hot, dry and stormy/windy years (Koskey et al., 2022). This is in agreement with the latest findings of Li et al. (2021) that intercropping systems had greater year-to-year yield stability than monocultures.

We found greater temporal yield stability in diversified rotations with intercropping than in the conventional wheat-maize and wheat-legume rotations (Table 5). To our knowledge, this is the first report to show intercropping during one growing season could have a positive effect on yield stability of a double cropping system over a whole year at field-level. These results are generally consistent with positive effects of higher diversity of crop species or crop species groups at national or regional levels (Renard and Tilman, 2019; Egli et al., 2021) and at the field scale (Jungers et al., 2021). A growing body of evidence indicates that the stability of the dominant species may often partly determine the ecosystem stability (Liu et al., 2019). Indeed, we found significant positive Pearson correlations between the temporal grain yield stability of intercropped maize and the intercropping system as a whole ($n = 24$, $r = 0.700$, $P < 0.001$), and between that of intercropped maize and the integrated rotation system with intercropping (n = 24, $r = 0.468$, $P = 0.021$), but not among those of intercropped legume, the intercropping system, and the integrated rotation system with intercropping in the present study. Therefore, we conclude that it was the higher yield stability of the dominant maize in intercropping as compared to monoculture that contributed to the higher production stability of the intercropping systems and the rotation systems of W-MS and W-MP in our study.

Renwick et al. (2021) showed that diversifying maize-soybean rotations in Canada with small grain cereals and cover crops enhanced maize drought resistance in the long term through improved soil organic matter. Similar results were reported by Bowles et al. (2020) covering 347 site-years of yield data from 11 experiments in North America. Mori et al. (2021) indicated that biodiversity-productivity relationships are key to nature-based climate solutions. Here, we highlight that crop rotation diversification by intercropping in the NCP could be adopted as an effective ecological intensification strategy towards greater resilience to climate change.

4.4. Synergies between intercropping and optimized N management

The year variation in climatic conditions and cumulative effects of N fertilization resulted in significant year differences in yield and gross margin of all crop species and cropping systems, and also resulted in some significant interactions of year and N input (Tables 1-4 and S1-S3; Figs. 1, 3 and 4). With the increase of experimental years, cumulative effects of fertilizer N applications on soil N contents and crop yields are supposed to be strengthened, resulting in the yield level decline at zero N supply, a yearly-increased yield gap between low and high N supply, and high N surplus at high N application rate. The time to establish steady state between N input, crop yield, N losses and the soil N pool can exceed decades (van Grinsven et al., 2022). Increasing the planting density of maize in monoculture may decrease yield stability due to lodging (Winans et al., 2021). To address these unsustainability issues, a single technology is not applicable everywhere and integrated approaches with the multiple criteria (productivity, economics and sustainability) would be required (Bhatt et al., 2021). The year-to-year yield stability revealed the sustainability of crops to maintain yield as affected by management, climatic and environmental changes (Renard and Tilman, 2019; Li et al., 2021; Liang et al., 2022). Our results found, compared to the annual monoculture rotation of W-M30 or W-M20, an integrated approach including (1) diversifying conventional wheat-maize double cropping by a suitable legume crop species intercropping, (2) appropriately increasing the planting density of maize in maize strips (based on M20, with a higher density than the conventional M30), and (3) a lower N supply, had a higher stability to sustain a higher total productivity and profitability (Tables 5, S2 and S3; Figs. 4-7). However, an inappropriate legume crop species and management, e.g. peanut in this study, decreased the total productivity and profitability, resulting in a negative yield and profit effect. With the increase of N input, two types of yield and profit responses (Type 1-Positive and Type 2-Negative) caused by legume incorporation into the W-M annual system were summarized in Fig. 7. The type 1-positive effect indicated integration of legumes via intercropping or monoculture saved N input and maintained a higher yield and profit than double cropping of wheat-maize. Compared to W-M with a total of 240–360 kg N/ha/year application rate (N1 and N2), the diversified rotation of W-MS with a total of 210–320 kg N/ha/year saved 11.1–12.5% fertilizer N input while maintaining or improving production by 9.1–13.0%, and improving profitability by 12.1–15.6% and temporal yield stability by 12.8–50.6%.

A recent report showed a total of only 225 kg N/ha (with nitrification and urease inhibitors) for the wheat-maize system could reduce the environmental pollution of N and increase the net economic benefit by 24.7% in the NCP (Liu et al., 2022). At county scale, a recommended total of 319 kg N/ha, averaged over all 3824 countries for wheat and maize in China, could reduce N fertilizer by 21–28% and reactive N losses by 23.2–28.9% while maintaining or increasing yields by 6.0–7.0% and N productivity (yield/N fertilizer) by 26.0–33.2%, compared to current smallholder practices (Yin et al., 2021). In addition to the optimization of N application amount and advanced fertilization techniques (e.g. nitrification and urease inhibitors, slow-release N fertilizers, and fertigation), other practices (including innovative cropping system patterns, conservation tillage, improvements in seed quality/nutrients, manure inputs, and pest management) may help maintaining or improving productivity and reducing total N losses (van Kessel et al., 2013; Li et al., 2018; Zhang et al., 2020b; Morris et al., 2021). Our results suggest that the optimal N rate could even be reduced to only 210 kg/ha/year, mainly due to the rotation diversification by intercropping with legumes. Therefore, maize and soybean intercropping and rotation with wheat, in combination with rational N application, provides comparable productivity and profitability, with higher temporal yield stability and lower N loss than the conventional wheat-maize system, showing opportunities for a more sustainable agricultural production in the NCP. In addition, our research provides strong support for crop systems diversification by legumes and has a global relevance for other double cropping systems, such as maize-rice in South China, and rice-wheat, rice-maize and maize-wheat in South Asia (Timsina et al., 2010; Chauhan et al., 2012; Sun et al., 2019; Mehmood et al., 2020; Bhatt et al., 2021).

4.5. Limitations of this study

There are several limitations in this study. Firstly, the findings reported are mostly based on a 4-year average result, the inter-annual variability was less considered. As the time to establish steady state between N input, crop yield of the six annual cropping systems (with and without legumes), N losses and the soil N pool can exceed decades (van Grinsven et al., 2022), the current findings need a longer time verification. Secondly, fluctuations of market prices of grain/pod or seed of different crops and fertilizers involved in this study may affect the evaluation on gross margin. Thirdly, a further investigation on soil fertility and environmental impact, such as greenhouse gas emission footprint, is lacking in this study, and needed in the future. Finally, in terms of social adaptability and impact, although some new machines suitable for sowing of maize and soybean strips simultaneously have been invented and adopted recently in China (Zhang et al., 2020a), the globally widespread of intercropping is still constrained due to complexity and the lack of effective mechanization of harvest (Brooker et al., 2015; Li et al., 2021).

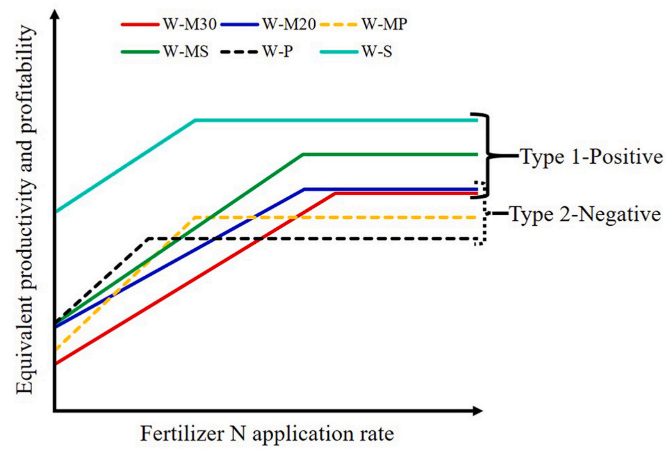


Fig. 7. Schematic diagram illustrating responses of equivalent productivity and profitability of six double cropping systems (with legumes via monoculture or intercropping and without legumes) to fertilizer N application rates. W-M, W-P, W-S, W-MP and W-MS indicate the double cropping of wheat with sole maize, with sole peanut (W-P) or soybean (W-S), and with intercropping of maize and peanut (W-MP) or soybean (W-MS), respectively. The inter-plant distance of maize is 30 cm in M30, and 20 cm in M20 and intercropping.

5. Conclusion

This study investigated productivity, gross margin, and the year-to-year temporal yield stability of six double cropping systems (W-M30, W-M20, W-MP, W-MS, W-P, and W-S) at 4 levels of fertilizer N input (N0, N1, N2, and N3) in a 4 years continuous field experiment in the NCP. The current high N input in practice (comparable to N3), which has substantial negative environmental side effects, did not significantly increase annual total actual/equivalent grain yields, gross margins and yield stability of these six double cropping systems above the level of N1 or N2, could be moderated without negative economic effects for farmers. Total N input, productivity, and profitability of rotations with intercrops (W-MS or W-MP) were consistently intermediate between rotations of W-M and W-legume. Therefore, the diversified rotation with intercropping played a neutralizing effect between monoculture rotations of W-M and W-legume. Furthermore, intercropping with peanut or soybean enhanced the temporal yield stability of the diversified rotation system compared to the monoculture rotations of W-M and W-legume. Compared to the conventional W-M, W-MS had a better comprehensive performance (yield, profit and stability) with lower N application, however, W-MP decreased the yield and profit. Therefore, W-MS with moderate N application is highly recommended to alleviate the pressure on the land to produce food and feed cereals as well as oil crops, and move towards more environmentally sustainable and profitable agricultural production in the NCP. A three-crops-per-year way via intercropping with legumes provides a potential approach to the sustainable intensification and diversification of double cropping worldwide.

Declaration of Competing 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.

Data availability

Data will be made available on request.

Acknowledgments

The research was funded by the Natural Science Foundation of Shandong Province of China (ZR2021MC059), the National Key R&D Program of China (2016YFD0300202, 2017YFD0300407, 2021YFD1901003), and the Taishan Scholarship Project of Shandong Province (TS201712082). The Funding for Study Abroad Program by the Government of Shandong Province for financial support of Haiyong Xia was also gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103540.

References

Barbieri, P., Pellerin, S., Seufert, V., Nesme, T., 2019. Changes in crop rotations would impact food production in an organically farmed world. Nat. Sustain. 2, 378–385.
Bellarby, J., Surridge, B.W.J., Haygarth, P.M., Liu, K., Siciliano, G., Smith, L., Rahn, C., Meng, F., 2018. The stocks and flows of nitrogen, phosphorus and potassium across a 30-year time series for agriculture in Huantai county, China. Sci. Total Environ. 619-620, 606–620.
Bhatt, R., Singh, P., Hossain, A., Timsina, J., 2021. Rice-wheat system in the northwest indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy Water Environ. 19, 345–365.
Bowles, T.M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M.A., Culman, S.W., Deen, W., Drury, C.F., Garcia, A.G.Y., Gaudin, A.C.M., Harkcom, W.S., Lehman, R. M., Osborne, S.L., Robertson, G.P., Salerno, J., Schmer, M.R., Strock, J., Grandy, A. S., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2, 284–293.
Brooker, R.W., Bennett, A.E., Cong, W.-F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J., Li, L., McKenzie, B.M., Pakeman, R.J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C.A., Zhang, C., Zhang, F., Zhang, J., White, P.J., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol. 206, 107–117.
Cao, H., Wang, Z., He, G., Dai, J., Huang, M., Wang, S., Luo, L., Sadras, V.O., Hoogmoed, M., Malhi, S.S., 2017. Tailoring NPK fertilizer application to precipitation for dryland winter wheat in the loess plateau. Field Crop Res. 209, 88–95.
Chai, Q., Nemecek, T., Liang, C., Zhao, C., Yu, A.Z., Coulter, J.A., Wang, Y.F., Hu, F.L., Wang, L., Siddique, K.H.M., Gan, Y.T., 2021. Integrated farming with intercropping increases food production while reducing environmental footprint. Proc. Natl. Acad. Sci. U. S. A. 118, 2106382118.
Chauhan, B.S., Mahajan, G., Sardana, V., Timsina, J., Jat, M.L., 2012. Chapter Six - productivity and sustainability of the rice-wheat cropping system in the indo-Gangetic Plains of the Indian subcontinent. Adv. Agron. 117, 315–369.
Chen, P., Song, C., Liu, X.M., Zhou, L., Yang, H., Zhang, X.N., Zhou, Y., Du, Q., Pang, T., Fu, Z.D., Wang, X.C., Liu, W.G., Yang, F., Shu, K., Du, J.B., Liu, J., Yang, W.Y., Yong, T.W., 2019. Yield advantage and nitrogen fate in an additive maize-soybean relay intercropping system. Sci. Total Environ. 657, 987–999.
China's No. 1 Central Document. Retrieved from. http://www.news.cn/politics/zywj/2022-02/22/c_1128406721.htm.
Dai, J., He, G., Wang, S., Cao, H., Hui, X., Ma, Q., Liu, J., Siddique, K.H.M., Wang, Z., Sadras, V.O., 2022. Matching NPK fertilization to summer rainfall for improved wheat production and reduced environmental cost. Field Crop Res. 286, 108613.
Egli, L., Schröter, M., Scherber, C., Tscharntke, T., Seppelt, R., 2021. Crop diversity effects on temporal agricultural production stability across European regions. Reg. Environ. Chang. 21, 96.
Feike, T., Doluschitz, R., Chen, Q., Graeff-Hönninger, S., Claupein, W., 2012. How to overcome the slow death of intercropping in the North China Plain. Sustainability 4, 2550–2565.
Feng, C., Sun, Z., Zhang, L., Feng, L., Zheng, J., Bai, W., Gu, C., Wang, Q., Xu, Z., van der Werf, W., 2021. Maize/peanut intercropping increases land productivity: a meta-analysis. Field Crop Res. 270, 108208.
Fung, K.M., Tai, A.P.K., Yong, T., Liu, X., Lam, H.M., 2019. Co-benefits of intercropping as a sustainable farming method for safeguarding both food security and air quality. Environ. Res. Lett. 14, 044011.
Gao, H.X., Meng, W.W., Zhang, C.C., van der Werf, W., Zhang, Z., Wan, S.B., Zhang, F.S., 2020. Yield and nitrogen uptake of sole and intercropped maize and peanut in response to N fertilizer input. Food Energy Secur. 9, e187.
General Office of the State Council of China, 2015. Retrieved from. http://www.gov.cn/zhengce/content/2015-08/07/content_10057.htm.
Grman, E., Lau, J.A., Schoolmaster Jr., D.R., Gross, K.L., 2010. Mechanisms contributing to stability in ecosystem function depend on the environmental context. Ecol. Lett. 13, 1400–1410.
Guinet, M., Nicolardot, B., Voisin, A.-S., 2020. Nitrogen benefits of ten legume pre-crops for wheat assessed by field measurements and modelling. Eur. J. Agron. 120, 126151.
Hao, J.J., Li, Y.Q., Liu, J.Z., Xie, S.N., Wang, X.T., Ding, J.Q., Ye, J.R., Song, X., Hao, G. T., 2020. Comparative analysis of resistance to abiotic stresses in four maize hybrids. J. Anhui Agric. Sci. 48, 43–47 (in Chinese with English abstract).
Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., von Fragstein, P., Pristeri, A., Monti, M., Jensen, E.S., 2009a. Pea–barley intercropping and short-term subsequent crop effects across European organic cropping conditions. Nutr. Cycl. Agroecosyst. 85, 141–155.
Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., von Fragstein, P., Pristeri, A., Monti, M., Jensen, E.S., 2009b. Pea–barley intercropping for efficient symbiotic N2-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. Field Crop Res. 113, 64–71.
Hautier, Y., Tilman, D., Isbell, F., Seabloom, E.W., Borer, E.T., Reich, P.B., 2015. Anthropogenic environmental changes affect ecosystem stability via biodiversity. Science 348, 336–340.
Huang, C.D., Liu, Q.Q., Heerink, N., Stomph, T., Li, B.S., Liu, R.L., Zhang, H.Y., Wang, C., Li, X.L., Zhang, C.C., van der Werf, W., Zhang, F.S., 2015. Economic performance and sustainability of a novel intercropping system on the North China Plain. PLoS One 10, e0135518.
Jensen, E.S., Carlsson, G., Hauggaard-Nielsen, H., 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron. Sustain. Dev. 40, 5.
Jeong, S.J., Ho, C.H., Piao, S., Kim, J., Ciais, P., Lee, Y.B., Jhun, J.G., Park, S.K., 2014. Effects of double cropping on summer climate of the North China Plain and neighbouring regions. Nat. Clim. Chang. 4, 615–619.
Jungers, J.M., Yang, Y., Fernandez, C.W., Isbell, F., Lehman, C., Wyse, D., Sheaffer, C., 2021. Diversifying bioenergy crops increases yield and yield stability by reducing weed abundance. Sci. Adv. 7, eabg8531.
Koskey, G., Leoni, F., Carlesi, S., Avio, L., Bàrberi, P., 2022. Exploiting plant functional diversity in durum wheat-lentil relay intercropping to stabilize crop yields under contrasting climatic conditions. Agronomy 12, 210.
Li, L., Sun, J., Zhang, F., Li, X., Yang, S., Rengel, Z., 2001. Wheat/maize or wheat/soybean strip intercropping: I. Yield advantage and interspecific interactions on nutrients. Field Crop Res. 71, 123–137.
Li, C.-J., Li, Y.-Y., Yu, C.-B., Sun, J.-H., Christie, P., An, M., Zhang, F.-S., Li, L., 2011. Crop nitrogen use and soil mineral nitrogen accumulation under different crop combinations and patterns of strip intercropping in northwest China. Plant Soil 342, 221–231.
Li, L., Zhang, L., Zhang, F., 2013. Crop mixtures and the mechanisms of overyielding. In: Levin, S.A. (Ed.), Encyclopedia of Biodiversity, second ed. Academic Press, Waltham, pp. 382–395.
Li, T., Zhang, W., Yin, J., Chadwick, D., Norse, D., Lu, Y., Liu, X., Chen, X., Zhang, F., Powlson, D., Dou, Z., 2018. Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem. Glob. Chang. Biol. 24, e511–e521.
Li, C.J., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C.C., Li, H.G., Zhang, F.S., van der Werf, W., 2020. Syndromes of production in intercropping impact yield gains. Nat. Plants 6, 653–660.
Li, X.F., Wang, Z.G., Bao, X.G., Sun, J.H., Yang, S.C., Wang, P., Wang, C.B., Wu, J.P., Liu, X.R., Tian, X.L., Wang, Y., Li, J.P., Wang, Y., Xia, H.Y., Mei, P.P., Wang, X.F., Zhao, J.H., Yu, R.P., Zhang, W.P., Che, Z.X., Gui, L.G., Callaway, R.M., Tilman, D., Li, L., 2021. Long-term increased grain yield and soil fertility from intercropping. Nat. Sustain. 4, 943–950.
Liang, G.P., 2022. Nitrogen fertilization mitigates global food insecurity by increasing cereal yield and its stability. Glob. Food Secur. 34, 100652.
Liu, H., Wang, Z., Yu, R., Li, F., Li, K., Cao, H., Yang, N., Li, M., Dai, J., Zan, Y., Li, Q., Xue, C., He, G., Huang, D., Huang, M., Liu, J., Qiu, W., Zhao, H., Mao, H., 2016. Optimal nitrogen input for higher efficiency and lower environmental impacts of winter wheat production in China. Agric. Ecosyst. Environ. 224, 1–11.
Liu, X., Rahman, T., Song, C., Su, B., Yang, F., Yong, T., Wu, Y., Zhang, C., Yang, W., 2017. Changes in light environment, morphology, growth and yield of soybean in maize-soybean intercropping systems. Field Crop Res. 200, 38–46.
Liu, J.S., Li, X.F., Ma, Q.H., Zhang, X., Chen, Y., Isbell, F., Wang, D.L., 2019. Nitrogen addition reduced ecosystem stability regardless of its impacts on plant diversity. J. Ecol. 107, 2427–2435.
Liu, C., Ren, D., Liu, H., Zhang, Y., Wang, L., Li, Z., Zhang, M., 2022. Optimizing nitrogen management diminished reactive nitrogen loss and acquired optimal net ecosystem economic benefit in a wheat-maize rotation system. J. Clean. Prod. 331, 129964.
Long, G.Q., Li, L.H., Wang, D., Zhao, P., Tang, L., Zhou, Y.L., Yin, X.H., 2021. Nitrogen levels regulate intercropping-related mitigation of potential nitrate leaching. Agric. Ecosyst. Environ. 319, 107540.
Lu, J.S., Geng, C.M., Cui, X.L., Li, M.Y., Chen, S.H., Hu, T.T., 2021. Response of drip fertigated wheat-maize rotation system on grain yield, water productivity and economic benefits using different water and nitrogen amounts. Agric. Water Manag. 258, 107220.
Mehmood, I., Qiao, L., Chen, H., Tang, Q., Woolf, D., Fan, M., 2020. Biochar addition leads to more soil organic carbon sequestration under a maize-rice cropping system than continuous flooded rice. Agric. Ecosyst. Environ. 298, 106965.
Mehrabi, Z., Ramankutty, N., 2019. Synchronized failure of global crop production. Nat. Ecol. Evol. 3, 780–786.
Mori, A.S., Dee, L.E., Gonzalez, A., Ohashi, H., Cowles, J., Wright, A.J., Loreau, M., Hautier, Y., Newbold, T., Reich, P.B., Matsui, T., Takeuchi, W., Okada, K., Seidl, R., Isbell, F., 2021. Biodiversity-productivity relationships are key to nature-based climate solutions. Nat. Clim. Chang. 11, 543–550.
Morris, A.H., Isbell, S.A., Saha, D., Kaye, J.P., 2021. Mitigating nitrogen pollution with under-sown legume–grass cover crop mixtures in winter cereals. J. Environ. Qual. 50, 324–335.

Muschietti-Piana, P., McBeath, T.M., McNeill, A.M., Cipriotti, P.A., Gupta, V.V.S.R., 2020. Combined nitrogen input from legume residues and fertilizer improves early nitrogen supply and uptake by wheat. J. Plant Nutr. Soil Sci. 183, 355–366.

Nemecek, T., von Richthofen, J.-S., Dubois, G., Casta, P., Charles, R., Pahl, H., 2008. Environmental impacts of introducing grain legumes into European crop rotations. Eur. J. Agron. 28, 380–393.

Pradhan, A., Chan, C., Roul, P.K., Halbrendt, J., Sipes, B., 2018. Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: a transdisciplinary approach. Agric. Syst. 163, 27–35.

Raji, S.G., Dörsch, P., 2020. Effect of legume intercropping on N_2O emissions and CH_4 uptake during maize production in the Great Rift Valley, Ethiopia. Biogeosciences 17, 345–359.

Raza, M.A., Cui, L., Qin, R.J., Yang, F., Yang, W.Y., 2020. Strip-width determines competitive strengths and grain yields of intercrop species in relay intercropping system. Sci. Rep. 10, 21910.

Ren, Y.Y., Wang, X.L., Zhang, S.Q., Palta, J.A., Chen, Y.L., 2017. Influence of spatial arrangement in maize-soybean intercropping on root growth and water use efficiency. Plant Soil 415, 131–144.

Renard, D., Tilman, D., 2019. National food production stabilized by crop diversity. Nature 571, 257–260.

Renwick, L.L.R., Deen, W., Silva, L., Gilbert, M.E., Maxwell, T., Bowles, T.M., Gaudin, A.C.M., 2021. Long-term crop rotation diversification enhances maize drought resistance through soil organic matter. Environ. Res. Lett. 16, 084067.

Rodriguez, C., Carlsson, G., Englund, J.E., Flöhr, A., Pelzer, E., Jeuffroy, M.H., Makowski, D., Jensen, E.S., 2020. Grain legume-cereal intercropping enhances the use of soil-derived and biologically fixed nitrogen in temperate agroecosystems. a meta-analysis. Eur. J. Agron. 118, 126077.

Rose, T.J., Kearney, L.J., Erler, D.V., van Zwieten, L., 2019. Integration and potential nitrogen contributions of green manure inter-row legumes in coppiced tree cropping systems. Eur. J. Agron. 103, 47–53.

Silva, J.V., van Ittersum, M.K., ten Berge, H.F.M., Spätjens, L., Tenreiro, T.R., Anten, N.P.R., Reidsma, P., 2021. Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: An appraisal of big data from commercial farms. Field Crop Res. 269, 108176.

Stomph, T., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., Gu, C., Li, L., Simon, J., Jensen, E.S., Wang, Q., Wang, Y., Wang, Z., Xu, H., Zhang, C., Zhang, L., Zhang, W.-P., Bedoussac, L., van der Werf, W., 2020. Chapter One - Designing intercrops for high yield, yield stability and efficient use of resources: are there principles? Adv. Agron. 160, 1–50.

Sun, M., Huo, Z., Zheng, Y., Dai, X., Feng, S., Mao, X., 2018. Quantifying long-term responses of crop yield and nitrate leaching in an intensive farmland using agro-eco-environmental model. Sci. Total Environ. 613-614, 1003–1012.

Sun, M., Zhan, M., Zhao, M., Tang, L.L., Qin, M.G., Cao, C.G., Cai, M.L., Jiang, Y., Liu, Z.H., 2019. Maize and rice double cropping benefits carbon footprint and soil carbon budget in paddy field. Field Crop Res. 2019 (243), 107620.

Sun, T., Feng, X.M., Lal, R., Cao, T.H., Guo, J.R., Deng, A.X., Zheng, C.Y., Zhang, J., Song, Z.W., Zhang, W.J., 2021. Crop diversification practice faces a tradeoff between increasing productivity and reducing carbon footprints. Agric. Ecosyst. Environ. 321, 107614.

The China Agricultural Sector Development Report, 2020. Retrieved from. https://iaed.caas.cn/docs/2020-06/20200605102008307704.pdf.

Thierfelder, C., Cheesman, S., Rusinamhodzi, L., 2012. A comparative analysis of conservation agriculture systems: benefits and challenges of rotations and intercropping in Zimbabwe. Field Crop Res. 137, 237–250.

Timsina, J., Jat, M.L., Majumdar, K., 2010. Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. Plant Soil 335, 65–82.

van Grinsven, H.J.M., Ebanyat, P., Glendining, M., Gu, B., Hijbeek, R., Lam, S.K., Lassaletta, L., Mueller, N.D., Pacheco, F.S., Quemada, M., Bruulsema, T.W., Jacobsen, B.H., ten Berge, H.F.M., 2022. Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates. Nat. Food 3, 122–132.

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J., 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Glob. Chang. Biol. 19, 33–44.

van Oort, P.A.J., Gou, F., Stomph, T.J., van der Werf, W., 2020. Effects of strip width on yields in relay-strip intercropping: a simulation study. Eur. J. Agron. 112, 125936.

Vandermeer, J., 1989. The Ecology of Intercropping. Cambridge University Press, New York.

Wang, M., Wang, L., Cui, Z., Chen, X., Xie, J., Hou, Y., 2017. Closing the yield gap and achieving high N use efficiency and low apparent N losses. Field Crop Res. 209, 39–46.

Wang, Y., Yang, J., Zhang, R., Jia, Z., 2018. Synthesis of climate, soil factors, and nitrogen management practices affecting the responses of wheat productivity and nitrogen use efficiency to nitrogen fertilizer in China. Sustainability 10, 3533.

Winans, E.T., Beyrer, T.A., Below, F.E., 2021. Managing density stress to close the maize yield gap. Front. Plant Sci. 12, 767465.

Xia, H.Y., Wang, L., Xue, Y.F., Kong, W.L., Xue, Y.H., Yu, R.P., Xu, H.S., Wang, X.F., Wang, J., Liu, Z., Guo, X.T., 2019. Impact of increasing maize densities on agronomic performances and the community stability of productivity of maize/peanut intercropping systems. Agronomy 9, 150.

Xiao, H., van Es, H.M., Amsili, J.P., Shi, Q., Sun, J., Chen, Y., Sui, P., 2022. Lowering soil greenhouse gas emissions without sacrificing yields by increasing crop rotation diversity in the North China Plain. Field Crop Res. 276, 108366.

Xu, Z., Li, C.J., Zhang, C.C., Yu, Y., van der Werf, W., Zhang, F.S., 2020. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; a meta-analysis. Field Crop Res. 246, 107661.

Xu, R.X., Zhao, H.M., Liu, G.B., Li, Y., Li, S.J., Zhang, Y.J., Liu, N., Ma, L., 2022. Alfalfa and silage maize intercropping provides comparable productivity and profitability with lower environmental impacts than wheat-maize system in the North China plain. Agric. Syst. 195, 103305.

Yang, H., Wu, M., Liu, W., Zhang, Z., Zhang, N., Wan, S., 2011. Community structure and composition in response to climate change in a temperate steppe. Glob. Chang. Biol. 17, 452–465.

Yan, P., Yue, S., Qiu, M., Chen, X., Cui, Z., Chen, F., 2014. Using maize hybrids and in-season nitrogen management to improve grain yield and grain nitrogen concentrations. Field Crop Res 166, 38–45.

Yang, X., Steenhuis, T.S., Davis, K.F., van der Werf, W., Ritsema, C.J., Pacenka, S., Zhang, F., Siddique, K.H.M., Du, T., 2021. Diversified crop rotations enhance groundwater and economic sustainability of food production. Food Energy Secur. 10, e311.

Yin, Y.L., Zhao, R.F., Yang, Y., Meng, Q.F., Ying, H., Cassman, K.G., Cong, W.F., Tian, X.S., He, K., Wang, Y.C., Cui, Z.L., Chen, X.P., Zhang, F.S., 2021. A steady-state N balance approach for sustainable smallholder farming. Proc. Natl. Acad. Sci. U. S. A. 118, e2106576118.

Yu, Y., Stomph, T.-J., Makowski, D., van der Werf, W., 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: a meta-analysis. Field Crop Res. 184, 133–144.

Zhang, F., Li, L., 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil 248, 305–312.

Zhang, L., van der Werf, W., Zhang, S., Li, B., Spiertz, J.H.J., 2007. Growth, yield and quality of wheat and cotton in relay strip intercropping systems. Field Crop Res. 103, 178–188.

Zhang, L., Cai, J., Li, Y., Wang, X., Yang, W., 2020a. Research progress of mechanization technology and equipment for whole process of corn-soybean strip compound planting. J. Xihua Univ. (Nat. Sci. Ed.) 39, 91–97 (in Chinese with English abstract).

Zhang, X., Fang, Q., Zhang, T., Ma, W., Velthof, G.L., Hou, Y., Oenema, O., Zhang, F., 2020b. Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: a meta-analysis. Glob. Chang. Biol. 26, 888–900.

Zhao, Z., Qin, X., Wang, E., Carberry, P., Zhang, Y., Zhou, S., Zhang, X., Hu, C., Wang, Z., 2015. Modelling to increase the eco-efficiency of a wheat–maize double cropping system. Agric. Ecosyst. Environ. 210, 36–46.

Zhao, H., Qin, J., Gao, T., Zhang, M., Sun, H., Zhu, S., Xu, C., Ning, T., 2022a. Immediate and long-term effects of tillage practices with crop residue on soil water and organic carbon storage changes under a wheat-maize cropping system. Soil Tillage Res. 218, 105309.

Zhao, J., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P., Zeng, Z., Olesen, J.E., Zang, H., 2022b. Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. Nat. Commun. 13, 4926.