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Maize//Soybean Intercropping Improves Yield Stability and Sustainability in Red Soil under Different Phosphate Application Rates in Southwest China

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Abstract: Studying the effects of maize and soybean intercropping for improving the maize yield and sustaining stability of the maize yield under different phosphate (P) application rates in red soil is crucial for promoting maize productivity, improving soil fertility and optimizing P nutrient management in southwest China. The objective of this study was to evaluate the dynamic changes in maize yield, yield stability and soil fertility under monoculture and intercropping maize with different P application rates. A six-year field experiment was conducted from 2017 to 2022 to investigate the effects of maize intercropping with soybean on the yield stability and sustainability of maize according to the changes in the maize yield, biomass, partial land equivalent ratio of yield (pLERY), actual yield loss index (AYL), contribution rate of soil capacity and fertilizer (SCR, SFCR) over time, as well as the differences in the coefficient of variation (CV) and sustainable yield index (SYI) at four P application rates (0 kg P_2O_5 ha^{-1}, P0; 60 kg P_2O_5 ha^{-1}, P1; 90 kg P_2O_5 ha^{-1}, P2; and 120 kg P_2O_5 ha^{-1}, P3) based on the two-factor randomized block design. The linear-platform model was utilized to simulate the relationship between the grain yield, the SYI and the amount of P fertilizer under different P application rates. The maize yield in intercropping was significantly superior to the maize yield in monoculture throughout the entire six-year experiment. For all planting years, the yield and biomass of the intercropping were higher than those of the matched monoculture average by 56.0% and 56.1%, respectively. Intercropping had an advantage of pLERY and AYL for maize. Otherwise, intercropping reduced the CV by 30.8% and 39.1% and increased the SYI by 39.4% and 23.0% in P0 and P3 compared with the matched monoculture, respectively. For all planting years, the average SFCR in intercropping treatment was higher than that in monoculture treatment. The linear-plateau model fitted showed that intercropping increased the yield and SYI by 19.8% and 40.7% on the platform and reduced the P application rate by 37.8% and 11.9% at the inflection point, respectively. These results demonstrate that maize and soybean intercropping could achieve a higher yield, a higher yield stability and an SYI with a lower P input than monoculture. Maize and soybean intercropping could be a sustainable practice for promoting the maize productivity and the yield sustainability in the red soil of southwest China.

Keywords: maize//soybean intercropping; phosphate application rates; yield stability; soil fertility contribution; red soil

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1. Introduction

In the face of the current sustained growth in the global population, the food demand and continued degradation of soil fertility, improving sustainable crop productivity, soil fertility and reducing fertilizer inputs have become important topics of concern for scientists

around the world [1]. Sustainable agriculture is to produce high crop yields and to maintain yield stability and sustainability using a method that is ecologically friendly to the natural environment [2–4]. To develop sustainable agriculture, it is necessary to adopt eco-friendly fertilizer application methods for the natural environment to achieve high crop yields and to maintain yield stability during year-to-year changes [4]. Intercropping is an eco-friendly cropping practice that can enhance the sustainability of agriculture by utilizing crop diversity to exploit synergies between species [5,6]. Therefore, there is a need for balanced fertilizer applications and good cropping practices to maintain stable crop yields and prevent environmental damage.

Crop yield stability and sustainability are important indicators for judging the quality of farmland ecosystems and the sustainability of productivity [7,8], which are affected by many factors, including soil fertility, fertilization, cultivation measures and climatic conditions, as well as the genotype, agronomic management and weather (including sunshine duration, relative humidity and wind speed), which are also substantially correlated with the crop yield [9–12]. Among them, fertilizer application is a necessary and important measure for achieving high and stable grain yields and maintaining the sustainable development of soil fertility [7].

Rational intercropping is a sustainable way to develop agriculture with increasing crop species diversity, which could assist in the suppression of weeds, the control of pests and diseases, the efficient use of light and water, the increase in the yield and resource-use efficiency and the minimization of environmental costs with complementary ecological niches [13–17]. Meanwhile, intercropping has been found to increase yield stability and maintain soil fertility over the long term and increase systemic resistance to the external environment (e.g., contrasting climatic conditions, nutrient deficiencies) [18–20]. Li et al. [15] showed that the low- and high-yield intercropping strategies saved 16–29% of the land and 19–36% of the fertilizer compared with monoculture grown under the same management as the intercrop. Raseduzzaman et al. [21] showed the yield stability in intercropping with the respective monocultures from 33 published papers and found that cereal-grain legume intercropping (CV = 22%) significantly increased the yield stability compared to the corresponding grain legume monocultures (CV = 32%) [21].

Maize and soybean intercropping has been the main and most popular planting pattern in southwest China due to its higher LER, and temporal differentiation in sowing and harvesting dates improves nutrient use efficiency and leads to the over-yield of the entire intercropping system [17,22,23]. It has been introduced to be one of the practices for boosting maize and soybean production and realizing the transition of agriculture to the more efficient use of chemical fertilizers in farming in China [24]. Many studies have reported that maize//soybean intercropping increased the maize yield and LER. Fan et al. [25] and Zhang et al. [26] found that the total economic yield of maize//soybean intercropping was higher than that of the monoculture system according to complementarity and selection effects. Ren et al. [27] and Sun et al. [28] reported that maize//soybean intercropping had an average grain yield LER from 1.05 to 1.07. Chen et al. [22] observed that a grain yield LER as high as 1.85–2.20 was achieved in the maize//soybean intercropping.

Crop yield stability and sustainability are important parameters for measuring whether farmland ecosystems can sustain production. The influence of intercropping on yield stability has been studied regarding N application, mollisol and calcareous yellow fluvo-aquic sandy loam [29]. Long-term intercropping can increase the grain yield and soil fertility in calcareous soil [16]. P is a crucial nutrient for crop growth and plays a vital role in maintaining soil fertility and the sustainability of a crop yield, while P availability is low due to the dissolution, precipitation and sorption [17,18,25]. Maize//soybean intercropping can increase the maize yield and P use efficiency in the red soil of southwest China [17,23], but its long-term and continuous effect on the yield stability, sustainability and fertilizer contribution under different P application rates is little known. The theoretical evidence for maintaining the sustainability of maize and soybean intercropping and improving the soil fertility effect in the red soil of southwest China has been limited to few studies. The

dominance of red soil in southern China and the lower utilization of P fertilizer in this region emphasize the urgency of unlocking the potential of the red soil P pool. Red soil is a typical acidic soil type, encompassing approximately 20% of China's total land area and sustaining 40% of its population [30].

The present study aims to evaluate the dynamic changes in the maize yield, yield stability and soil fertilizer contribution rate under different P application rates in both maize monoculture and maize intercropped with soybean for six consecutive years (from 2017 to 2022) and assess the direct and indirect effects of the year, cropping system and P application rate on the maize yield, yield stability, soil fertility and utilization rate of P fertilizer. The optimum P application rate for promoting the maize productivity, improving soil fertility and optimizing P nutrient management is explored through the response curves of a linear-platform model between the yield and SYI and the amount of phosphorus fertilizer under different P application rates.

Here, we hypothesized that (i) intercropping maize and soybean could have an advantage of yield stability and yield sustainability; (ii) maize and soybean intercropping could contribute to a lower annual P input while maintaining a higher annual yield and an SYI with a high yield stability; (iii) the moderation of P inputs below the current high level does not result in yield penalties.

2. Materials and Methods

2.1. Description of the Experiment Site

A six-year long-term localization experiment was conducted in Xiaoshao (24°54′ N and 102°41′ E), Kunming, Yunnan Province, China, from May 2017 to October 2022. The research location is under a northern subtropical monsoon climate, with a mean annual temperature of 14.4 °C and a mean annual precipitation of 850 mm. Most precipitation falls between June and September; however, the growing season was March to November. The annual precipitation and mean temperature in the maize season during 2017–2022 are shown in Figure 1. The soil was typical plateau red soil (Ferralsols, based on USDA nomenclature), and the physicochemical properties of the topsoil at depths of 0–20 cm before the start of the experiment in 2017 were pH 4.53 (using a ratio of water to soil of 2.5:1), organic matter 4.50 g·kg^{-1}, nitrate nitrogen 2.19 mg·kg^{-1}, Olsen-P 4.02 mg·kg^{-1} and bulk density 1.36 mg·cm^{-3}.

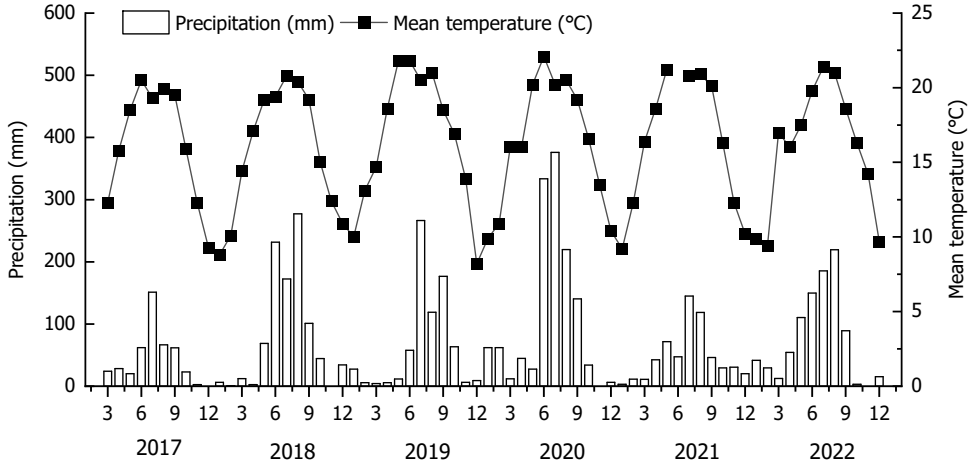

Figure 1. Annual precipitation and mean temperature in the maize growing season during 2017–2022.

2.2. Experimental Design and Crop Management

The experiment was organized as a randomized complete block design with two cropping systems and four P application rates. The main plot constituted two cropping systems: maize monoculture (MM) and maize intercropped with soybean (IM). In the subplot, there were four P application rates: 0, 60, 90 and 120 kg P_2O_5 ha^{-1}, expressed as

P0, P1, P2 and P3, respectively. There were 8 treatment combinations with 3 replications in a total of 24 plots, and each plot area was 24 m^2 (4 m × 6 m). Each plot was planted with 12 rows of maize in a monoculture or 6 rows of maize and 6 rows of soybean in intercropping. The maize//soybean intercropping mode was two rows of maize intercropped with two rows of soybean (2:2). The monoculture maize was planted with a 50 cm row spacing and 25 cm inter-plant distance, resulting in a planting density of 75,000 plants·ha^{-1}, and the intercropping maize and soybean were planted with a 50 cm row spacing and 25 cm inter-plant distance, with a 25 cm edge distance, respectively. The maize variety was 'Yunrui 88' and the soybean variety was 'Kaiyu-2'. The maize was sown in May and harvested in October or November, and the soybean was sown in May and harvested in August from 2017 to 2022.

For nutrient management, urea, superphosphate and potassium sulfate were applied for Nitrogen (N), phosphate (P_2O_5) and potassium (K_2O) fertilizers, respectively. Before the maize and soybean were planted each year, 100 kg N ha^{-1} and 75 kg K_2O ha^{-1} were applied to all plots, and P fertilizers (60 kg P_2O_5 ha^{-1}, 90 kg P_2O_5 ha^{-1} and 120 kg P_2O_5 ha^{-1}) were added to the respective plots following the experimental design. During the maize growing season, extra urea of 62.5 kg N ha^{-1} and 87.5 kg N ha^{-1} was applied as the topdressing at the maize V6 and V12 stages, respectively, for both monoculture and intercropping maize strips. Throughout the growing season for maize and soybean, the field management practices were the same for all treatments.

2.3. Plant Sampling and Measurements

The crop yield was measured through the manual harvesting of maize at the physiological maturity of the crop each year. In order to measure the yields, two central rows of each experimental block of maize were collected in each row to measure the yields and biomass, cutting at 10 mm above the soil surface in the maize monoculture and intercropping plots. All the sample yield units were presented in kg ha^{-1}. The experimental plots were left fallow between cropping seasons. After harvesting, the stove was completely removed, while root residues were kept in the field.

2.4. Indices Calculation

(1) 'Δ' is defined as a symbol of relative quantity, which means the difference between the intercropping and monoculture involved yield (ΔYield), biomass (ΔYield), harvest index (ΔHI), etc.

(2) Partial land equivalent ratio

pLERY is defined as the relative yield of intercropping to the matched monoculture, which is used to evaluate the productivity of intercropped arable lands [26]:

$$\text{pLERY} = Y_{IM}/Y_{MM} \quad (1)$$

where Y_{IM} and Y_{MM} indicate the yield of intercropping and monoculture maize, respectively. pLERY < 0.5 indicates that intercropping is inferior to monoculture, while pLERY (pLERP) > 0.5 means that intercropping is superior to monoculture.

(3) Harvest index (HI, %)

The harvest index refers to the ratio of the economic yield to the biological yield at crop harvest, and its physiological nature reflects the distribution ratio of crop assimilation products on the kernel and vegetative organs.

$$\text{HI} = \frac{Y}{B} \times 100 \quad (2)$$

where Y and B indicate the yield and biomass of maize for each treatment at physiological maturity, respectively.

(4) Actual yield loss index (AYL)

The AYL is calculated with reference to Khonde et al. [31]:

$$\mathrm{AYL} = \frac{Y_{IM}/P_{IM}}{Y_{MM}/P_{MM}} - 1 \quad (3)$$

where P_{IM} and P_{MM} indicate the proportions of maize in intercropping and monoculture, respectively. AYL indicates the relative yield loss or increase in the intercropping compared with the monoculture at a specified planting ratio. AYL > 0 indicates that the yield of the intercropping is higher than that of the monoculture; AYL < 0 indicates that the yield of the intercropping is lower than that of the monoculture.

(5) Yield stability and sustainability

The yield stability index is expressed by the coefficient of variation (CV) commonly used in plant ecology, which measures the variation degree of the yield between years. The higher the CV value, the lower the yield stability [32]. The calculation formula is

$$\mathrm{CV} = \frac{\sigma}{\overline{\mathrm{Y}}} \quad (4)$$

where σ indicates the standard deviation of the yield for each treatment during the experimental period, and $\overline{\mathrm{Y}}$ indicates the average yield for each treatment during the experimental period.

Yield sustainability is represented by a sustainable yield index, and the higher the index, the better the sustainability of the system. The calculation formula is

$$\mathrm{SYI} = \frac{\overline{\mathrm{Y}} - \sigma}{\mathrm{Y}_{max}} \quad (5)$$

where Y_{max} indicates the highest yield for each treatment during the experimental period. SYI varied from 0 to 1, and a higher SYI indicates higher yield sustainability.

(6) Contribution rate of soil capacity and fertilizer

The contribution rate of the soil capacity (SCR) and fertilizer (SFCR) are calculated as follows by Liu et al. [29] and Han et al. [33]:

$$\mathrm{SCR} = \frac{Y_{NF}}{\mathrm{Y}_{max}} \times 100 \quad (6)$$

$$\mathrm{SFCR} = \frac{\mathrm{Y}_F - \mathrm{Y}_{NF}}{\mathrm{Y}_F} \times 100 \quad (7)$$

(7) Phosphate fertilizer application threshold

The maize grain yield, SYI and P fertilizer application amount response curves to the P application rates in the different annual cropping systems are generated using the linear-plateau model to obtain the critical value of P application [34].

$$\mathrm{Y} = \begin{cases} a + bX, & (X < C) \\ P, & (X \geq C) \end{cases} \quad (8)$$

where Y indicates the predicted production of the platform (kg·ha^{-1}), X is the P application amount (kg·ha^{-1}), C is the predicted critical value of P application rates (kg·ha^{-1}) and P is the relative maximum yield and SYI predicted by the platform.

2.5. Statistics

Statistical analysis was performed using the IBM-SPSS software (SPSS Inc., Chicago, IL, USA, version 24.0), and the significance of difference (least at the 0.05 probability level) for all treatments was tested using 'LSD' and Duncan's multiple comparison method. One-way ANOVA analyses were conducted to identify significant differences between the years

(Y), cropping system (C) and P application rates (P), respectively. The two-way ANOVA analyses were conducted to identify the interaction effect of either or both years (Y), the cropping system (C) and P application rates (P), and three-way ANOVA analyses were performed to identify significant effects of the year, planting pattern and P application rates on each index/parameter from the six-year experiment. Yield and SYI response curves to the P application rate in both intercropping and monoculture for all planting years were generated using the linear-plateau model according to the NLIN procedure in SAS [34].

3. Results

3.1. Effect of Intercropping on the Maize Yield and Harvest Index

Six years of field experiments demonstrated that intercropping maize with soybean significantly improved the maize yield, biomass and harvest index (HI) (Figure 2). The effects of the P application rate and cropping system on the maize yield were highly significant during the six years, and the interaction effect on the maize yield was significant (Figure 2a, Table 1). For all the years of the experiment (from 2017 to 2022), the maize yield under fertilization was significantly higher than that without fertilization, irrespective of monoculture or intercropping.

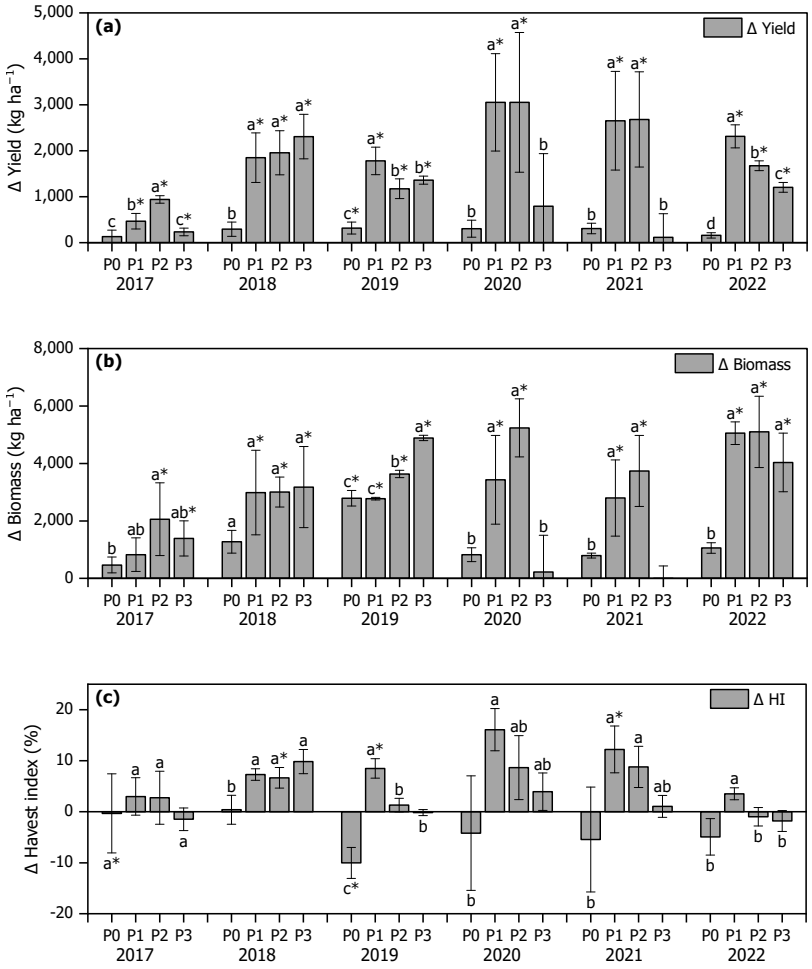

Figure 2. Effect of intercropping on the change in the maize yield (**a**), biomass (**b**) and harvest index (**c**) under P application rates of 0, 60, 90 and 120 kg P ha^{-1} annually (P0, P1, P2 and P3, respectively) from 2017 to 2022. Values are means ± standard errors (n = 3). Values with the same lower-case letters are not significantly different among different P application rates at the 5% level by the LSD. * indicates a significant difference between the cropping system at the same P application rate at the 5% level by the LSD.

Table 1. Three-way ANOVA on the interactions of the maize yield, biomass and HI with the year (Y: 2017 to 2022), P application rates (P: 0, 60, 90, and 120 kg P ha^{-1}) and cropping system (C: monoculture maize and intercropping maize).

Factors	Df	Maize Yield	Biomass	HI
Year (Y)	5	102.59 ***	150.93 ***	26.68 ***
Phosphate application rates (P)	3	851.08 ***	2,619.88 ***	7.02 ***
Cropping system (C)	1	351.54 ***	575.34 ***	15.38 ***
Y × P	15	29.644 ***	86.91 ***	12.62 ***
Y × C	5	7.76 ***	14.63 ***	2.83 *
P × C	3	36.17 ***	26.70 ***	11.59 ***
Y × P × C	15	3.68 ***	5.32 ***	1.00

Note: Df represents degrees of freedom; * $p < 0.05$, *** $p < 0.001$.

As a whole, the maize yield, biomass and HI of the intercropping treatment were higher than those of the monoculture treatment over the six-year period, with the same P application rate (Figure 2). In most cases, the yield and biomass of maize intercropping under all P application rates were significantly higher than those of the monoculture. The maize yield of intercropping was 23.4% to 115.1% and 29.9% to 89.5% higher than that of monoculture in P1 and P2 treatment across all years, respectively ($p < 0.05$). The biomass of intercropping was 24.7% to 44.8% higher than that of monoculture in the P2 treatment across all years, respectively ($p < 0.05$) (Figure 2b). However, the HI of intercropping was only enhanced by 19.9%, 47.0% and 38.5% in the P2 treatment in 2018, 2019 and 2021, respectively ($p < 0.05$).

With the increase in planting years, the maize yield and biomass of intercropping the P0 treatment were initially increased and then decreased. In all planting years, the maize yield and biomass of intercropping were initially increased and then decreased with the increase in the P application rate, with P1 and P2 giving the highest effect.

The three-way ANOVA results showed that the maize yield, biomass and HI were all significantly affected by the year (Y), P application rates (P) and cropping system (C), with a significant interaction effect except for HI under Y × P × C (Table 1).

3.2. Effect of Intercropping on the Land Equivalent Ratio and Actual Yield Loss Index

The partial land equivalent ratio of yield (pLERY) was defined as the relative yields of intercropping to the matched monoculture. To cover all trial years from 2017 to 2022, the maize pLERY values of different P application treatments were all greater than one (Figure 3a). The results indicate that maize and soybean intercropping produced a significant yield advantage for maize, which significantly improved land use efficiency. With the increase in planting years, the maize pLERY value gradually increased in the initial years (2017 and 2018), then increased and decreased (2019 and 2020) and finally gradually decreased with the increase in the P application (2021 and 2022).

The actual yield loss index (AYL) is the relative yield loss or increase in the intercropping maize compared with the monoculture maize. In all trial years from 2017 to 2022, the maize AYL values of different P application treatments were all greater than 0 (Figure 3b). The results indicate that maize and soybean intercropping promoted the growth of maize. With the increase in planting years, the maize AYL value gradually increased or first increased and then decreased in the initial years (2017 to 2020); then, it gradually decreased with the increase in the P application (2021 and 2022). The year, the P application rate and their interaction significantly affect the AYL value (Figure 3b). This indicates that the effects of intercropping on maize growth were influenced by the P application and changed with the planting years.

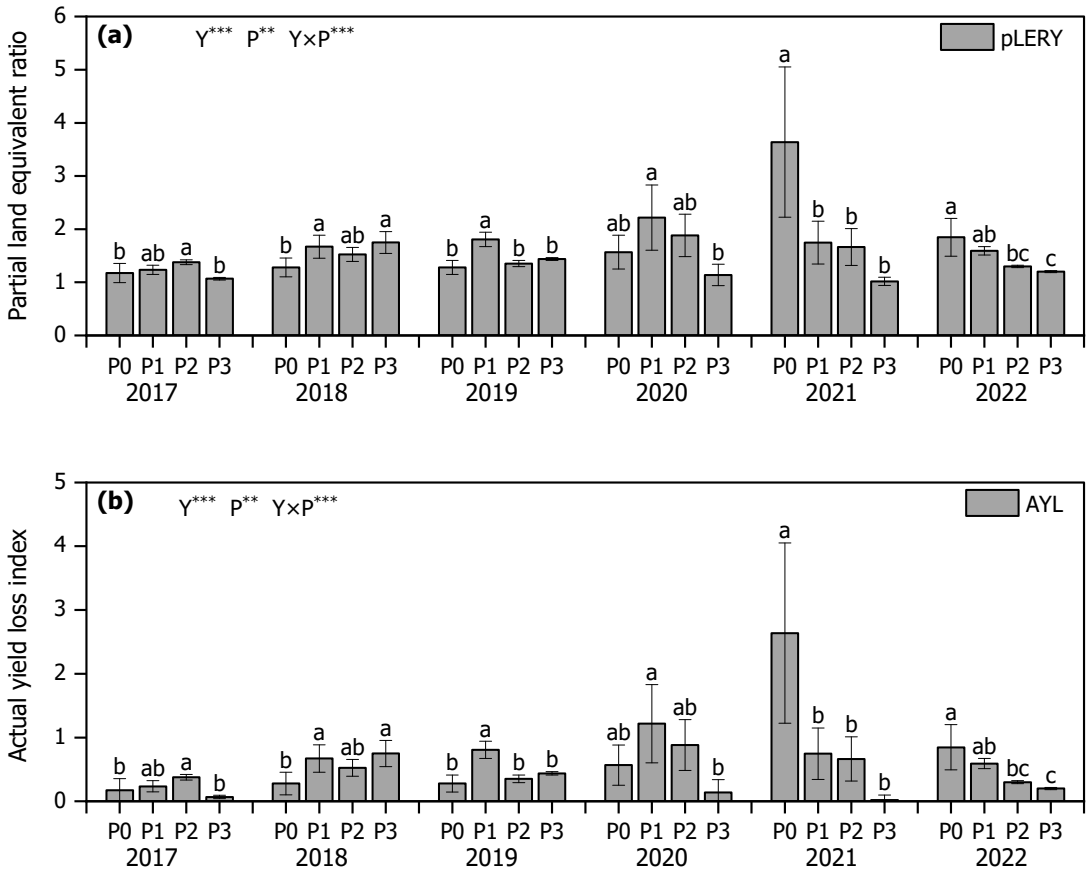

Figure 3. Effect of intercropping on the partial land equivalent ratio (**a**) and actual yield loss index (**b**) under P application rates of 0, 60, 90 and 120 kg P ha^{-1} annually (P0, P1, P2 and P3, respectively) from 2017 and 2022. Values are means ± standard errors (n = 3). Values with the same lower-case letters are not significantly different among different P application rates at the 5% level by the LSD. Y represents years, P represents the P application rate and Y × P represents the interaction between the year and the P application rate. ** $p < 0.01$, *** $p < 0.001$.

3.3. Effect of Intercropping on the Maize Yield Stability and Sustainability

During the 6-year experiment, the main effects of the P application rate on the CV and SYI of the maize yield were highly significant ($p < 0.01$), but the cropping system and their interaction effect were not significant ($p > 0.05$) (Figure 4). Under the same P application rate, the CV value of the maize monoculture was higher than those of intercropping in the P1 and P3 treatments. The CV values of the maize monoculture were 30.8% and 39.1% higher than those of intercropping, respectively (Figure 4a). Under the same P application rate, the SYI of maize monocultures was lower than that of intercropping in the P1 and P3 treatments, and the SYI of maize monocultures was significantly reduced by 39.4% and 23.0% compared with that of intercropping, respectively ($p < 0.05$) (Figure 4b). Therefore, the intercropping treatment can significantly induce CV and increase the SYI of the maize yield, thus enhancing the stability and sustainability of this crop, especially in the treatment with no or excessive P application.

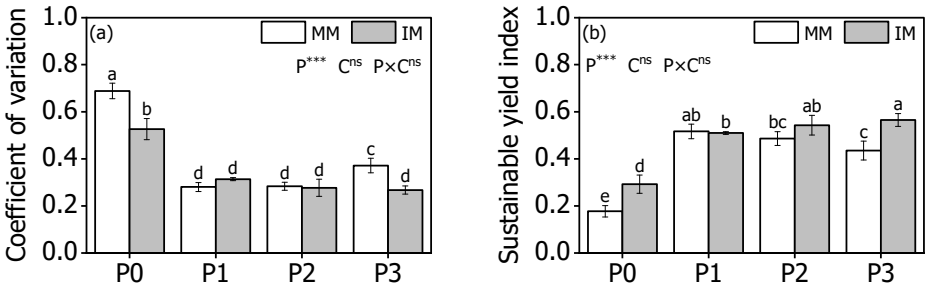

Figure 4. Effect of intercropping (monoculture maize (MM) and intercropping maize (IM)) on the coefficient of variation (**a**) and sustainable yield index (**b**) under P application rates of 0, 60, 90 and 120 kg P ha^{-1} annually (P0, P1, P2 and P3, respectively) from 2017 and 2022. Values are means ± standard errors (n = 3). Values with the same lower-case letters are not significantly different among different planting patterns and P application rates at the 5% level by the LSD. P represents the P application rate, C represents the cropping system and P × C represents the interaction between the P application rate and the cropping system. *** $p < 0.001$, ns $p > 0.05$.

3.4. Effect of Intercropping on Soil and Fertilizer Contribution Rate

Across all experiment years from 2017 to 2022, the two-way ANOVA results showed that the year (Y) and the interaction of the year (Y) and cropping system (C) had a significant effect on the contribution rate of soil capacity (SCR) ($p < 0.01$) (Figure 5a). With the increase in planting years, the intercropping effect of SCR became more apparent, and the SCR of intercropping maize was 217.6% and 51.9% higher than that of the monoculture in 2021 and 2022, respectively.

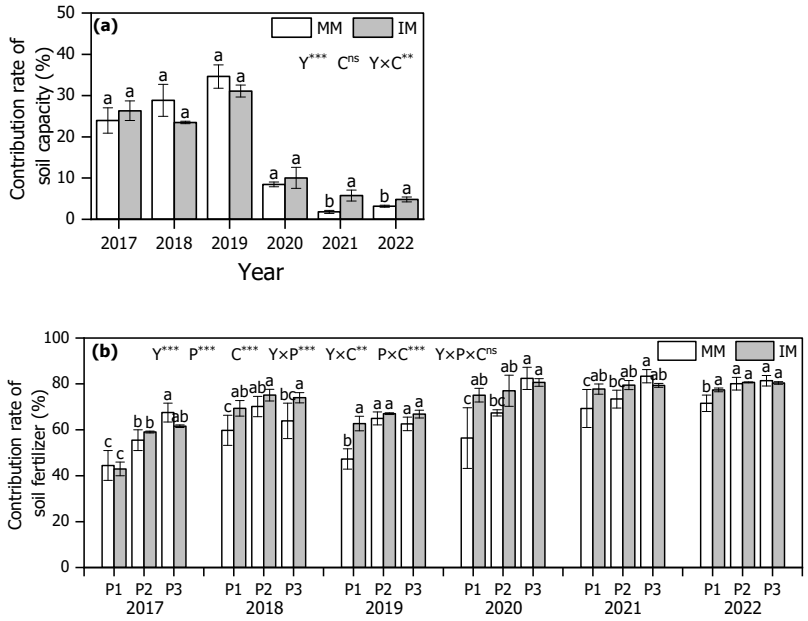

Figure 5. Effect of intercropping (monoculture maize (MM) and intercropping maize (IM)) on SCR (**a**) and SFCR (**b**) under P application rates of 0, 60, 90 and 120 kg P ha^{-1} annually (P0, P1, P2 and P3, respectively) from 2017 to 2022. Values are means ± standard errors (n = 3). Values followed by the same lower-case letters are not significantly different among different planting patterns and P application rates at the 5% level by the LSD. Y represents the year, P represents the P application rate, C represents the cropping system, Y × P represents the interaction between the year and P application rate, Y × C represents the interaction between the year and the cropping system, P × C represents the interaction between the P application rate and the cropping system and Y × P × C represents the interaction among the year, the P application rate and the cropping system. ** $p < 0.01$, *** $p < 0.001$, ns $p > 0.05$.

In the six-year experiment from 2017 to 2022, the three-way ANOVA results showed that the year (Y), P application rate (P), cropping system (C) and their interaction (except Y × P × C) all significantly affect the contribution rate of soil fertilizer (SFCR). In both monoculture and intercropping, the SFCR in maize showed a trend of increasing first and then keeping steady with the increase in planting years, while the intercropping advantage of SFCR gradually decreased. Except for 2017, the intercropping maize significantly increased the SFCR by 8.2% to 33.1% in all treatments from 2018 to 2022 (Figure 5b). Regardless of the P application rates or cropping system, the SFCR of all treatments increases first and then keeps steady with the increase in planting years. The SFCR under a conventional and a higher P application rate (P2 and P3) was higher than that under a low P application rate (P1).

3.5. Recommended Fertilizer Dosage Based on Optimal Yield under Intercropping

The maize yield response of each annual cropping system to the P application rate is shown in Figure 6, and a linear-plateau model fitted the data well for all indexes ($p < 0.01$). For the yield, the plateau of intercropping maize was reached at input rates between P1 and P2, and the monoculture maize was between P2 and P3. The highest yields (platform yield) were 5758.1 kg ha^{-1} and 4806.6 kg ha^{-1} when the P application rate (inflection point) was 73.0 kg ha^{-1} in intercropping and 117.3 kg ha^{-1} in monoculture cropping, respectively (Figure 6a). The intercropping maize had a higher platform yield and reached the inflection point earlier than the monoculture. Compared with the monoculture, the platform yield of intercropping increased by 19.8%, and it decreased the P application rate at the inflection point by 37.8% (Figure 6a); this indicates that intercropping maize could achieve a higher yield with a lower P input. The SYI response of each annual cropping system to the P application rate was similar to that of the yield; the highest SYIs were 0.788 and 0.536 when the P application rate (inflection point) was 79.3 kg ha^{-1} in intercropping and 90.0 kg ha^{-1} in monoculture cropping, respectively. The platform SYI of intercropping increased by 40.7%, and it decreased the P application rate at the inflection point by 11.9% (Figure 6b).

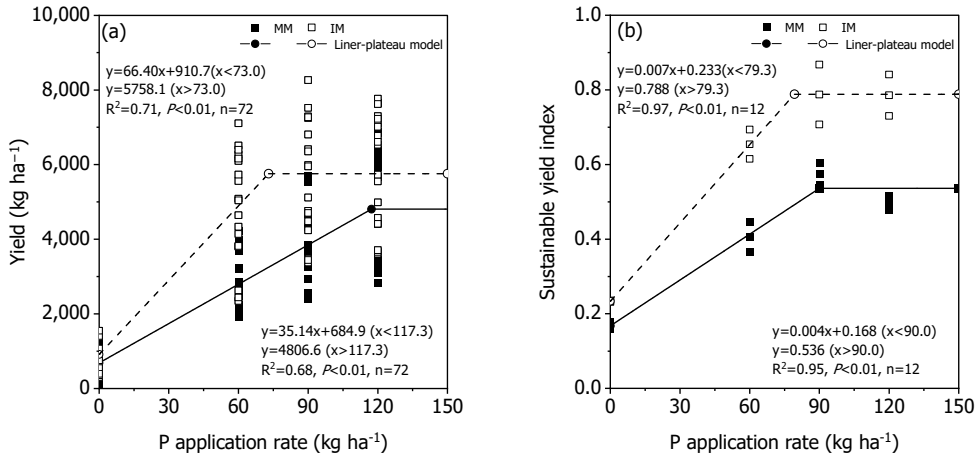

Figure 6. The relationship fitted by the linear plateau model between the yield (**a**) and SYI (**b**) with P application rates of 0, 60, 90 and 120 kg P ha^{-1} annually (P0, P1, P2 and P3, respectively) from 2017 to 2022 in a maize and soybean intercropping system (monoculture maize (MM) and intercropping maize (IM)).

4. Discussions

4.1. Yield Advantage of Intercropping Affected by P Application

Worldwide, intercropping has been extensively demonstrated to provide higher yields per unit of land and fertilizer compared to monoculture, providing opportunities for the sustainable intensification of agriculture [15,35]. In our study, the maize yield, biomass and HI of the intercropping treatment were higher than those of the monoculture treatment over

the six-year period under the same P application rate. Consistent with the findings of Wang et al. [36] and Xu et al. [37], although intercropping and P application had a significant effect on the maize yield, significant differences existed between different P application rates, and they were also affected by the planting year [17,38]. In this study, the maize yield and biomass of intercropping were initially increased and then decreased with the increase in the P application rate, with P1 and P2 giving the highest effect. There was a significance of the years (Y), P application rates (P) and cropping system (C) with their interaction, except for HI under Y × P × C (Table 1). Furthermore, with the increase in the planting year, the maize yield and biomass of intercropping the P0 treatment were initially increased and then decreased. This suggests that despite the yield advantages of intercropping, soil nutrients are gradually depleted by increasing the years of cultivation without nutrient input. Many studies have shown that the efficient use of resources determines whether there was an advantage in the grain yield, and the balance between competition and interaction in the intercropping system was the key to the effective utilization of resources [33,39,40].

The LER was the most-used convention for intercrop versus monoculture comparisons, while the partial AYL showed yield losses or gains through its symbol and value, which could more accurately reflect the competition between and within component crops [31,41]. In this study, the partial land equivalent ratio of maize yield (pLERY) was from 1.02 to 3.64, and the average pLERY was 1.57 (Figure 3a). The same phenomenon can be seen in maize//soybean intercropping under different nitrogen-application rates in the mollisol area of the Southeast [29] and the higher wheat–maize double-cropping intercropping with soybean in calcareous yellow fluvo-aquic sandy loam in the North China Plain [42]. A global meta-analysis also showed that the average LER of maize//soybean intercropping is 1.32 due to the temporal niche differentiation driven by different planting times of crops in intercropping systems [37]. The LER value of this study was higher than one in all treatments, indicating that the maize//soybean intercropping system still showed yield advantages; meanwhile, the yield advantage of intercropping maize was affected by P application and changed with the planting years.

In this study, all AYL values of different P application treatments in maize were greater than 0 in all trial years from 2017 to 2022. This indicates that maize has an intercropping advantage in the maize//soybean intercropping system, which is consistent with previous research [29,43,44]. According to interactive analysis, the year, the P application rate and their interaction significantly affect the AYL value (Figure 3b); this indicates that the effects of intercropping on maize growth were influenced by P application and changed with the planting years, which is consistent with the yield. However, with the increase in planting years, the overall trend of the maize AYL value is to increase first and then decrease or directly decrease with the increase in P application (Figure 3b). This indicates that intercropping maize and soybean has the potential to raise the maize yield in red soil, but one needs to make sure an appropriate amount of P fertilizer is added for enhancing the effective utilization of P. The findings of Mudare et al. [35] and Liu et al. [29] substantiate our findings with similar outcomes.

4.2. Yield Stability Sustainability of Intercropping

The stability of crop yields is an important indicator for assessing the quality of agricultural environments, while the sustainability of crop yields is an important metric for assessing whether agricultural environments are capable of supporting sustained production [7]. Chen et al. [11], through a 36-year long-term fertilization experiment, demonstrated that inorganic + organic fertilizer could increase the wheat yield and its stability by improving the soil fertility and reducing variability to climate change. Wang et al. [18] showed that wheat//maize and maize//faba bean intercropping overyielded compared with monoculture and also maintained the stability of most of the soil chemical and enzyme activities relative to the monoculture in the relatively fertile soil studied on a timescale of one decade. Zan et al. [45] found that long-term maize intercropping with peanut and phosphorus application maintains sustainable farmland productivity

by improving the soil aggregate stability and p availability in the North of China. Our results showed that the yield stability of intercropping was consistently higher in P0 and P3 treatments compared with monoculture, but there was no significant difference in the P1 and P2 treatments (Figure 4a). Furthermore, the yield sustainability of intercropping was significantly higher than that of monoculture in the P0 and P3 treatments (Figure 4b), which indicates that intercropping might maintain a yield stability and sustainability under extreme fertilization conditions (P0 and P3) as a result of within-field variation in interspecific interactions [46]. This result is consistent with the research results of Liu et al. [29], in which maize//soybean intercropping had a higher yield stability than monoculture under different nitrogen application rates over time.

The year-to-year yield stability revealed the sustainability of crops to maintain the yield, as affected by management, climatic and environmental changes [14,16,47]. Martin et al. [48] found that only the case of faba bean and wheat grown in Denmark conferred statistical evidence for greater yield stability in the intercrops compared to sole cropping of the intercrop components. Our results further confirm that crop diversification by the intercropping of maize with legume crops improved the year-to-year yield stability of maize. This is in agreement with the latest findings of Li et al. [16] showing that intercropping systems had greater year-to-year yield stability than monocultures [49].

4.3. Soil and Fertilizer Contribution Rate of Intercropping

Soil productivity and fertilizer contribution rates are two important indicators in evaluating planting management systems. In this study, the maize//soybean intercropping system showed a clear advantage in terms of P use efficiency; the soil capacity contribution rate of maize and soybean intercropping was 217.6% and 51.9% higher than that of monoculture in 2021 and 2022, respectively. The soil fertilizer contribution rate of maize and soybean intercropping was significantly increased by 8.2% to 33.1% in all treatments from 2018 to 2022. This may be because the interspecific interactions may facilitate maize and soybean crops to increase the effective P concentration via root–root interactions and microbial processes by increasing AMF diversity and macro-aggregates and secreting organic acids or phosphatase to mobilize and hydrolyze insoluble forms of P [17,50–52], which can enhance the absorption and utilization of soil P by grass crops, thus improving the P use efficiency and enhancing the contribution rate of soil fertility in the intercropping system [29,53].

Numerous studies have confirmed that maize//soybean intercropping increases the maize yield and soil fertility, and intercropping legume crops is the key to improving soil productivity per unit area and ensuring the stable and sustainable yield of farmland ecosystems [54–57]. In this study, the contribution rates of the soil fertility and fertilizer to the yield fluctuated between different years, but as a whole, with the increase in planting years, the contribution rate of soil fertility first increased and then decreased, while the contribution rate of soil fertilizer increased year by year. This indicates that the increase in the P uptake in the maize intercropping system was more dependent on the consumption of P from the fertilizer and the complementary use of P resources. This echoes the view in the previous chapter that the maize yield, biomass and P uptake of the P0 treatment initially increased and then gradually decreased with the increase in planting years. The depletion of P through interspecific interactions may increase the soil demand for exogenous P [17,58]. Therefore, improving the basic fertility of the soil can reduce the dependence of the maize yield on exogenous fertilizers and thus reduce the application amount of fertilizers.

4.4. Synergies between Intercropping and Optimized P Management

The establishment of a fertilizer effect function through field experiments is a conventional method for obtaining the appropriate fertilizer application amount [42,59]. Currently, the functional models used include a one-dimensional quadratic model, linear platform model, exponential model, square root model, etc. The optimal fertilizer amount obtained has the advantage of high accuracy, and the economic fertilizer application amount, up-

per limit and lower limit of fertilization can be calculated [60–62]. In our study, with the increase in experimental years, the cumulative effects of fertilizer P application on soil P availability and crop yield were supposed to be strengthened, resulting in a yield level decline at zero P supply, a yearly increased yield gap between low and high P supplies and a high P surplus at a high P application rate [17,63].

The appropriate amount of fertilizer obtained through single-season crop field trials is often greatly affected by climate conditions, while the appropriate amount of fertilizer obtained through multi-year field trials overcomes the influence of climate change and other factors and is more reliable, practical and statistically significant [10,64,65]. For the application of P fertilizer, it is particularly important to obtain the appropriate amount of P fertilizer through a multi-year positioning test [42,53,59]. On the one hand, the optimum amount of P fertilizer obtained from many years of P fertilizer experiments is related to the continuous decline in the P supply capacity and the effect and efficiency of the continuous application of each P fertilizer treatment. On the other hand, the optimum amount of P fertilizer is related to crop absorption and the fixation and release of phosphorus in the soil [66,67]. The conversion rate of various forms of P in soil into available P is slower than that of P absorbed by crops. With the increase in planting years, more P fertilizer needs to be applied to maintain soil P fertility and promote a high and stable crop yield, which inevitably leads to the accumulation of soil P [42]. After the long-term input of P fertilizer and the continuous release of slow-available P in soil, the fixation and release of soil P will gradually balance [17].

The year-to-year yield stability revealed the sustainability of crops in maintaining the yield, as affected by climatic and environmental changes [14,16,47]. Meanwhile, our results found that, compared to the annual monoculture, intercropping increased the yield and SYI by 19.8% and 40.7% on the platform and decreased the P application rate by 37.8% and 11.9% at the inflection point through the linear-plateau model, respectively. Our results suggest that the optimal P application rate could even be reduced to only 73 to 82 kg ha^{-1} $year^{-1}$, mainly due to the diversity achieved by intercropping with legumes. This recommendation of P fertilizer was consistent with Wu et al. [68], in which the average recommended P application in each ecological region was 75 kg ha^{-1} according to the basic NPK fertilizer recommendation for maize production regions in China. Therefore, maize and soybean intercropping in combination with rational P application provides comparable productivity and P uptake, with a higher yield stability and lower P loss than those of the monoculture maize, showing opportunities for more sustainable agricultural production.

5. Conclusions

The present study reveals that continuous maize//soybean intercropping for 6 years showed the obvious advantages of intercropping and increased the yield and biomass with higher pLERY and AYL relative to the corresponding monocultures. Meanwhile, intercropping enhanced the maize yield stability and sustainability, especially in the treatment with no and excessive P applications (P0 and P3). With the increase in planting years, the contribution rate of the soil capacity of the P fertilizer first increased and then gradually decreased, and it showed the advantage of intercropping in the later planting period. However, the advantage of intercropping gradually decreased with the increase in the P application rate. The linear-plateau model showed that intercropping maize with soybean could achieve a higher maize yield and SYI with a lower P input than monoculture. Taking into account the crop yield and SYI, controlling the amount of P application from 73 to 82 kg ha^{-1} $year^{-1}$ could ensure the yield advantage of intercropping and enhance the yield stability and sustainability in the red soil of southwest China.

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