

Article

Co-Ridge Planting Enhances Yield Advantages of Maize Intercropping with Peanut by Improving Soil Aggregate Stability and the Ecological Stoichiometric Characteristics of Carbon, Nitrogen, and Phosphorus

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Abstract

Long-term maize (*Zea mays* L.) intercropping with peanut (*Arachis hypogaea* L.) (M|P) improves soil aggregate stability and phosphorus (P) availability, sustaining farmland productivity. In contrast, co-ridge planting (R-M|P) further enhances yield. However, the relationship between yield increase and improvements in soil aggregate stability and ecological stoichiometric characteristics under R-M|P remains unclear. Therefore, this study examined the effects of R-M|P on aggregate fractions and stability, bulk density (BD), porosity (Pt), soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), total phosphorus (TP), and inorganic phosphorus, along with the ecological stoichiometric characteristics of C, N, and P. R-M|P substantially increased the proportion of topsoil macroaggregates, both mechanically stable (>0.5 mm) and water-stable (>1 mm), compared with flat planting. Additionally, it enhanced $WR_{0.25}$ and mean weight diameter, substantially reduced BD, and increased Pt. Furthermore, R-M|P significantly increased the concentrations of SOC, TN, TP, AP, Ca_2 -P, Ca_8 -P, Al-P, and Fe-P. It also enhanced the contribution rates of SOC, TN, TP, and AP in macroaggregates, leading to increased storage of carbon (SCS), nitrogen (SNS), and phosphorus (SPS). R-M|P significantly elevated C:N and C:P ratios. Phosphorus application increased SOC and nutrient concentrations, positively regulated C:N, and enhanced C, N, and P storage. However, it negatively influenced C:P and N:P ratios. SOC and AP were the main driving factors affecting the intercropping advantage, with explanatory rates of 33.2% and 22.7%, respectively, under R-M|P. These findings suggest that R-M|P combined with P application enhances yield by promoting aggregate stability, increasing the concentrations and storage of C, N, and P, and establishing a new ecological stoichiometric balance.

Keywords: co-ridge intercropping; soil C-N-P stoichiometry; soil structure stability; long-term field experiment



Academic Editor: Andrea Baglieri

Received: 26 July 2025

Revised: 6 September 2025

Accepted: 19 September 2025

Published: 20 September 2025

Citation: Zan, Z.; Ma, R.; Wang, J.; Liu, L.; Ning, T.; Jiao, N. Co-Ridge Planting Enhances Yield Advantages of Maize Intercropping with Peanut by Improving Soil Aggregate Stability and the Ecological Stoichiometric Characteristics of Carbon, Nitrogen, and Phosphorus. *Agronomy* **2025**, *15*, 2227. <https://doi.org/10.3390/agronomy15092227>

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1. Introduction

Maize intercropping with peanuts (M|P) is a classic cereal–legume intercropping system that exhibits significant above- and belowground interspecific interactions, leading to a notable yield advantage [1]. However, intense interspecific light competition between

maize and peanuts during the mid-to-late growth stages limits further yield enhancement in the M||P system. To overcome this yield bottleneck, this study adopted the co-ridge planting method based on the traditional flat intercropping system and conducted in-depth research on its yield-enhancing effects. Our previous study showed that co-ridge intercropping (R-M||P) increases both maize and peanut yields, further strengthening the yield advantage in the M||P system. Key factors driving these results include improved spatial distribution of soil moisture and better coordination between functional leaf photosystems [2]. However, the relationship between increased yield under R-M||P and soil aggregate fractions and stability, soil nutrients, and ecological stoichiometric characteristics remains unclear. Therefore, further research is needed.

Most previous studies on maize–peanut intercropping focused on short-term yield benefits (1–3 years) but overlooked long-term (14-year) effects on soil aggregate formation and nutrient cycling—a gap addressed by our permanent plot experiment. Our 14-year continuous trial (2010–2023) provides a unique opportunity to explore long-term soil–plant interactions under co-ridge intercropping, which is critical for assessing the sustainability of the system beyond immediate yield gains. Notably, soil aggregate formation and nutrient cycling are processes that require long-term observation to capture cumulative effects, making our 14-year dataset particularly valuable for disentangling their links to the yield advantages of co-ridge intercropping.

Rational intercropping can promote the formation of soil macroaggregates through the entanglement of roots from different crops and the organic binding substances secreted by these roots, thereby enhancing soil structure. It also increases soil porosity (Pt), reduces soil bulk density (BD), and improves soil structural stability [3,4]. By increasing species diversity, the intercropping system enables the decomposition of organic residues (e.g., leaves and roots) from various crops, thereby boosting soil organic matter and nutrient concentrations [5–7]. Additionally, it regulates the ecological stoichiometric ratios of soil carbon, nitrogen, and phosphorus, alleviates soil nutrient limitations, and enhances the sustainable productivity of agriculture [8,9].

Ridge planting is an agricultural practice with strong water- and nutrient-retention capabilities [10]. Compared with conventional flat planting, co-ridge planting significantly increases humus concentrations in the topsoil. Nutrients released from humus decomposition enhance SOC and nutrient availability [11]. Research has shown that ridge planting can increase the proportion of soil macroaggregates (>2 mm), with the highest nutrient concentrations observed in these macroaggregates. Moreover, the C:N, C:P, and N:P ratios in the topsoil align more closely with the national averages [12]. Ridge planting also thickens the active soil layer, improves soil water retention and fertilizer-holding capacity, and promotes early seedling emergence and root development, leading to significant increases in crop yield [13,14]. Co-ridge intercropping further enhances soil quality and the persistence of soil organic matter [15], facilitates the formation of soil macroaggregates, boosts soil nutrient concentrations, and supports the sustainable development of crop productivity [16,17]. This occurs because intercropping combined with ridge tillage enhances nutrient utilization efficiency [18,19], increases root biomass [20], and improves soil aggregate stability through root intertwining [21,22]. These processes help prevent the biodegradation and erosion of soil compounds while increasing SOC and nutrient concentrations [23,24].

Fertilization is a critical practice in agricultural production, as it replenishes soil nutrients and ensures the healthy growth of crops, which in turn positively influences soil aggregate proportions, bulk density (BD), porosity (Pt), and mean weight diameter (MWD) [8,25–27]. The substantially higher productivity resulting from fertilization increases the input of organic matter in the form of root exudates, decaying roots, and aboveground residues, thereby enlarging the carbon pool of soil microorganisms, which

positively impacts microbial community diversity [28,29]. Furthermore, investigating alterations in soil stoichiometric characteristics under prolonged fertilization improves our understanding of nutrient cycling and limitations in soil ecosystems, ultimately enhancing crop yield and maintaining soil health [30].

However, long-term fertilization can undermine the soil ecosystem by altering the soil's physicochemical microenvironment and disrupting the nutrient cycle [8,31,32]. Fertilization combined with intercropping can counteract the decline in soil structural stability and C depletion [27], enhance nutrient supply and storage capacity, modulate soil C, N, and P stoichiometric characteristics, reduce BD, and boost crop yield [33]. Additionally, co-ridge intercropping with fertilization enhances soil Pt and permeability, facilitating water and nutrient absorption [34,35], increasing fertilizer utilization efficiency, and improving both intercropping yield and land equivalent ratio [36,37]. Our research group's previous study concluded that R-M || P with fertilization enhances crop yield and intercropping advantages by improving the soil water environment and photosynthetic rate [2]. Nevertheless, two critical questions remain: (i) does the increased yield advantage of R-M || P result from its ability to improve soil BD and Pt, strengthen soil aggregate stability, enhance SOC and nutrient concentrations, and regulate ecological stoichiometric characteristics, and (ii) what are the regulatory effects of phosphorus application?

Consequently, our initial hypotheses were as follows: compared with maize–peanut flat intercropping (F-M || P), (i) R-M || P improves macroaggregate fractions, enhances aggregate stability and porosity (Pt), and reduces BD in topsoil; (ii) R-M || P increases the concentrations of SOC, TN, TP, and AP in aggregate fractions and in topsoil, along with their contribution rates in macroaggregates; and (iii) R-M || P boosts C, N, and P storage, as well as the C:N and C:P ratios in topsoil, significantly enhancing C:N and C:P in aggregates. To verify these hypotheses, a long-term M || P experiment with two levels of P fertilizer application was conducted. Overall, this study aimed to investigate the effects of R-M || P on soil aggregate fractions and stability, as well as the concentrations and ecological stoichiometric characteristics of C, N, and P in aggregate fractions and topsoil. Furthermore, it sought to examine how these factors contribute to the intercropping advantage, providing a theoretical basis for further yield improvement in the M || P system (Figure 1).

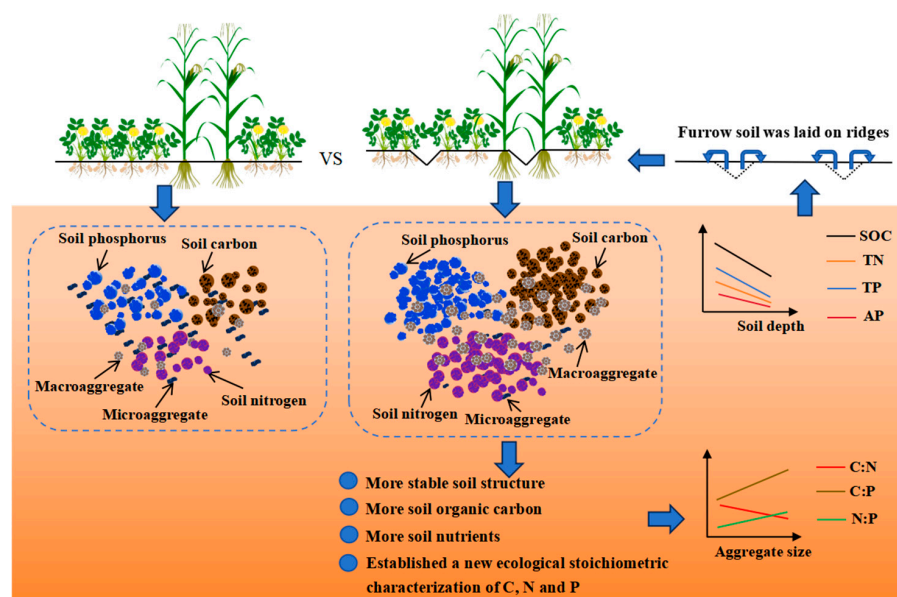


Figure 1. Hypotheses for key factors and mechanisms of maintaining farmland productivity in maize–peanut co-ridge planting. The letters SCS, SNS, and SPS represent the storage of C, N, and P, respectively. C:N, C:P, and N:P represent the C-N, C-P, and N-P ratios, respectively.

2. Materials and Methods

2.1. Experimental Site

The experiment (M|P) was conducted in the experimental field on the farm of Henan University of Science and Technology (latitude 33°35′–35°05′ N, longitude 111°08′–112°59′ E). Situated in the temperate zone, the site has a warm temperate continental monsoon climate. The mean annual temperature is approximately 13.6 °C. The average annual precipitation is 611 mm, while annual evaporation reaches 2113 mm. The frost-free period lasts about 210 days, and the annual sunshine duration is about 2060 h.

The soil at the experimental site is loam-textured yellow soil (medium-textured), classified as Luvisols (WRB). Soil texture was determined using the hydrometer method [GB/T 50123-2019]. The particle size distribution (0–20 cm) was: sand (20–2000 µm), 32.5% ± 1.2%, silt (2–20 µm), 45.3% ± 0.8%; and clay (<2 µm), 22.2% ± 0.5%.

The characteristics of the 0–20 cm topsoil were measured using standard methods at the beginning of the experiment in 2010, yielding the following results: pH, 7.66; organic C, 10.74 g·kg^{−1}; available N, 33.96 mg·kg^{−1}; available K, 223.8 mg·kg^{−1}; AP, 6.84 mg·kg^{−1}; available Fe, 5.98 mg·kg^{−1}; and BD, 1.31 g·cm^{−3}.

2.2. Experimental Design

The maize cultivar (cv.) Zhengdan 958 and peanut cultivar (cv.) Huayu 16, a type commonly used by local farmers, was studied. A completely randomized block field experiment was conducted from 2010 to 2023, involving three cropping systems and two P fertilizer treatments. The cropping systems included sole-crop maize (SM), sole-crop peanut (SP), and M|P. The two P application levels were 0 kg P₂O₅·ha^{−1} (P₀) and 180 kg P₂O₅·ha^{−1} (P₁₈₀). P₀ served as the control to assess the inherent soil P supply capacity and the effect of cropping patterns (e.g., R-M|P vs. F-M|P) without external P input. At the same time, P₁₈₀ represented the locally recommended optimal rate for maize–peanut intercropping systems in Henan Province, China—consistent with regional agricultural extension practices and our previous long-term experiment [5].

Starting in 2018, an additional R-M|P system was introduced, in which maize and peanuts were sown on the same ridge using the same row and plant spacing as F-M|P. Thus, the experiment had four treatments, each replicated 3 times, resulting in a total of 12 plots. Each plot was 8 m long and 6 m wide, with an area of 48 m². From 2010 to 2023, each plot was permanently assigned to one summer cropping system (e.g., Plot 1 was consistently M|P, Plot 2 consistently SM, etc.), ensuring that treatment effects were not confounded by spatial variability across years.

In the M|P system, the 2:4 mode (two rows of maize intercropped with four rows of peanuts) was implemented, with relative densities of maize and peanuts at 0.56 and 0.44, respectively. The total strip width was 200 cm. Maize had a row spacing of 40 cm and a plant spacing of 40 cm and 20 cm, resulting in a planting density of 50,000 plants ha^{−1}. Peanuts had a row spacing of 30 cm and plant spacing of 20 cm, resulting in a planting density of 100,000 plants ha^{−1}. The spacing between maize and peanut strips was 35 cm.

In sole cropping, peanut rows were spaced 30 cm apart, with 20 cm between plants, leading to a density of 166,667 holes·ha^{−1}. Maize rows were spaced 60 cm apart, with 25 cm between plants, resulting in a density of 66,667 plants·ha^{−1}. Urea (90 kg N·ha^{−1}) was applied to the field before crop sowing. During the maize grain-filling period, an additional 90 kg N·ha^{−1} was applied as a furrow dressing using urea. The two P application levels (P₀ and P₁₈₀) were applied as diammonium phosphate before sowing.

The annual cropping sequence was as follows: mid-June sowing of maize and peanut → mid-October harvest → late October sowing of winter wheat → early June wheat harvest in the following year → repeat. To ensure that the system reached a stable state and to

eliminate initial interference factors, measurements were delayed until the second year of the co-ridge intercropping trial (i.e., 2019). A final round of measurements was conducted in 2023, the concluding year of the experiment. This approach ensured the stability and representativeness of the data presented.

2.3. Soil Sampling

Soil samples were collected after harvesting maize and peanuts in 2019 and 2023 to a depth of 20 cm from the crop planting strips using an auger (10 cm diameter). A total of 12 plots were sampled (4 treatments $\times$ 3 replicates), with samples taken at three specific positions in the corresponding crop strips: midway between the maize and peanut strips, between the 1st and 2nd rows, and between the 3rd and 4th rows of the peanut strip. Two sampling points were selected at each of these three positions, resulting in a total of six sampling points per plot to ensure uniform coverage of spatial variability.

The soil from the six sampling points of each plot was thoroughly mixed to form one composite sample. Impurities such as stones, roots, and plant litter, were removed, and the composite sample was gently broken into 10–12 mm diameter aggregates, preserving its natural structure. The composite sample was then divided into two subsamples using the quartering method to ensure representativeness.

One subsample was air-dried and sieved through a 2 mm mesh to measure soil physical and chemical properties. The other was air-dried and sieved through a 10 mm mesh for aggregate fractions.

2.4. Determination of Soil Aggregate

Soil mechanical aggregates were measured using the dry-sieving method [38] and divided into five size classes: (1) >2 mm, huge macroaggregates; (2) 1–2 mm, large macroaggregates; (3) 0.5–1 mm, small macroaggregates (in this study, “macroaggregates” refers to aggregates >0.5 mm); (4) 0.25–0.5 mm, microaggregates; and (5) <0.25 mm, silt and clay (here, “microaggregates” refers to aggregates <0.5 mm). The weights of the aggregate fractions were recorded, and the concentrations of SOC, TN, TP, AP, and inorganic phosphorus (Pi) were determined for each fraction.

Soil water-stable aggregates were measured using the wet-sieving method [39]. The procedure was as follows: 50 g of soil, gently broken by hand and passed through a 10 mm sieve, was weighed and placed on the top layer of a nested sieve set (apertures from top to bottom: 2 mm, 1 mm, 0.5 mm, 0.25 mm, and 0.053 mm). The sieve set was pre-immersed in deionized water for 5 min to allow gradual infiltration. It was then mounted on a wet-sieving apparatus (Model YMJ-II) and oscillated vertically at a frequency of 30 times per minute with an amplitude of 3 cm for 30 min. During oscillation, unstable aggregates disintegrated and passed through the sieves, while stable aggregates remained on their respective sieve layers. Aggregates retained on each sieve were rinsed into pre-weighed aluminum boxes, oven-dried at 105 °C for 24 h to a constant weight, and then weighed. Soil water-stable aggregates were divided into six size classes: (1) >2 mm, huge macroaggregates; (2) 1–2 mm, large macroaggregates; (3) 0.5–1 mm, small macroaggregates (in this study, “macroaggregates” refers to aggregates >0.5 mm); (4) 0.25–0.5 mm, microaggregates; (5) 0.053–0.25 mm, silt; and (6) <0.053 mm, clay.

2.5. Analysis of Soil Physical and Chemical Properties

Soil organic carbon (SOC) determination: Soil organic carbon was oxidized using 0.8 mol·L^{−1} potassium dichromate-sulfuric acid solution under external heating (oil bath at 180 °C, boiled for 5 min). The remaining potassium dichromate was titrated with ferrous sulfate, and organic carbon content was calculated based on the amount of potassium dichromate consumed [40].

Soil total nitrogen (TN) determination: After digestion using the Kjeldahl method (with a $\text{CuSO}_4\text{-K}_2\text{SO}_4$ accelerator and concentrated H_2SO_4), TN content was determined with a Kjeldahl nitrogen analyzer [40].

Soil total phosphorus (TP) determination: After digestion with concentrated sulfuric and perchloric acids, TP content was determined by inductively coupled plasma (ICP) [40].

Soil available phosphorus (AP) determination: Soil samples were extracted with $0.5 \text{ mol}\cdot\text{L}^{-1} \text{ NaHCO}_3$ (pH 8.5), and AP content was determined using an inductively coupled plasma atomic emission spectrometer (ICP-AES) [40].

Determination of inorganic phosphorus forms: Soil samples were sequentially extracted with NaHCO_3 , NH_4OAc , NH_4F , and $\text{NaOH-Na}_2\text{CO}_3$ to obtain extracts containing $\text{Ca}_2\text{-P}$, $\text{Ca}_8\text{-P}$, Al-P , and Fe-P , respectively. The residual soil was then treated with $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7\text{-Na}_2\text{S}_2\text{O}_4$ solution (heated in an $80\text{--}90^\circ\text{C}$ water bath), and the supernatant was digested with $\text{H}_2\text{SO}_4\text{-HClO}_4\text{-HNO}_3$ to obtain Olsen-P. Finally, $\text{Ca}_{10}\text{-P}$ was extracted with H_2SO_4 . Concentrations of all inorganic phosphorus forms were determined by ICP-AES [40]. pH determination: Soil pH was measured by the potentiometric method using a soil-water suspension (1:2.5, m/v) [40].

2.6. Determination of Crop Yields

At harvest (mid-October), three sampling points were uniformly distributed within each plot ($8 \text{ m} \times 6 \text{ m}$, 48 m^2)—one at the front, one in the middle, and one at the rear—to avoid spatial bias. At each sampling point, all plants within a 5 m double-row segment were sampled, resulting in three replicates per plot. This setup yielded a total sampled area of $3 \times 5 \text{ m} \times 0.8 \text{ m}$ for maize (40 cm row spacing $\times 2$ rows) = 12 m^2 and $3 \times 5 \text{ m} \times 0.6 \text{ m}$ for peanut (30 cm row spacing $\times 2$ rows) = 9 m^2 per plot, accounting for $\sim 43.75\%$ of the total plot area to ensure representativeness.

Each 5 m double-row segment contained approximately 25 maize plants and 50 peanut plants. Harvested maize ears were threshed after air-drying (grain moisture $\leq 13\%$), and peanut pods were detached from roots after air-drying (pod moisture $\leq 10\%$). Both were then cleaned and oven-dried at 75°C to constant weight for yield measurement. Whole-plot yield was extrapolated from the average yield of the three uniform sampling points, and aboveground total biomass (stems + leaves + economic yield organs) of both crops was determined after oven-drying to constant weight.

2.7. Calculations

2.7.1. Stability Index of Soil Aggregates

Soil aggregate stability was quantified using the following indices: the proportion of mechanical aggregates $>0.25 \text{ mm}$ ($\text{DR}_{0.25}$, %), the proportion of water-stable aggregates $>0.25 \text{ mm}$ ($\text{WR}_{0.25}$, %), mean weight diameter (MWD, mm), geometric mean diameter (GMD, mm), unstable aggregate index (E_{LT}), and percentage of aggregate destruction (PAD). The formula is as follows [41,42]:

$$\text{Nutrient contribution rate of aggregate fractions (\%)} = \left[\frac{\text{the nutrient concentration within the aggregate fraction (g}\cdot\text{kg}^{-1}) \times \text{the proportion occupied by the aggregate fraction (\%)}}{\text{the concentration of nutrients in the soil}} \right] \times 100, \quad (1)$$

$$\text{WR}_{0.25} = W_{\text{S}>0.25} / W_{\text{S}} \times 100\%, \quad (2)$$

$$\text{DR}_{0.25} = M_{\text{r}>0.25} / M_{\text{r}} \times 100\%, \quad (3)$$

$$E_{\text{LT}} = (W_{\text{T}} - \text{WR}_{0.25}) / W_{\text{T}} \times 100\%, \quad (4)$$

$$\text{PAD} = (\text{DR}_{0.25} - \text{WR}_{0.25}) / \text{DR}_{0.25} \times 100\%, \quad (5)$$

$$MWD = \sum_{i=1}^{n=6} W_i X_i, \quad (6)$$

and

$$GMD = \exp \left[\frac{\sum_{i=1}^{n=6} W_i X_i}{\sum_{i=1}^{n=6} W_i} \right] \quad (7)$$

where $W_{S>0.25}$ (g) and W_S (g) the weight of water-stable aggregates >0.25 mm and the total weight of all water-stable aggregate fractions (g), respectively. $M_r > 0.25$ (g) and M_r (g) denote the weight of mechanical aggregates >0.25 mm and the total weight of all mechanical aggregate fractions (g), respectively. X_i (mm) and W_i (%) represent the mean diameter and proportion of each size fraction of water-stable aggregates, respectively. W_T (g) is the total weight of water-stable aggregates (g).

2.7.2. Soil Bulk Density

Soil bulk density (BD) was determined using the cutting-ring method [43] and Equation (8), as follows:

$$BD \text{ (g} \cdot \text{cm}^{-3}) = (m_2 - m_1)/V \quad (8)$$

where m_1 (g) represents the weight of the cutting ring, m_2 (g) denotes the combined weight of the cutting ring and dried soil, and V (cm^{-3}) indicates the volume of the cutting ring.

2.7.3. Soil Porosity

Soil porosity (Pt) was determined using Equation (9), as follows:

$$Pt \text{ (\%)} = (1 - BD/G_s) \times 100 \quad (9)$$

where G_s represents the soil-specific gravity, the specific gravity of cultivated soil is typically taken as an average value of 2.65 cm^{-2} .

2.7.4. Soil Carbon, Nitrogen, and Phosphorus Storage

Soil C, N, and P storage (S_i) was determined using Equation (10), as follows:

$$S_i \text{ (kg} \cdot \text{m}^{-2}) = C_i \times BD \times H_i/100 \quad (10)$$

where C_i ($\text{g} \cdot \text{kg}^{-1}$) represents the concentration of C, N, and P in topsoil, and H_i (cm) denotes the depth of the topsoil (20 cm in this case).

2.7.5. Intercropping Yield Advantage

Intercropping yield advantage (Y_a) was calculated according to Equation (11), as follows:

$$Y_a \text{ (kg} \cdot \text{hm}^{-2}) = Y_i - (Y_{sm} \times F_m + Y_{sp} \times F_p), Y_i = Y_{im} + Y_{ip} \quad (11)$$

where Y_i represents the yield of the intercropping system, and Y_{im} and Y_{ip} represent the yields of maize and peanuts in the intercropping system, respectively. Y_{sm} and Y_{sp} denote the yields of SM and SP, respectively. F_m and F_p indicate the planting densities of intercropped maize and peanuts, respectively. In this experiment, $F_m = 0.56$ and $F_p = 0.44$.

2.8. Statistical Analyses

Statistical analyses were performed using SPSS 24.0 (SPSS Inc., Chicago, IL, USA), CANOCO 5.0 (Ithaca, NY, USA), and Origin 22.0 (Northampton, MA, USA). Figures were prepared with Excel 2019 (Microsoft Corporation, Redmond, WA, USA). The effects of planting patterns and P application on aggregate proportions and stability, BD, Pt, SOC, and nutrient concentrations, and ecological stoichiometric characteristics of C, N, and P

were evaluated using one-way and two-way analysis of variance (ANOVA). Treatment means were compared using Duncan's multiple range test at $p < 0.05$. Redundancy analysis (RDA) was applied to study the relationships among soil nutrients, ecological stoichiometric characteristics of C, N, and P, and soil aggregate stability indices. Correlation analysis was conducted to examine the relationships between the yield advantage of intercropping and soil physicochemical indices under different P application levels. Data were normalized using the maximum value method in Origin 2022 software (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Effects of Co-Ridge Planting on Soil Aggregate Proportion, Stability, Bulk Density, and Porosity

The proportion of mechanical macroaggregates (>1 mm) and water-stable macroaggregates (>0.5 mm) was significantly higher ($p < 0.05$) in R-M || P plots than in F-M || P plots, with increases of 17.48–18.59% and 12.97–44.86%, respectively (Figure 2). Additionally, compared with F-M || P, R-M || P significantly increased ($p < 0.05$) $WR_{0.25}$ (13.03–13.38%), MWD (13.54–20.27%), and GMD (6.43–12.45%). However, it significantly reduced E_{LT} (22.57–26.29%) and PAD (25.65–31.70%) (Table 1).

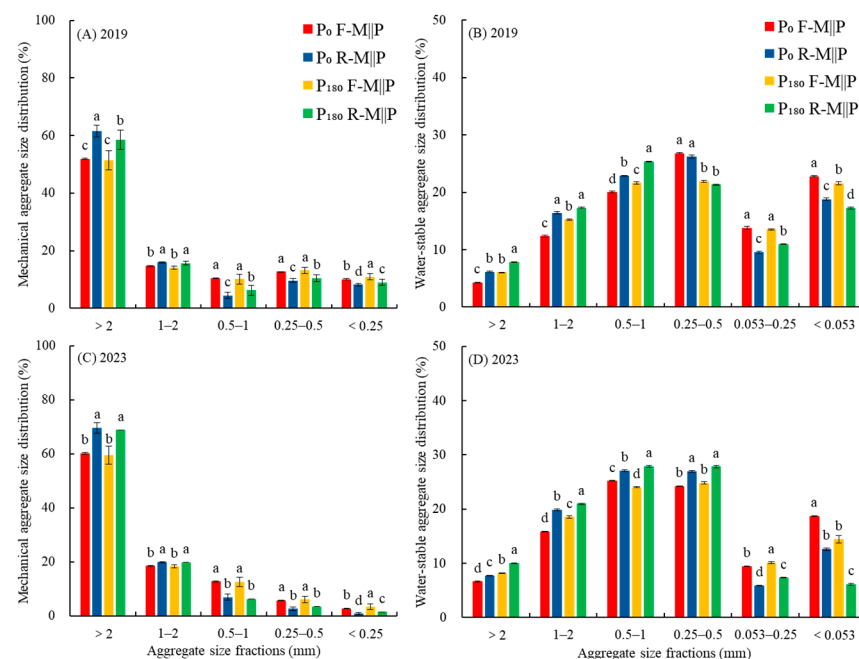


Figure 2. Effects of R-M || P and P application on the size distribution of mechanical and water-stable aggregates in topsoil. (A) and (C) represent the distribution of mechanical aggregates in 2019 and 2023, respectively; (B) and (D) represent the distribution of water-stable aggregates in 2019 and 2023, respectively. P_0 F-M || P: maize–peanut flat intercropping under $0 \text{ kg P}_2\text{O}_5 \cdot \text{ha}^{-1}$; P_{180} F-M || P: maize–peanut flat intercropping under $180 \text{ kg P}_2\text{O}_5 \cdot \text{ha}^{-1}$; P_0 R-M || P: maize–peanut co-ridge intercropping under $0 \text{ kg P}_2\text{O}_5 \cdot \text{ha}^{-1}$; P_{180} R-M || P: maize–peanut co-ridge intercropping under $180 \text{ kg P}_2\text{O}_5 \cdot \text{ha}^{-1}$. Bars marked with different letters indicate significant differences between treatments, based on Duncan's test at $p < 0.05$.

The application of P (P_{180}) increased ($p < 0.05$) the proportion of water-stable macroaggregates (>0.5 mm) (5.31–42.85%), $WR_{0.25}$ (2.20–6.23%), MWD (7.06–13.40%), and GMD (4.45–11.71%) compared with no P application (P_0) (Figure 2, Table 1). Compared with F-M || P, R-M || P significantly reduced ($p < 0.05$) BD (3.42–3.57%) while significantly increasing ($p < 0.05$) soil Pt (3.23–3.53%) in 2023 (Table 1). P_{180} followed a trend consistent with these observations.

Table 1. Effects of R-M | P and P application on stability indices of topsoil aggregates, BD and Pt.

Year	P Level	PP	DR _{0.25} (%)	WR _{0.25} (%)	E _{LT} (%)	PAD (%)	MWD (mm)	GMD (mm)	BD (g·cm ⁻³)	Pt (%)
2019	P ₀	F-M P	89.90 ± 0.14 c	63.41 ± 0.24 c	36.59 ± 0.24 a	29.47 ± 0.25 a	0.55 ± 0.00 d	0.88 ± 0.00 c	/	/
		R-M P	91.78 ± 0.16 a	71.67 ± 0.19 a	28.33 ± 0.19 c	21.91 ± 0.11 c	0.66 ± 0.00 b	0.99 ± 0.00 b	/	/
	P ₁₈₀	F-M P	89.01 ± 0.09 d	64.89 ± 0.16 b	35.11 ± 0.16 b	27.10 ± 0.20 b	0.62 ± 0.00 c	0.98 ± 0.00 b	/	/
		R-M P	91.00 ± 0.05 b	71.81 ± 0.07 a	28.19 ± 0.07 c	21.09 ± 0.04 c	0.71 ± 0.00 a	1.05 ± 0.00 a	/	/
2023	P ₀	F-M P	97.22 ± 0.03 c	71.90 ± 0.02 d	28.10 ± 0.02 a	26.05 ± 0.00 a	0.67 ± 0.00 d	1.00 ± 0.00 c	1.32 ± 0.01 a	50.28 ± 0.23 c
		R-M P	99.15 ± 0.02 a	81.51 ± 0.25 b	20.72 ± 0.25 b	17.79 ± 0.25 c	0.76 ± 0.00 b	1.06 ± 0.00 b	1.27 ± 0.01 bc	52.06 ± 0.26 ab
	P ₁₈₀	F-M P	96.55 ± 0.03 d	75.48 ± 0.55 c	27.30 ± 0.41 a	21.82 ± 0.58 b	0.72 ± 0.00 c	1.06 ± 0.00 b	1.29 ± 0.00 b	51.46 ± 0.14 b
		R-M P	98.48 ± 0.03 b	86.59 ± 0.24 a	20.36 ± 0.38 b	12.08 ± 0.23 d	0.81 ± 0.01 a	1.11 ± 0.00 a	1.24 ± 0.00 c	53.12 ± 0.15 a
	P level		***	***	***	***	***	***	***	***
	PP		***	***	***	***	***	***	*	**
	P level × PP		***	***	***	***	**	***	***	***

F-M | P: maize–peanut flat intercropping; R-M | P: maize–peanut co-ridge intercropping. P₀: 0 kg P₂O₅·ha⁻¹; P₁₈₀: 180 kg P₂O₅·ha⁻¹. PP: Planting pattern; DR_{0.25}: proportion of mechanical aggregates >0.25 mm; WR_{0.25}: proportion of water-stable aggregates >0.25 mm; E_{LT}: unstable aggregate index; PAD: percentage of aggregation destruction; MWD: mean weight diameter; GMD: geometric mean diameter; BD: soil bulk density; Pt: soil porosity. Values indicate the mean ± standard error (n = 3). Lowercase letters within columns denote significant differences by Duncan's test ($p < 0.05$). * indicates significance at $p < 0.05$, ** at $p < 0.01$, *** at $p < 0.001$.

3.2. Effects of Co-Ridge Planting on the Concentration and Contribution Rate of Soil Organic Carbon and Nutrients, and Ecological Stoichiometric Characteristics of Carbon, Nitrogen, and Phosphorus

As shown in Figure 3, compared with F-M | P, R-M | P increased the concentrations of SOC, TN, TP, and AP in all aggregate sizes, with increment ranges of 15.19–21.45%, 4.83–8.64%, 6.34–21.28%, and 13.53–37.79%, respectively—most of which reached significant difference ($p < 0.05$). Compared with P₀, P₁₈₀ significantly increased SOC, TN, TP, and AP concentrations in all aggregates; the interaction between P₁₈₀ and R-M | P further enhanced these, leading to additional increments of 12.35–22.53% (SOC), 5.66–32.22% (TN), 4.11–30.41% (TP), and 18.14–31.82% (AP) across aggregates. In 2023, the concentrations of SOC, TN, TP, and AP under all treatments were higher than those in 2019, reflecting the cumulative effects of long-term intercropping. In addition, compared with F-M | P, R-M | P significantly increased ($p < 0.05$) the contribution rates of SOC, TN, TP, and AP in macroaggregates (>1 mm) by 7.81–19.29%, 3.09–14.48%, 6.08–19.94%, and 12.93–16.60%, respectively. Conversely, R-M | P significantly reduced ($p < 0.05$) the contribution rates of these nutrients in microaggregates (<1 mm) by 19.54–55.02%, 25.65–57.98%, 9.21–56.86%, and 12.50–58.07%, respectively (Figure 3). Compared with F-M | P, R-M | P significantly increased ($p < 0.05$) the C:N and C:P ratios in aggregates but had no significant effect on the N:P ratio. Compared with P₀, P₁₈₀ significantly reduced the C:N ratio in microaggregates (<0.5 mm), the C:P ratio in aggregates, and the N:P ratio in macroaggregates (>0.5 mm), while increasing the N:P ratio in microaggregates (<0.5 mm) ($p < 0.05$) (Figure 3).

In Table 2, the concentrations of all inorganic phosphorus (Pi) fractions generally increased with decreasing aggregate particle size. Compared with F-M | P, R-M | P significantly increased ($p < 0.05$) the concentrations of Ca₂-P, Ca₈-P, Al-P, and Fe-P in all aggregate sizes, with increment ranges of 37.05–61.06%, 20.68–45.81%, 32.21–42.65%, and 20.62–63.66%, respectively. Conversely, R-M | P significantly reduced ($p < 0.05$) Olsen-P and Ca₁₀-P concentrations in all aggregates, with reduction ranges of 34.79–56.83% and 20.68–45.81%, respectively. Compared with P₀, P₁₈₀ significantly increased ($p < 0.05$) Pi concentrations in all aggregates; the interaction between P₁₈₀ and R-M | P further amplified these changes, leading to increments of 206.19–344.59% (Ca₂-P), 43.40–109.56% (Ca₈-P), 40.80–66.58% (Al-P), 48.33–88.62% (Fe-P), 90.72–153.66% (Olsen-P), and 10.92–23.31% (Ca₁₀-P) across aggregates. The differences in Pi fractions between treatments were more pro-

nounced in 2023 than in 2019, reflecting the cumulative effects of long-term intercropping (Table 2).

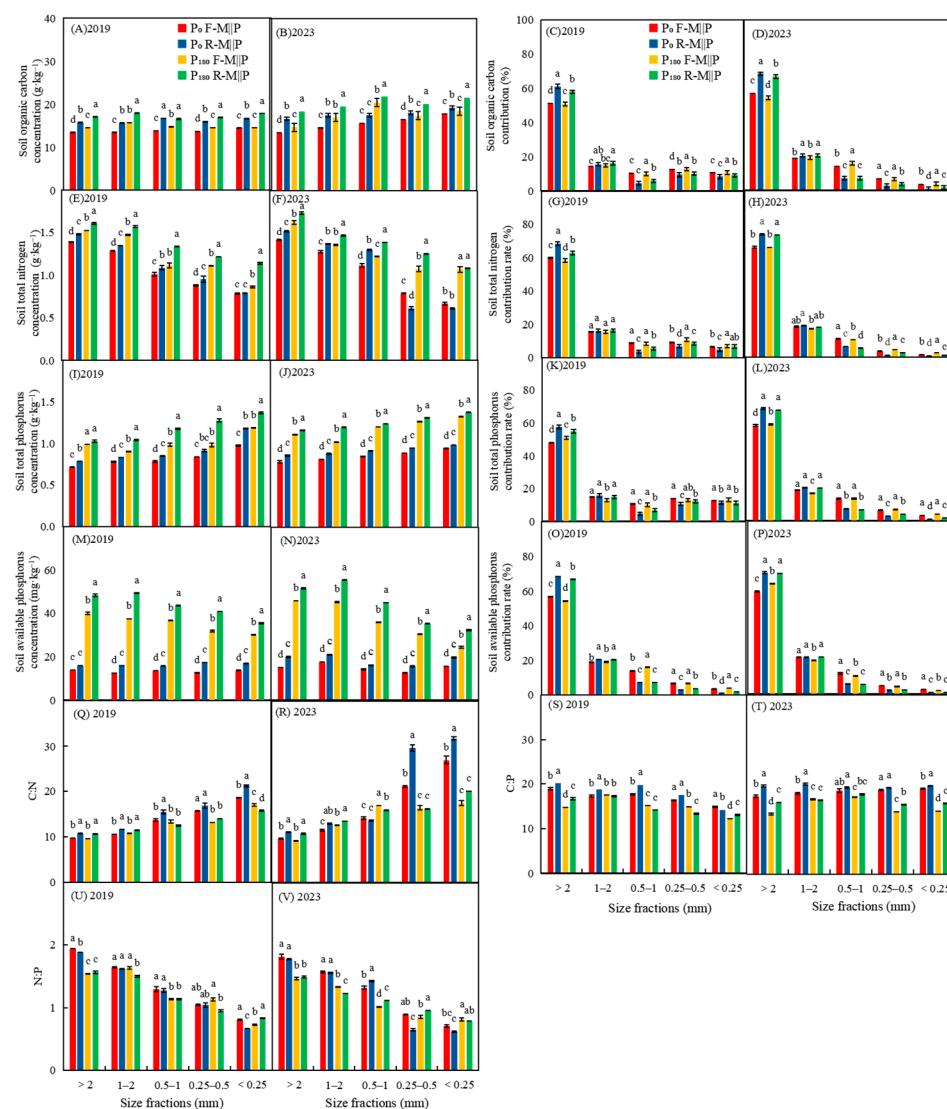


Figure 3. Effects of R-M || P and P application on the concentration and contribution rate of SOC and nutrients and the ratio of carbon, nitrogen, and phosphorus in aggregates. (A) and (B) respectively represent the organic carbon concentration of aggregates in each particle size; (C) and (D) respectively represent the organic carbon contribution of aggregates in each particle size; (E) and (F) respectively represent the total nitrogen concentration of aggregates in each particle size; (G) and (H) respectively represent the total nitrogen contribution of aggregates in each particle size; (I) and (J) respectively represent the total phosphorus concentration of aggregates in each particle size; (K) and (L) respectively represent the total phosphorus contribution of aggregates in each particle size; (M) and (N) respectively represent the available phosphorus concentration of aggregates in each particle size; (O) and (P) respectively represent the available phosphorus contribution of aggregates in each particle size; (Q) and (R) respectively represent the C:N of aggregates in each particle size; (S) and (T) respectively represent the C:P of aggregates in each particle size; (U) and (V) respectively represent the N:P of aggregates in each particle size. P₀ F-M || P: maize–peanut flat intercropping under 0 kg P₂O₅·ha^{−1}; P₁₈₀ F-M || P: maize–peanut flat intercropping under 180 kg P₂O₅·ha^{−1}; P₀ R-M || P: maize–peanut co-ridge intercropping under 0 kg P₂O₅·ha^{−1}; P₁₈₀ R-M || P: maize–peanut co-ridge intercropping under 180 kg P₂O₅·ha^{−1}. Bars marked with different letters indicate significant differences between treatments, based on Duncan’s test at $p < 0.05$.

Table 2. Effects of R-M || P and P application on inorganic phosphorus concentration in aggregates (mg·kg^{−1}).

Year	Size Fractions (mm)	P Level	PP	Ca ₂ -P	Ca ₈ -P	Al-P	Fe-P	Olsen-P	Ca ₁₀ -P
2019	>2	P ₀	F-M P	2.20 ± 0.04 d	147.43 ± 2.11 d	29.34 ± 0.13 d	58.06 ± 0.96 d	2.98 ± 0.06 b	159.15 ± 0.85 b
		P ₀	R-M P	3.54 ± 0.00 c	177.92 ± 0.28 c	41.06 ± 0.09 c	95.02 ± 0.26 c	1.37 ± 0.02 c	135.48 ± 0.39 d
		P ₁₈₀	F-M P	7.65 ± 0.11 b	197.24 ± 3.57 b	52.20 ± 0.21 b	102.41 ± 0.31 b	5.22 ± 0.13 a	181.63 ± 0.80 a
	1–2	P ₀	R-M P	10.84 ± 0.03 a	255.14 ± 0.92 a	68.40 ± 0.34 a	140.94 ± 0.38 a	2.61 ± 0.03 b	150.28 ± 1.37 c
		P ₀	F-M P	2.69 ± 0.04 d	147.43 ± 2.11 d	29.34 ± 0.13 d	58.06 ± 0.96 d	2.98 ± 0.06 b	182.08 ± 0.32 b
		P ₀	R-M P	4.03 ± 0.03 c	177.92 ± 0.28 c	41.06 ± 0.09 c	95.02 ± 0.26 c	1.37 ± 0.02 c	151.80 ± 1.25 c
	0.5–1	P ₁₈₀	F-M P	10.60 ± 0.21 b	197.24 ± 3.57 b	52.20 ± 0.21 b	102.41 ± 0.31 b	5.22 ± 0.13 a	210.67 ± 0.95 a
		P ₀	R-M P	15.00 ± 0.21 a	255.14 ± 0.92 a	68.40 ± 0.34 a	140.94 ± 0.38 a	2.61 ± 0.03 b	183.20 ± 0.45 b
		P ₀	F-M P	3.33 ± 0.04 d	137.83 ± 0.53 d	39.04 ± 0.08 d	89.07 ± 0.49 d	3.10 ± 0.02 c	197.29 ± 2.09 c
	0.25–0.5	P ₀	R-M P	4.70 ± 0.03 c	171.92 ± 0.62 c	55.65 ± 0.10 c	108.86 ± 0.32 c	1.55 ± 0.03 d	171.57 ± 1.22 d
		P ₁₈₀	F-M P	12.69 ± 0.20 b	217.72 ± 1.71 b	65.99 ± 0.09 b	134.40 ± 1.04 b	6.74 ± 0.03 a	231.73 ± 1.65 a
		P ₁₈₀	R-M P	18.18 ± 0.16 a	297.05 ± 0.10 a	81.54 ± 0.50 a	168.70 ± 0.86 a	3.92 ± 0.11 b	211.57 ± 0.18 b
	<0.25	P ₀	F-M P	3.92 ± 0.04 d	150.27 ± 0.76 d	49.30 ± 0.10 d	103.54 ± 0.60 d	5.96 ± 0.06 b	228.18 ± 0.60 c
		P ₀	R-M P	5.37 ± 0.04 c	206.52 ± 2.76 c	65.18 ± 0.08 c	122.82 ± 0.11 c	2.57 ± 0.09 c	199.65 ± 1.21 d
		P ₁₈₀	F-M P	15.56 ± 0.17 b	256.20 ± 0.96 b	72.64 ± 0.55 b	179.56 ± 0.67 b	8.96 ± 0.15 a	260.60 ± 0.48 a
		P ₁₈₀	R-M P	23.87 ± 0.13 a	319.69 ± 2.00 a	91.78 ± 0.34 a	210.02 ± 0.69 a	5.84 ± 0.16 b	239.04 ± 0.21 b
		P ₀	F-M P	5.02 ± 0.09 d	142.31 ± 0.53 d	51.28 ± 0.63 d	115.57 ± 0.15 d	6.90 ± 0.20 b	258.07 ± 0.46 c
		P ₀	R-M P	6.48 ± 0.06 c	207.51 ± 3.84 c	73.14 ± 0.97 c	143.32 ± 0.95 c	3.04 ± 0.05 c	227.90 ± 0.87 d
		P ₁₈₀	F-M P	15.84 ± 0.02 b	298.42 ± 2.59 b	87.01 ± 0.40 b	215.99 ± 0.11 b	12.86 ± 0.11 a	286.97 ± 0.31 a
		P ₁₈₀	R-M P	21.81 ± 0.23 a	353.84 ± 0.95 a	105.26 ± 0.69 a	248.12 ± 1.46 a	7.35 ± 0.24 b	269.59 ± 1.36 b
2023	>2	P ₀	F-M P	3.21 ± 0.02 c	173.44 ± 1.48 d	43.15 ± 0.06 d	103.07 ± 0.30 d	1.77 ± 0.01 b	119.36 ± 0.64 b
		P ₀	R-M P	4.57 ± 0.02 c	215.48 ± 1.48 c	56.29 ± 0.30 c	123.45 ± 0.56 c	0.81 ± 0.01 d	101.61 ± 0.29 d
		P ₁₈₀	F-M P	10.41 ± 0.41 b	266.14 ± 1.66 b	69.49 ± 0.19 b	146.57 ± 0.55 b	2.74 ± 0.03 a	136.22 ± 0.60 a
	1–2	P ₀	R-M P	12.41 ± 0.29 a	314.78 ± 2.24 a	81.84 ± 0.23 a	188.05 ± 0.54 a	1.43 ± 0.02 c	112.71 ± 1.03 c
		P ₀	F-M P	3.70 ± 0.02 d	173.44 ± 1.48 d	43.15 ± 0.06 d	103.07 ± 0.30 d	1.77 ± 0.01 b	136.56 ± 0.24 b
		P ₀	R-M P	5.06 ± 0.02 c	215.48 ± 1.48 c	56.29 ± 0.30 c	123.45 ± 0.56 c	0.81 ± 0.01 d	113.85 ± 0.94 c
	0.5–1	P ₁₈₀	F-M P	13.15 ± 0.14 b	266.14 ± 1.66 b	69.49 ± 0.19 b	146.57 ± 0.55 b	2.74 ± 0.03 a	158.00 ± 0.71 a
		P ₀	R-M P	16.04 ± 0.25 a	314.78 ± 2.24 a	81.84 ± 0.23 a	188.05 ± 0.54 a	1.43 ± 0.02 c	137.40 ± 0.34 b
		P ₀	F-M P	4.28 ± 0.03 d	173.43 ± 0.93 d	54.92 ± 0.12 d	116.35 ± 0.20 d	2.44 ± 0.01 b	147.97 ± 1.56 c
	0.25–0.5	P ₀	R-M P	5.64 ± 0.03 c	215.48 ± 0.93 c	71.74 ± 0.15 c	135.35 ± 0.21 c	1.01 ± 0.01 d	128.68 ± 0.92 d
		P ₁₈₀	F-M P	15.24 ± 0.15 b	297.80 ± 0.32 b	87.87 ± 0.32 b	172.49 ± 0.64 b	3.72 ± 0.03 a	173.80 ± 1.24 a
		P ₁₈₀	R-M P	19.21 ± 0.17 a	360.17 ± 1.02 a	98.93 ± 0.27 a	226.48 ± 1.06 a	2.02 ± 0.03 c	158.68 ± 0.13 b
	<0.25	P ₀	F-M P	4.78 ± 0.02 d	180.75 ± 2.66 d	66.18 ± 0.26 d	132.42 ± 0.41 d	3.36 ± 0.03 b	171.13 ± 0.45 c
		P ₀	R-M P	6.14 ± 0.02 c	222.79 ± 2.66 c	82.78 ± 0.22 c	150.62 ± 0.32 c	1.44 ± 0.01 d	149.74 ± 0.91 d
		P ₁₈₀	F-M P	18.11 ± 0.09 b	323.29 ± 0.81 b	101.19 ± 0.48 b	220.11 ± 0.62 b	4.80 ± 0.08 a	195.45 ± 0.36 a
		P ₁₈₀	R-M P	24.90 ± 0.21 a	391.21 ± 1.65 a	112.16 ± 0.90 a	252.54 ± 1.39 a	3.03 ± 0.05 c	179.28 ± 0.16 b
		P ₀	F-M P	5.88 ± 0.03 c	187.17 ± 3.61 d	77.67 ± 0.15 d	150.16 ± 0.38 d	4.37 ± 0.00 b	193.55 ± 0.35 c
		P ₀	R-M P	7.24 ± 0.03 c	229.21 ± 3.61 c	98.11 ± 0.10 c	168.29 ± 0.21 c	1.95 ± 0.01 d	170.93 ± 0.65 d
		P ₁₈₀	F-M P	25.45 ± 0.36 b	370.30 ± 3.65 b	117.43 ± 0.82 b	259.80 ± 1.26 b	6.38 ± 0.08 a	215.23 ± 0.23 a
		P ₁₈₀	R-M P	32.20 ± 0.39 a	426.16 ± 1.57 a	126.32 ± 0.87 a	290.37 ± 1.00 a	4.04 ± 0.02 c	202.19 ± 1.02 b
		P level		***	***	***	***	***	***
		PP		***	***	***	***	***	***
		P level × PP		***	***	***	***	***	*

M || P: maize-peanut flat intercropping; R-M || P: maize-peanut co-ridge intercropping; P₀: 0 kg P₂O₅·ha^{−1}; P₁₈₀: 180 kg P₂O₅·ha^{−1}; PP: Planting pattern; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus. Ca₂-P, Ca₈-P, Al-P, Fe-P, Olsen-P, and Ca₁₀-P are forms of soil inorganic phosphorus. Values indicate the mean ± standard error (n = 3). Lowercase letters within columns denote significant differences by Duncan's test (*p* < 0.05). * indicates significance at *p* < 0.05, *** at *p* < 0.001.

As shown in Table 3, compared with F-M || P, R-M || P significantly increased (*p* < 0.05) the concentrations of SOC, TN, TP, AP, Ca₂-P, Ca₈-P, Al-P, and Fe-P in the topsoil, with respective increments of 16.51%, 10.33%, 8.77%, 19.21%, 41.38%, 24.04%, 31.94%, and 32.02%. Compared with P₀, P₁₈₀ also significantly increased (*p* < 0.05) the concentrations of the nutrients mentioned above; notably, the interaction between P₁₈₀ and R-M || P further enhanced these, with respective increments of 16.87%, 11.53%, 10.10%, 24.51%, 35.93%, 23.62%, 20.83%, and 18.96% (Table 3). Soil C, N, and P storage were higher (*p* < 0.05) in R-M || P than in F-M || P, with increases of 11.04–14.46%, 6.01–6.10%, and 3.15–4.88%, respectively. Compared with P₀, P₁₈₀ significantly increased (*p* < 0.05) soil C, N, and P storage by 9.82–14.56%, 5.41–8.88%, and 25.75–35.84%, respectively (Table 3). The C:N and C:P ratios in the topsoil were significantly higher (*p* < 0.05) in R-M || P plots than in F-M || P plots, with increases of 4.74–7.86% and 7.62–9.15%, respectively. However, no significant difference was observed in the N:P ratio in the topsoil among treatments (Table 3). Compared with P₀, P₁₈₀ significantly increased (*p* < 0.05) the C:N ratio in the topsoil by 4.05–6.17% and significantly reduced (*p* < 0.05) the C:P and N:P ratios by 11.12–16.66% and 16.17–19.84% (Table 3).

Table 3. Effects of R-M || P and P application on total organic carbon, nutrient concentration in the topsoil, and ecological stoichiometric characteristics of carbon, nitrogen, and phosphorus.

Year	P	PP	SOC g·kg ^{−1}	TN g·kg ^{−1}	TP g·kg ^{−1}	AP mg·kg ^{−1}	Ca ₂ -P mg·kg ^{−1}	Ca ₈ -P mg·kg ^{−1}	Al-P mg·kg ^{−1}	Fe-P mg·kg ^{−1}	Olsen-P mg·kg ^{−1}	Ca ₁₀ -P mg·kg ^{−1}	SCS g·m ^{−2}	SNS g·m ^{−2}	SPS g·m ^{−2}	C:N	C:P	N:P
2019	P ₀	F-M P	13.21 ± 0.02 d	1.21 ± 0.00 c	0.77 ± 0.00 d	13.46 ± 0.03 b	2.89 ± 0.03 b	147.36 ± 1.15 b	39.05 ± 0.11 b	82.01 ± 0.51 b	4.45 ± 0.03 b	185.29 ± 0.28 c	3.48 ± 0.01 d	0.32 ± 0.00 c	0.20 ± 0.00 d	10.95 ± 0.04 c	17.10 ± 0.06 b	1.56 ± 0.01 a
		R-M P	15.68 ± 0.08 b	1.33 ± 0.01 b	0.84 ± 0.00 c	16.04 ± 0.02 a	4.09 ± 0.01 a	182.79 ± 0.56 a	51.51 ± 0.12 a	108.26 ± 0.12 a	1.85 ± 0.01 c	153.53 ± 0.69 d	3.99 ± 0.02 b	0.34 ± 0.00 b	0.21 ± 0.00 c	11.81 ± 0.02 ab	18.66 ± 0.15 a	1.58 ± 0.01 a
		P ₁₈₀	15.13 ± 0.09 c	1.30 ± 0.01 b	1.00 ± 0.00 b	37.14 ± 0.28 b	10.52 ± 0.10 b	235.12 ± 2.52 b	67.40 ± 0.13 b	146.98 ± 0.28 b	8.03 ± 0.09 c	212.82 ± 0.83 c	3.89 ± 0.03 c	0.34 ± 0.00 b	0.26 ± 0.00 b	11.61 ± 0.12 b	15.20 ± 0.11 d	1.31 ± 0.01 b
	P ₁₈₀	F-M P	17.61 ± 0.08 a	1.43 ± 0.01 a	1.10 ± 0.01 a	46.24 ± 0.28 a	14.30 ± 0.04 a	290.65 ± 0.49 a	81.43 ± 0.15 a	174.84 ± 0.42 a	4.11 ± 0.03 d	179.29 ± 0.68 d	4.38 ± 0.03 a	0.36 ± 0.00 a	0.27 ± 0.00 a	12.30 ± 0.13 a	16.07 ± 0.07 c	1.31 ± 0.02 b
		R-M P	14.02 ± 0.04 c	1.31 ± 0.01 c	0.81 ± 0.01 d	15.63 ± 0.06 b	3.60 ± 0.02 b	175.73 ± 1.65 b	51.67 ± 0.09 b	113.94 ± 0.22 b	2.35 ± 0.01 c	131.25 ± 0.29 c	3.69 ± 0.02 c	0.35 ± 0.00 c	0.21 ± 0.00 b	10.68 ± 0.09 b	17.39 ± 0.21 b	1.63 ± 0.01 a
		P ₁₈₀	16.14 ± 0.07 b	1.44 ± 0.01 b	0.86 ± 0.01 c	20.03 ± 0.23 a	4.80 ± 0.01 a	216.52 ± 1.46 a	62.80 ± 0.24 a	129.47 ± 0.34 a	0.94 ± 0.00 d	107.82 ± 0.37 d	4.10 ± 0.04 b	0.37 ± 0.00 b	0.22 ± 0.00 b	11.19 ± 0.02 b	18.72 ± 0.06 a	1.67 ± 0.00 a
2023	P ₀	F-M P	16.26 ± 0.04 b	1.46 ± 0.01 b	1.12 ± 0.00 b	43.08 ± 0.07 b	12.51 ± 0.23 b	291.12 ± 1.42 b	81.84 ± 0.15 b	173.11 ± 0.49 b	3.59 ± 0.04 c	151.30 ± 0.66 c	4.18 ± 0.01 b	0.38 ± 0.00 b	0.29 ± 0.00 a	11.11 ± 0.11 b	14.50 ± 0.01 d	1.31 ± 0.01 b
	P ₁₈₀	R-M P	18.91 ± 0.03 a	1.59 ± 0.03 a	1.18 ± 0.00 a	51.40 ± 0.17 a	14.30 ± 0.16 a	335.42 ± 1.60 a	89.68 ± 0.22 a	205.73 ± 0.61 a	1.80 ± 0.02 d	124.21 ± 0.61 d	4.70 ± 0.01 a	0.40 ± 0.01 a	0.29 ± 0.00 a	11.88 ± 0.18 a	16.01 ± 0.04 c	1.35 ± 0.02 b
		P	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	P × PP	PP	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	ns
		P × PP	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
			***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***

F-M || P: maize–peanut flat intercropping; R-M || P: maize–peanut co-ridge intercropping; P₀: 0 kg P₂O₅·ha^{−1}; P₁₈₀: 180 kg P₂O₅·ha^{−1}; PP: Planting pattern; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus. The letters SCS, SNS, and SPS represent the storage of C, N, and P, respectively. C:N, C:P, and N:P represent the C-N, C-P, and N-P ratios, respectively. Ca₂-P, Ca₈-P, Al-P, Fe-P, Olsen-P, and Ca₁₀-P are forms of soil inorganic phosphorus. Values indicate the mean ± standard error (n = 3). Lowercase letters within columns denote significant differences by Duncan's test ($p < 0.05$). *** at $p < 0.001$, and ns means not significant at $p > 0.05$.

3.3. Relationship Between Intercropping Advantage in Yield and Soil Physical–Chemical Properties

Table A3 shows that M | P has a significant intercropping advantage. Regression analysis (Figure 4A) revealed a significant correlation between intercropping yield advantage (Ya) and soil physicochemical properties in flat intercropping ($p > 0.05$). SOC, TN, $WR_{0.25}$, GMD, Ca_8 -P, Al-P, and Fe-P all exhibited significant positive correlations with Ya in flat intercropping ($p < 0.05$), whereas PAD was significantly negatively correlated with Ya ($p < 0.05$) (Figure 4A). Significant positive relationships were observed between Ya and SOC, TP, AP, GMD, Ca_8 -P, Al-P, and Fe-P in co-ridge intercropping ($p < 0.05$). At the same time, Ya was significantly negatively correlated with PAD ($p < 0.05$) (Figure 4B). SOC showed significant positive correlations with TN, TP, AP, GMD, Ca_8 -P, Al-P, and Fe-P, but significant negative correlations with BD, PAD, C:P, and N:P (Figure 4B). Increased aggregate stability (mainly GMD) significantly enhanced SOC and nutrient (TN, TP, AP, Ca_8 -P, Al-P, and Fe-P) concentrations ($p < 0.01$) (Figure 4B). Additionally, no significant correlations were found between Ya and C:N, C:P, or N:P in either flat or co-ridge intercropping (Figure 4).

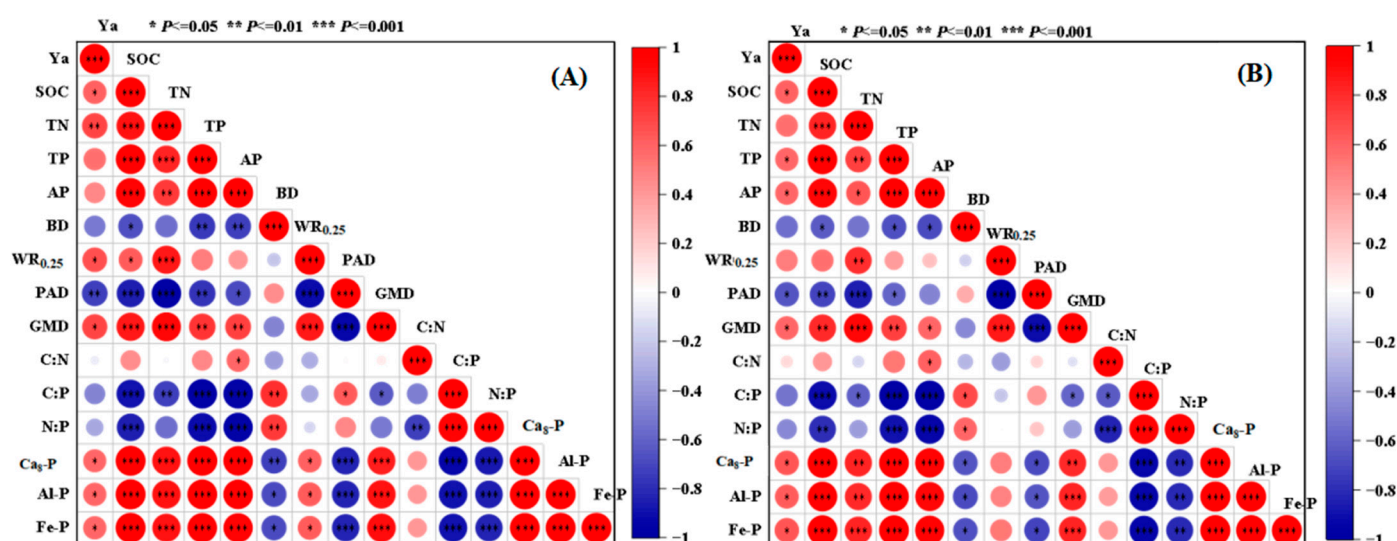


Figure 4. Correlation analysis between intercropping advantage in yield and soil physical–chemical properties. (A,B) represent flat intercropping and co-ridge intercropping. SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; PAD: percentage of aggregation destruction; GMD: geometric mean diameter; BD: soil bulk density; C:N, C:P, and N:P represent the C-N, C-P, and N-P ratios, respectively; Ca_8 -P, Al-P and Fe-P are forms of soil inorganic phosphorus. R-M | P: maize–peanut co-ridge intercropping. * indicates significance at $p < 0.05$, ** at $p < 0.01$, *** at $p < 0.001$, and Without * means not significant at $p > 0.05$.

To identify the key factors by which planting patterns influence intercropping advantage, redundancy analysis (RDA) was conducted. The study used soil nutrients—including SOC, TN, TP, AP, and C:N:P stoichiometric ratios, as well as inorganic phosphorus fractions (Ca_8 -P, Al-P, and Fe-P), as explanatory variables, and intercropping advantage (Ya and LER) as response variables (Figure 5A,B). The cumulative contribution rate of the first two principal components exceeded 95% (Figure 5A,B). SOC, TP, GMD, Ca_8 -P, Al-P, and Fe-P showed extremely significant positive correlations with Ya, while PAD, BD, C:P, and N:P showed extremely substantial negative correlations with Ya in flat intercropping; PAD and C:N showed significant negative correlations with LER (Figure 5A). SOC was the main factor affecting intercropping advantage, accounting for 34.7% of the explanatory rate in flat intercropping (Table A1). SOC, TN, AP, $WR_{0.25}$, GMD, Ca_8 -P, Al-P, and Fe-P were significantly positively correlated with Ya in co-ridge intercropping; BD, PAD, and C:P were significantly negatively correlated with Ya; PAD and AP were significantly negatively

correlated with LER (Figure 5B). SOC and AP were the primary driving factors influencing the intercropping advantage, with explanatory rates of 33.2% and 22.7%, respectively, in co-ridge intercropping (Table A1). SOC, AP, PAD, Ca₈-P, WR_{0.25}, C:P, and Fe-P jointly explained 91.7% of the intercropping advantage. The order of influence of soil factors from greatest to least was: SOC, AP, PAD, Ca₈-P, WR_{0.25}, C:P, and Fe-P (Table A1).

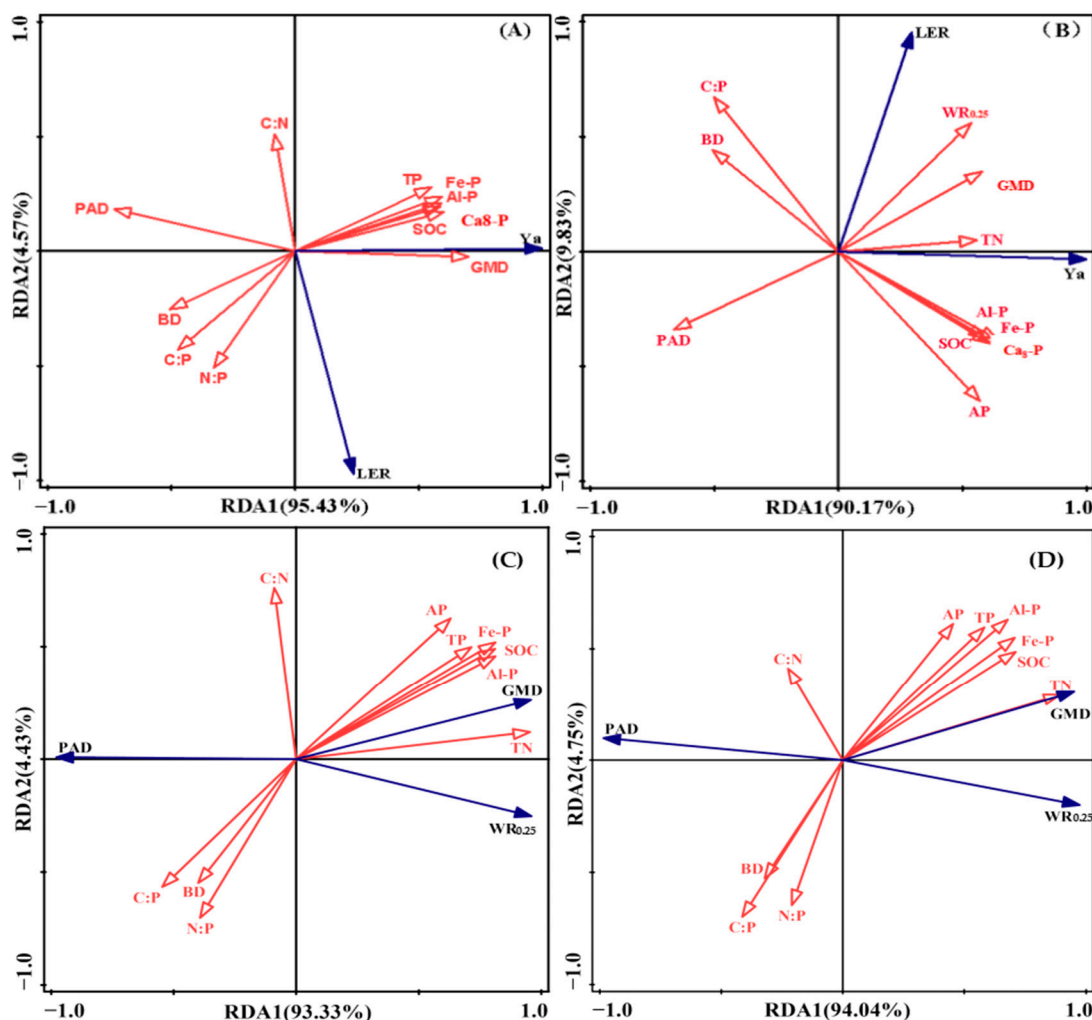


Figure 5. Redundancy analysis (RDA) ordering charts of Ya, LER, aggregate stability indices, and soil nutrients under (A,C) flat intercropping and (B,D) co-ridge intercropping. SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; Ca₈-P, Al-P and Fe-P are forms of soil inorganic phosphorus; WR_{0.25}: proportion of water-stable aggregates > 0.25 mm; PAD: percentage of aggregation destruction; GMD: geometric mean diameter; BD: soil bulk density; C:N, C:P, and N:P represent the C-N, C-P, and N-P ratios, respectively; Ya: intercropping yield advantage; LER: land equivalent ratio.

The redundancy analysis (RDA) in Figure 5C,D used soil nutrients (including SOC, TN, TP, AP, and stoichiometric ratios of C:N, C:P, and N:P) and inorganic phosphorus fractions (Al-P, Fe-P) as explanatory variables, with soil aggregate stability indices (WR_{0.25}, GMD, and PAD) as response variables, to explore the key driving factors affecting soil aggregate stability. SOC, TN, TP, AP, Al-P, and Fe-P were all significantly positively correlated with GMD and WR_{0.25} in both flat and co-ridge intercropping (Figure 5C,D), while BD, C:P, and N:P showed extremely significant negative correlations with GMD and WR_{0.25} (Figure 5C,D). The cumulative contribution rate of the first two principal components exceeded 95%, explaining most of the variability (Figure 5C,D). SOC, TN, N:P, Al-P, and

C:P were the main factors affecting soil aggregate stability in flat intercropping, with explanatory rates of 62.7%, 25.5%, 7.7%, 2.0%, and 0.7%, respectively (Table A2). In co-ridge intercropping, the main driving factors influencing soil aggregate stability were SOC, C:N, AP, and Al-P, which explained 48.8%, 30.2%, 8%, and 6.6% respectively (Table A2).

4. Discussion

4.1. Co-Ridge Planting Improves Soil Aggregate Stability and Soil Porosity While Reducing Bulk Density in Maize Intercropping with the Peanut System

Soil aggregate structure and stability are vital for maintaining soil fertility [44], and they are significantly correlated with soil BD and Pt [45]. Studies have shown that agricultural practices, including planting methods and fertilization, affect the stability of soil aggregates and BD [15,45,46]. In this study, R-M || P significantly increased the proportion and stability of macroaggregates, reduced BD, and enhanced soil Pt (Figure 2; Tables 1 and 2). These findings support our first hypothesis and are consistent with previous studies [6,7,47]. This consistency may be attributed to the advantage of co-ridge intercropping over traditional flat intercropping in improving the soil's dry-wet alternation capacity [2], which promotes the formation of water-stable aggregates and increases the proportion of macroaggregates [48].

Additionally, co-ridge intercropping enhances the activity and diversity of root-associated microorganisms [20,49], facilitating the release of more cementing substances and thereby improving the adhesive effect of microaggregates [50]. This enables intertwined roots to effectively strengthen the soil-binding capacity of crop roots [22]. As roots grow, they force soil particles to clump together, thereby accelerating the transformation of microaggregates into macroaggregates [51]. Co-ridge intercropping also increases the input of organic matter—such as plant residues, roots, and root exudates—into the soil, resulting in a significant increase in soil C concentration [3,52]. The formation and stability of aggregates, BD, and Pt were significantly related to the soil C pool [5,7,25]. Research has shown that soil organic matter influences soil structure and stability by binding to mineral particles, thereby enhancing the soil's stability. Furthermore, owing to the high specific surface area and cation exchange capacity of the topsoil, the accumulation of organic matter enhances soil aggregation. This process results in electrostatic bonding between soil particles, promoting the formation of macroaggregates, enhancing Pt, and decreasing BD [7,47,53,54].

The loam texture of the experimental soil (32.5% sand, 45.3% silt, 22.2% clay) provided a favorable matrix for aggregate formation. The moderate clay content (22.2%) facilitated the binding of soil particles via electrostatic forces, while silt and sand contributed to porosity [55]. R-M || P further enhanced this effect by improving soil aeration and water infiltration, which promoted the formation of water-stable macroaggregates—consistent with Zhang et al. [56], who reported that loam soils under ridge tillage have 15–20% lower aggregate destruction rates than sandy soils. However, some studies have shown that ridge culture increases the proportion of microaggregates (<1 mm) while decreasing the proportion of macroaggregates (>1 mm) and reducing soil structural stability [57]. This discrepancy may be due to the long-term nature of our experiment (6 years, 2018–2023), which allowed sufficient time for macroaggregate formation through root intertwining and organic matter accumulation. In contrast, short-term experiments [58] may only detect transient increases in microaggregates. Additionally, the loam texture in our study differs from the sandy or clayey soils in those studies, further influencing the effect of ridge tillage.

Besides the direct effect of planting methods, fertilization significantly affects aggregate stability, Pt, and BD. Our study showed that P fertilization significantly increased the proportion of soil macroaggregates, aggregate stability, and Pt while reducing BD

(Figure 2; Tables 1–3). These results are consistent with previous findings [25,27]. Du et al. [59] reported that inorganic fertilizers significantly increased the proportion of soil macroaggregates and MWD. The application of organic fertilizers maintains soil structural stability and reduces BD by increasing the amount of fertilizer applied or by applying fertilizer more frequently over a long period. However, the application of inorganic fertilizers has no significant effect on the stability of water-stable aggregates, MWD, and related indices [25,26]. The combination of fertilization with intercropping or ridge planting positively regulated macroaggregate formation, aggregate stability indices, BD, and Pt [5,7,27], which is consistent with our findings (Figure 2; Table 1 and 2).

4.2. Co-Ridge Planting Improves Soil Organic Carbon and Nutrient Concentrations in Maize Intercropping with the Peanut System

The basis of nutrient cycle transformation includes C, N, and P. Differences in the physical and chemical properties of aggregates across various size fractions influence soil C, N, and P pools as well as their ecological stoichiometric characteristics [60,61]. This study showed that R-M | P increased the concentrations of SOC and nutrients (TN, TP, and AP) in the topsoil and aggregates and promoted the conversion of potential P (Olsen-P and $\text{Ca}_{10}\text{-P}$) sources into available forms ($\text{Ca}_2\text{-P}$, $\text{Ca}_8\text{-P}$, Al-P , and Fe-P) in P_i (Tables 2 and 3; Figure 3). This finding is consistent with previous studies [21,62]. One possible explanation is that co-ridge intercropping promotes the formation of soil macroaggregates, which adsorb and retain organic matter, N, and P. This reduces the leaching losses of C, N, and P, minimizing their susceptibility to erosion and thereby increasing their concentrations within aggregates [63,64]. Consequently, more nutrients are made available for crop growth, potentially enhancing yield and productivity over time [15,16,24].

Ridge intercropping enhances soil Pt and structure while increasing the persistence of soil organic matter through enhanced biodiversity, thereby boosting soil C storage [65]. It also enhances P uptake by adjusting the soil water balance and modifying the distribution of crop root morphology [21,66,67], thereby stimulating root exudation of more acidic substances. This process releases and accumulates insoluble phosphorus nutrients in the soil, consequently increasing soil P concentrations [68].

The primary reason for the increases in SOC and nutrient concentrations under co-ridge intercropping may be that the 0–20 cm ridge soil in this study combined the 0–10 cm topsoil from the ridge and the 0–10 cm furrow soil, whereas the 0–10 cm topsoil contained higher plant residues and nutrient levels [69,70]. Notably, in long-term agricultural systems (our experiment spanned 2019–2023), soil properties such as SOC and aggregate stability typically exhibit slow, incremental changes. A consistent annual increase of 0.7–0.9% in SOC (resulting in a cumulative 3.8% increase over 5 years) aligns with regional studies on sustainable cropping systems [71] and indicates progressive improvement in soil quality. Under fertilization treatments, ridge tillage effectively reduces fertilizer usage while significantly improving soil nutrient status, enhancing intercropping interactions, and ultimately boosting crop yield [71]. The interaction between fertilization and intercropping significantly enhances soil carbon sequestration and nutrient concentrations, with increases in the soil C pool and nutrient concentrations becoming more pronounced over time [27,62].

4.3. Co-Ridge Planting Shapes New Ecological Stoichiometric Characteristics of Carbon, Nitrogen, and Phosphorus in Topsoil in Maize Intercropping with Peanut System

The ecological stoichiometric ratios of soil C, N, and P underpin biogeochemical cycling and soil functionality within ecosystems. They also serve as important indicators of soil nutrient limitations [72,73]. Soil C:N reflects the decomposition rate of soil organic matter and the mineralization of C and N, helping to assess soil nutrient balance [74]. Soil C:P is an indicator of P mineralization capacity and can measure the potential of soil to

release and absorb P [75]. Studies have shown that high C:N and C:P ratios in soil may limit nutrient availability, prompting plant–microbe competition for nutrients, whereas lower ratios may promote microbial mineralization, allowing microbes to acquire more C and achieve a balanced ecological stoichiometry [72].

In this study area, the C:N, C:P, and N:P in the topsoil ranged from 10.84 to 12.75%, 14.85 to 18.94%, and 1.24 to 1.61%, respectively, all of which were lower than the national level for cultivated soils [76]. This indicates that C is a limiting factor for soil fertility in the study area. The rapid mineralization of SOC by microorganisms increases the concentration of available N but hinders the accumulation of organic C. However, P concentrations appear relatively sufficient, with significant potential for further release [73,77].

In this study, co-ridge planting significantly increased the C:N and C:P ratios in the topsoil, while the N:P ratio remained unchanged (Table 3). This may be due to the relatively rapid decomposition of organic matter in co-ridge intercropping systems. Litter residues and roots introduced into the soil decompose and mineralize more readily, releasing N and other nutrients. Consequently, a significantly higher accumulation of soil C than N and P was observed, resulting in an enhanced nutrient supply for crop growth [11,16]. In this study, the C:N ratio increased as the aggregate size fraction decreased (Figure 3). This may be attributed to the high carbon mineralization rate and greater bioavailability of soil organic matter in macroaggregates compared with microaggregates [78].

Soil N:P reflects the constraints of N and P on crop growth [79,80] and directly influences plant nutrient use efficiency [81]. A low N:P ratio ($N:P < 14$) indicates N limitation for plant growth, while a high N:P ratio ($N:P > 14$) suggests P limitation [82]. This study showed that the N:P ratio was <14 in the topsoil and was not significantly affected by co-ridge intercropping ($p > 0.05$) (Table 3). This indicates minimal differences in the accumulation of N and P in the topsoil, with the N:P ratio remaining relatively stable within a range of 1.35 to 1.78. This stability may be attributed to the similar distribution patterns of N and P at the experimental site, allowing both elements to respond almost simultaneously to environmental changes. In this study, R-M | P reduced the N:P ratio as the aggregate size fraction decreased (Figure 3), indicating that N in the aggregates is the primary limiting factor. Furthermore, P application (P_{180}) lowered the C:P and N:P ratios in the aggregates, indicating that P_{180} accelerates the consumption of soil C and N. This may result in a limited soil C pool and N availability for crop growth.

The relationship between stoichiometric characteristics and soil aggregate stability is a critical indicator of the effects of soil remediation. Stoichiometric characteristics are the primary factors influencing soil aggregate stability [83]. Previous studies have shown that soil aggregate stability is significantly positively correlated with SOC and TN [84]. This may be because organic matter promotes the binding action of cementing materials in aggregates, thereby increasing their stability [50]. Total nitrogen promotes aggregate stability by supporting crop and root growth [85]. Therefore, the soil C:N ratio is considered the best predictor of aggregate stability [86]. Research has revealed that C:N positively correlates with aggregate stability [87], while C:P is the main driving factor affecting MWD, with this stoichiometric ratio accounting for 94% of the influence on aggregate stability, consistent with our findings (Figure 5; Table A2). This may be because intercropping promotes the accumulation of soil C, N, and P [5], and the addition of leguminous crops regulates soil stoichiometry and improves soil aggregation [2].

5. Conclusions

This study showed that R-M | P improves macroaggregate fractions, enhances aggregate stability and porosity (Pt), and reduces BD in the topsoil. It also increases the concentrations of SOC, TN, TP, and AP in aggregate fractions and in the topsoil, along

with their contribution rates in macroaggregates. In addition, R-M||P boosts C, N, and P storage, as well as the C:N and C:P ratios in the topsoil. R-M||P also promoted the conversion of non-directly available phosphorus sources (Olsen-P and Ca₁₀-P) into readily available phosphorus sources (Ca₂-P, Ca₈-P, Al-P, and Fe-P) in the topsoil. Moreover, P application increased SOC, TN, TP, and AP concentrations, as well as the C:N ratio, while reducing the C:P and N:P ratios.

In conclusion, R-M||P combined with P application enhances the yield advantage of intercropping by promoting macroaggregate formation and aggregate stability and by increasing the concentrations of C, N, and P, thereby establishing new ecological stoichiometric characteristics of C, N, and P. These changes improve soil properties associated with high-yield fields and contribute to the yield advantage observed in intercropping systems.

Author Contributions: Z.Z.: Investigation, Data collection and curation, Writing—original draft, Writing—review & editing, R.M.: Data analysis, Writing—review & editing, J.W.: Data analysis, Writing—review & editing, L.L.: Writing—review & editing, T.N.: Writing—review & editing; N.J.: Conceptualization, Methodology, Supervision, Funding acquisition, Project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (32272231), and the Natural Science Foundation of Henan Province (212300410342).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: This study is the result of a multi-actor collaboration. We would like to thank all the people who were directly or indirectly involved in this project. We also thank the three reviewers for their comments, which contributed greatly to the improvement of this paper.

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

Appendix A

Table A1. Interactions between soil physio-chemical properties and intercropping advantage.

Planting Pattern	Name	Explains (%)	Contribution (%)	Pseudo-F	p Value
F-M P	SOC	34.7	34.7	5.3	*
	PAD	18.4	18.4	3.5	ns
	BD	8.2	8.2	1.7	ns
	Ca ₈ -P	3.3	3.3	0.7	ns
	C:P	3.4	3.4	0.6	ns
	TP	8.9	8.9	1.9	ns
	Fe-P	14.8	14.8	7.3	ns
	GMD	3.6	3.6	2.4	ns
	C:N	0.9	0.9	0.5	ns
	N:P	1.8	1.8	1	ns
	Al-P	1.8	1.8	<0.1	ns
	SOC	33.2	33.2	5	*
	AP	22.7	22.7	6.9	*
	PAD	18	18	3.3	ns
R-M P	Ca ₈ -P	2.2	2.2	0.6	ns
	WR _{0.25}	6.2	6.2	2.1	ns
	C:P	7.2	7.2	3.4	ns
	Fe-P	2.2	2.2	1.1	ns
	MWD	1.7	1.7	0.8	ns
	Al-P	1.9	1.9	0.8	ns
	TN	1.1	1.1	0.3	ns
	BD	3.6	3.6	<0.1	ns

F-M||P: maize-peanut flat intercropping; R-M||P: maize-peanut co-ridge intercropping; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; WR_{0.25}: proportion of water-stable aggregates > 0.25 mm; PAD: percentage of aggregation destruction; GMD: geometric mean diameter; BD: soil bulk density; C:N, C:P, and N:P represent the C-N, C-P, and N-P ratios, respectively; Ca₈-P, Al-P and Fe-P are forms of soil inorganic phosphorus. * indicates significance at $p < 0.05$, and ns means not significant at $p > 0.05$.

Table A2. Interactions between soil physio-chemical properties and aggregate stability indices.

Planting Pattern	Name	Explains (%)	Contribution (%)	Pseudo-F	<i>p</i> Value
F-M P	SOC	62.7	62.8	16.8	**
	TN	25.5	25.6	19.6	**
	N:P	7.7	7.7	15	**
	Al-P	2	2	6.7	**
	C:P	0.7	0.7	3	*
	AP	0.3	0.3	1.5	ns
	TP	0.3	0.3	1.5	ns
	Fe-P	0.4	0.4	2.9	ns
	BD	0.2	0.2	2.8	ns
	C:N	<0.1	<0.1	1	ns
R-M P	SOC	48.8	48.8	9.5	*
	C:N	30.2	30.2	12.9	**
	AP	8	8	4.9	*
	Fe-P	4.4	4.4	3.6	ns
	Al-P	6.6	6.6	19.5	**
	N:P	0.3	0.3	0.8	ns
	TP	0.7	0.7	2.6	ns
	TN	0.5	0.5	2.5	ns
	BD	0.4	0.4	6	ns
	C:P	<0.1	<0.1	1.2	ns

F-M | | P: maize–peanut flat intercropping; R-M | | P: maize–peanut co-ridge intercropping; SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; $WR_{0.25}$: proportion of water-stable aggregates > 0.25 mm; PAD: percentage of aggregation destruction; GMD: geometric mean diameter; BD: soil bulk density; C:N, C:P, and N:P represent the C-N, C-P, and N-P ratios, respectively; Ca_s-P, Al-P and Fe-P are forms of soil inorganic phosphorus. * indicates significance at $p < 0.05$, ** at $p < 0.01$, and ns means not significant at $p > 0.05$.

Table A3. Effects of M||P and P application on yield and intercropping advantage during 2018–2023.

Year	P	Maize Yield (t·ha ⁻¹)				Peanut Yield (t·ha ⁻¹)		Intercropping Advantage (t·ha ⁻¹)		LER	
		SM	IM	R-IM	SP	IP	R-IP	M P	R-M P	M P	R-M P
2018	P ₀	5.25 ± 0.05 a	4.53 ± 0.03 b	5.03 ± 0.10 a	3.08 ± 0.22 a	0.95 ± 0.10 b	1.02 ± 0.02 b	1.18 ± 0.15 b	1.74 ± 0.05 a	1.18 ± 0.05 b	1.29 ± 0.01 a
	P ₁₈₀	7.44 ± 0.46 a	5.82 ± 0.03 b	6.22 ± 0.13 b	4.00 ± 0.13 a	1.07 ± 0.04 b	1.18 ± 0.07 b	0.95 ± 0.23 b	1.47 ± 0.34 a	1.05 ± 0.04 b	1.14 ± 0.07 a
2019	P ₀	5.63 ± 0.14 a	4.69 ± 0.15 b	5.32 ± 0.10 a	2.44 ± 0.01 a	0.72 ± 0.01 c	0.82 ± 0.01 b	1.18 ± 0.22 b	1.90 ± 0.08 a	1.13 ± 0.05 b	1.28 ± 0.02 a
	P ₁₈₀	9.62 ± 0.42 a	7.07 ± 0.12 b	8.02 ± 0.27 b	3.79 ± 0.02 a	1.06 ± 0.02 c	1.15 ± 0.02 b	1.07 ± 0.21 b	2.12 ± 0.24 a	1.02 ± 0.03 b	1.14 ± 0.03 a
2020	P ₀	6.36 ± 0.09 a	5.21 ± 0.08 c	5.83 ± 0.04 b	2.37 ± 0.03 a	0.85 ± 0.01 b	0.90 ± 0.01 b	1.45 ± 0.12 b	2.13 ± 0.07 a	1.18 ± 0.02 b	1.30 ± 0.01 a
	P ₁₈₀	9.63 ± 0.23 a	8.29 ± 0.09 b	9.10 ± 0.38 ab	3.52 ± 0.04 a	0.98 ± 0.01 b	1.00 ± 0.01 b	2.32 ± 0.20 b	3.16 ± 0.38 a	1.14 ± 0.03 b	1.23 ± 0.04 a
2021	P ₀	5.24 ± 0.13 a	4.49 ± 0.04 b	5.20 ± 0.08 a	3.17 ± 0.08 a	0.84 ± 0.01 b	0.98 ± 0.01 b	1.00 ± 0.12 b	1.85 ± 0.13 a	1.12 ± 0.03 b	1.30 ± 0.03 a
	P ₁₈₀	7.43 ± 0.10 a	6.08 ± 0.09 c	6.87 ± 0.23 b	4.13 ± 0.05 a	1.18 ± 0.04 b	1.36 ± 0.06 b	1.27 ± 0.10 b	2.25 ± 0.18 a	1.10 ± 0.02 b	1.25 ± 0.02 a
2022	P ₀	4.28 ± 0.04 a	3.51 ± 0.06 b	4.09 ± 0.13 a	4.35 ± 0.09 a	1.55 ± 0.04 c	2.17 ± 0.08 b	0.75 ± 0.10 b	1.95 ± 0.23 a	1.18 ± 0.02 b	1.46 ± 0.05 a
	P ₁₈₀	7.39 ± 0.21 a	5.99 ± 0.09 c	6.51 ± 0.08 b	5.23 ± 0.06 a	1.86 ± 0.03 c	2.47 ± 0.05 b	1.41 ± 0.17 b	2.54 ± 0.13 a	1.17 ± 0.03 b	1.35 ± 0.03 a
2023	P ₀	6.54 ± 0.23 a	5.31 ± 0.42 c	6.01 ± 0.42 b	4.17 ± 0.03 a	1.67 ± 0.03 c	2.03 ± 0.02 b	1.56 ± 0.42 b	2.61 ± 0.23 a	1.21 ± 0.02 b	1.41 ± 0.21 a
	P ₁₈₀	9.85 ± 0.42 a	7.41 ± 0.04 c	7.91 ± 0.32 b	5.70 ± 0.21 a	2.17 ± 0.02 c	2.78 ± 0.04 b	1.69 ± 0.31 b	2.8 ± 0.32 a	1.14 ± 0.06 b	1.29 ± 0.06 a
	P	***	***	***	***	***	***	*	**	**	***
	Year	***	***	***	***	***	***	***	*	**	***
	P*Year	**	***	***	ns	*	*	*	ns	ns	ns

SM: solo maize; SP:solo peanut; IM: intercropped maize; IP: intercropped peanut; R-IM: co-ridge intercropping maize; R-IP: co-ridge intercropping peanut; F-M||P: maize–peanut flat intercropping; R-M||P: maize–peanut co-ridge intercropping; LER: land equivalent ratio. Values indicate the mean ± standard error (n = 3). Lowercase letters within columns denote significant differences by Duncan’s test ($p < 0.05$). * indicates significance at $p < 0.05$, ** at $p < 0.01$, *** at $p < 0.001$, and ns means not significant at $p > 0.05$.

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