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Research on Marginal Effects of Dry Matter Accumulation and Extinction Coefficient in *Maize–Soybean* Intercropping Composite Population

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Abstract

Maize–soybean intercropping can improve land use efficiency and increase crop yields, thereby contributing to sustainable agricultural development. This study aimed to investigate the marginal effects of intercropping on dry matter accumulation and the extinction coefficient (K) of *maize* and *soybean* canopies, thereby providing theoretical guidance for efficient resource utilization and the realization of high-yield and high-efficiency *maize–soybean* intercropping systems. This experiment employed *maize* variety Jincheng 316 and *soybean* variety Heinong 531. Two intercropping treatments (S4M4: four rows *soybean* alternating with four rows *maize*; S6M4: six rows *soybean* alternating with four rows *maize*) and two sole cropping controls (M: sole *maize*; S: sole *soybean*) tested the marginal effects of different intercropping patterns on crop dry matter accumulation, SPAD, and K. Combined with analyses of yield, land equivalent ratio (LER), and intercropping advantage (IA), we determined the optimal row ratio configuration for intercropping. The results showed that, compared with monocropped *maize*, the leaf SPAD at the R1 stage and grain dry matter accumulation at the R6 stage under S4M4 and S6M4 treatments increased by 17.28%/20.12% and 8.07%/5.35%, respectively, while K values decreased by 21.80% and 14.37%. For *soybean*, relative to monocropping, the R4 leaf SPAD and R8 grain dry matter accumulation under S4M4 and S6M4 were elevated by 23.87%/19.40% and 26.66%/13.56%, respectively, with corresponding K values reductions of 21.94% and 21.82%. Moreover, S4M4 exhibited a 51.67% higher IA and a 9.48% higher LER than S6M4. In summary, *maize–soybean* intercropping significantly boosts dry matter accumulation and resource use efficiency, with the S4M4 configuration exhibiting the most distinct advantages.

Keywords: *maize–soybean* intercropping; marginal effect; dry matter accumulation; extinction coefficient; yield

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1. Introduction

China is a populous agricultural country, where agriculture serves as the foundational industry underpinning the construction and development of the national economy. As major grain and oil crops in China, *maize* (*Zea mays* L) and *soybeans* (*Glycine max* (L.) *Merr*) play a crucial role in safeguarding national food security. Data from 2025 indicated that the self-sufficiency rate of staple grains (*rice* and *wheat*) reached 99.3%, achieving almost full self-sufficiency. The self-sufficiency rate of cereals (including *maize*) stood at 93.4%,

corresponding to a supply deficit of approximately 25 million tons. In contrast, the self-sufficiency rate of *soybeans* remained below 10%, with an enormous supply deficit of up to 90 million tons [1]. *Soybean* supply security is confronting severe challenges [2–5]. Against this backdrop, *maize–soybean* intercropping technology can effectively resolve the conflict of limited arable land, which is also in line with the national strategy of promoting large-scale grain and oilseed yield increases. This practice not only stabilizes the grain planting area but also strengthens the comprehensive popularization of high-yield and high-efficiency farming patterns. Intercropping systems aim to leverage the ecological niche differences among intercropped crops to achieve more efficient utilization of resources such as water, heat, light, and nutrients [6–8], and are thus recognized as highly effective cropping [9,10].

The selection of crop varieties is crucial for intercropping systems. When intercropped with *soybeans*, compact *maize* varieties can effectively regulate the accumulation, translocation, and distribution of dry matter, thereby improving *soybean* yields [11]. *Maize* shading impairs the photosynthetic capacity and dry matter accumulation of *soybean* leaves, thereby threatening *soybean* yields. Thus, selecting appropriate *soybean* varieties helps mitigate yield losses induced by shading and ensure stable soybean production [12]. Intercropping with *maize* modifies the canopy structure, facilitating the capture of more photosynthetically active radiation and enhancing the coordination of light distribution within the canopy [13]. This practice enhances the photosynthetic rate and radiation use efficiency of *maize*, increases the capture of photosynthetically active radiation in the *soybean* canopy, and mitigates the disadvantage of *soybean* in interspecific competition [14]. Intercropping elongates *soybean* internodes, increases plant height and specific leaf area, but reduces branching. These morphological adjustments enable *soybeans* to capture light more effectively; meanwhile, shading can enhance the light use efficiency of *soybeans*. However, these benefits fail to offset the adverse effects of reduced leaf area and excessive light interception, ultimately leading to decreased biomass and grain yield [15]. All intercropping systems exhibited land-equivalent ratios greater than 1 [16,17], indicating high intercropping advantage indices. Moreover, these systems effectively coordinated the translocation and accumulation of dry matter, thereby manifesting the yield advantages of intercropping [18]. The Northeast Black Soil Region is a key production base for maize and *soybeans* in [19,20], providing an ideal foundation for high crop yields. *Maize–soybean* intercropping on black soil enhances the inherent advantages of the soil and further improves the productivity and sustainability of the cropping system through the synergistic effects between the two crops.

Intercropping significantly affects the dry matter accumulation in different plant organs and the canopy light transmittance. The Eastern Inner Mongolia Autonomous Region is a major *maize* production base and core growing area, and it is among the world's three "Golden *Maize* Belts". Its unique black soil provides abundant nutrients and an ideal rooting environment for *soybean* cultivation. Previous studies on *maize–soybean* intercropping have extensively investigated dry matter accumulation [12,21], nitrogen uptake [22–25], and photosynthetic efficiency [26,27]. However, most of these studies have adopted a holistic analytical approach, with limited research focusing on the performance of individual *maize* or *soybean* rows. This study systematically investigated the marginal effects of *maize–soybean* intercropping under field conditions, with the intercropped population as the research object. By analyzing dry matter accumulation and light extinction coefficients across different crop growth stages and plant organs, it further explored the marginal effects between *maize* and *soybean* rows. Through the exploration of these marginal effects, the study clarified the row-wise variation patterns of dry matter accumulation and light extinction coefficients in the intercropping system, as well as the optimal row ratio configuration. This provides a theoretical basis for selecting suitable *maize–soybean* intercropping technical models in eastern Inner Mongolia, which is conducive to improving land productivity and ecological

benefits, achieving high and stable yields, and realizing efficient resource utilization, but also lays a foundation for the effective popularization of intercropping technologies.

2. Materials and Methods

2.1. Overview of the Experimental Site

The experiment was conducted consecutively over two years (2024–2025) at the Zhalaite Banner Agricultural Science and Technology Demonstration Park, which is located in Xinli Village, Yinder Town, Zhalaite Banner, Inner Mongolia Autonomous Region. The soil type at the experimental site was sandy loam, and the preceding crop was *maize*. The soil properties were as follows: pH 6.36, organic matter 2.59%, total nitrogen 1.78 g/kg, available phosphorus 31.07 mg/kg, and available potassium 112.55 mg/kg. The climatic conditions included an effective accumulated temperature of approximately 2600 °C, an annual precipitation of around 400 mm, an average frost-free period of 110–130 days per year, and an annual temperature $\geq$ 10 °C; irrigation was available.

2.2. Experimental Materials

The *maize* variety used in the experiment was Jincheng 316, which has a compact plant type with upright leaves, ensuring good ventilation and light transmission. It exhibits high yield potential, strong comprehensive stress resistance, and excellent grain quality, and was developed by Henan Jinyuan Seed Industry Co., Ltd. (Zhoukou City, China). The *soybean* variety used in the experiment was Heinong 531, which has a well-proportioned plant architecture with lanceolate leaves, thus ensuring superior ventilation and light transmission within the canopy. It demonstrates excellent comprehensive stress tolerance, high yield potential, and desirable yield stability, and was bred by the *Soybean* Research Institute of Heilongjiang Academy of Agricultural Sciences (Harbin, China).

2.3. Experimental Design

A randomized block design with ridge cultivation was adopted in this experiment. *Soybeans* were sown in double-row zigzag pattern using no-till seeding technology on the ridges. Four treatments were set up, namely: four rows of *soybeans* intercropped with four rows of *maize* (S4M4), six rows of *soybeans* intercropped with four rows of *maize* (S6M4), monocropped *maize* (M), and monocropped *soybean* (S). Among them, the intercropping treatments were S4M4 and S6M4, with the following row and strip configurations: S4M4 (*maize* row spacing 80 cm, *maize* small row spacing 50 cm, *maize–soybean* spacing 65 cm, *soybean* row spacing 50 cm, sawtooth spacing 15 cm, total strip width 520 cm); S6M4 (*maize* row spacing 80 cm, *maize* small row spacing 50 cm, *maize–soybean* spacing 65 cm, *soybean* row spacing 50 cm, sawtooth spacing 15 cm, total strip width 650 cm). The plant spacing was 14.65 cm for *maize* and 12.82 cm for *soybean* in each strip. The other two treatments were monocropped *maize* (M) and monocropped *soybean* (S). Each treatment strip was 100 m in length. For fertilization, the *maize* strips (in intercropping) and monocropped *maize* plots received a basal application of compound fertilizer (N-P-K: 17-17-17) at 450 kg·hm^{-2}, followed by a topdressing of urea at 450 kg·hm^{-2}. The *soybean* strips (in intercropping) and monocropped *soybean* plots only received a basal application of compound fertilizer (N-P-K: 17-17-17) at 300 kg·hm^{-2}. All plots were oriented north–south, and *maize* and *soybean* were arranged sequentially from west to east to ensure sufficient sunlight for *soybean*. The experimental factors and their levels are presented in Table 1.

Table 1. Experimental factors and levels.

Serial Number	Planting Pattern	Treatment Combination
1	S4M4	A1
2	S6M4	A2
3	M	A3
4	S	A4

2.4. Determination Indicators and Methods

2.4.1. Dry Matter Accumulation

At the *maize* V1, V6, V12, R1, R3, and R6, three *maize* plants with uniform growth were selected. The selected plants were placed in paper sample bags, subjected to deactivation of enzymes at 105 °C for 30 min, then dried at 80 °C to a constant weight, and finally weighed to determine the dry matter accumulation. For *soybean*, three plants with consistent growth were selected at the V1, V3, R2, R4, R6, and R8, and their dry matter accumulation was determined using the same method as described above.

2.4.2. Photosynthetic Characteristics

(1) Determination of Leaf SPAD

Measurement Period: Maize: R1; soybean: R4.

SPAD values were measured using an SPAD-502 chlorophyll meter (KONICA MINOLTA, Inc., Tokyo, Japan). For both crops, measurements were performed on the upper, middle, and lower leaves of individual plants, following crop-specific protocols as described below: For *maize*, functional leaves at each canopy layer were selected, and three distinct positions (leaf tip, leaf middle, and leaf base) were measured per leaf, with three technical replicates conducted at each position. For *soybean*, the middle leaflet of fully expanded trifoliate compound leaves was selected for testing; measurements were taken at the widest part of the leaf blade near the base, with the midrib excluded from the measurement area. The mean value across all measured positions and replicates was calculated as the final SPAD value for the target leaf.

(2) Determination of the Extinction Coefficient

Measurement Period: *Maize*: V1, V6, V12, R1, R3, R6; *soybean*: V1, V3, R2, R4, R6, R8.

The extinction coefficient (K) was determined as follows: a digital lux meter was used to measure the light intensity above the *soybean* canopy and at the upper, middle, and lower layers of the canopy. The *soybean* canopy was divided into three layers (upper, middle, and lower) according to the natural upward angle of the leaves.

$$K = (lnI_0 - lnI_f)/LAI \quad (1)$$

In the equation, I_0 represents the natural light intensity at the top of the canopy; If denotes the light intensity within a specific canopy layer (unit: lux); and LAI stands for Leaf Area Index.

2.4.3. Yield and Yield Advantage Indicators

(1) Yield: For yield determination, a 5 m length of double *maize* rows and a 3 m^2 quadrat of *soybean* plants were harvested. The harvested grains were threshed, air-dried naturally, and weighed; the 100-grain weight was calculated; and the final yield was converted to the yield per hectare ($kg \cdot hm^{-2}$).

(2) Yield Advantage Analysis: The land equivalent ratio (LER) and intercropping advantage (IA) were calculated using the corresponding formulas.

$$LER = (Yis/Ys) + (Yim/Ym) \quad (2)$$

In the equation, Yis and Yim represent the yields of *soybean* and *maize* in the intercropping system, respectively; Ys and Ym represent the yields of *soybean* and *maize* in the monocropping system, respectively (the above notation applies to the following formulas). LER > 1 indicates that the intercropping system has a yield advantage, while an LER < 1 indicates a yield disadvantage.

$$IA = [(Yis + Yim) - (Ys \times Zs + Ym \times Zm)]/(Ys \times Zs + Ym \times Zm) \times 100\% \quad (3)$$

In the equation, Zs and Zm represent the area proportions of *soybean* and *maize* in the intercropping system, respectively. The interpretation of IA values is as follows: when IA > 0, the intercropping system has a yield advantage, and higher values indicate a more significant advantage; when IA = 0, the comprehensive benefit of the intercropping system is equivalent to that of the monocropping system, showing no yield advantage; when IA < 0, the intercropping system has a yield disadvantage, and its comprehensive benefit is lower than the total benefit of the monocropping system.

2.5. Data Processing

Preliminary collation of experimental data was conducted using Microsoft Excel (v2019) to calculate the arithmetic mean and standard deviation of each indicator. Statistical analysis of the data was performed using SPSS (v2024), and graphical visualization was generated using Origin (v2024).

3. Results and Analysis

3.1. SPAD Values of Canopy Leaves in Maize–Soybean Intercropping Composite Population

Analysis of Figures 1 and 2 showed that, over the two consecutive years of field trials, the SPAD values of R1-stage *maize* leaves across all canopy layers exhibited consistent patterns: intercropping > monocropping, border rows (BR) > inner rows (IR), and upper canopy layer (UCL) > middle canopy layer (MCL) > lower canopy layer (LCL). Compared with the IR and monocropping systems, the yields of BR in the S4M4 intercropping pattern increased by 8.97–10.07% and 11.30–17.28%, respectively; while those in the S6M4 pattern increased by 8.07–9.81% and 13.68–20.12%, respectively. The SPAD values of R4-stage *soybean* leaves across all canopy layers exhibited the following consistent pattern: intercropping > monocropping and UCL > MCL > LCL. Compared with the IR and monocropping treatments, the BR of the S4M4 intercropping pattern exhibited yield increases of 13.06–14.35% and 14.02–23.87%, respectively. For the S6M4 pattern, its BR showed a yield increase of 13.24–14.31% relative to the second border rows (SBR), 23.81–35.03% relative to the IR, and 12.11–19.40% relative to monocropping. The IR of *soybeans* in the S6M4 intercropping system exhibited a yield increase relative to the monocropping system, though the difference was not statistically significant. This finding suggests that a rational row spacing ratio exerts a positive regulatory effect on crop growth and development.

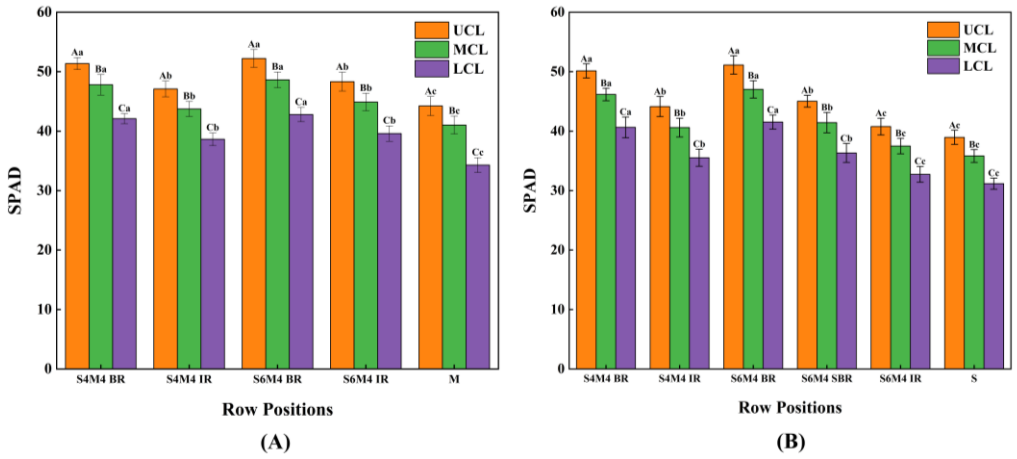


Figure 1. Canopy SPAD Values of *Maize* (R3) and *Soybean* (R6) under Different Cropping Patterns in 2024. Note: (**A**) *Maize*; (**B**) *Soybean*. Different lowercase letters indicate significant differences among different row positions within the same canopy layer ($p < 0.05$); different uppercase letters indicate significant differences among different canopy layers within the same row position ($p < 0.05$).

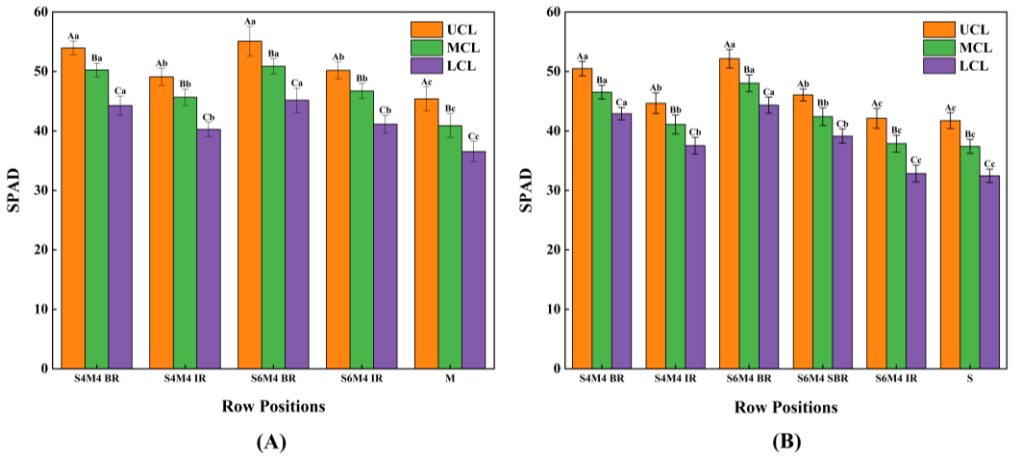


Figure 2. Canopy SPAD Values of *Maize* (R3) and *Soybean* (R6) under Different Cropping Patterns in 2025. Note: (**A**) *Maize*; (**B**) *Soybean*. Different lowercase letters indicate significant differences among different row positions within the same canopy layer ($p < 0.05$); different uppercase letters indicate significant differences among different canopy layers within the same row position ($p < 0.05$).

3.2. Extinction Coefficient (K) of Maize–Soybean Intercropping Composite Population

K values are a key parameter reflecting the light attenuation capacity of crop canopies. Higher K values indicate stronger light attenuation by the canopy, leading to less light penetration to the LCL. Conversely, lower K values signify superior light transmittance of the canopy, thus facilitating a more uniform distribution of light energy within the canopy. Analysis of Figures 3–6 showed that, over the two consecutive years of field trials, the K values of the MCL and LCL in the *maize–soybean* intercropping system exhibited a consistent rise-then-fall trend. Meanwhile, the trends illustrated in the figures also displayed an expansion–contraction pattern, with the K values of the MCL consistently lower than those of the LCL. For *maize*, K values peak occurs at the R1 stage (K = 0.78), while for *soybean*, they peak at the R4 stage (K = 1.07). This phenomenon reflects the asynchronous growth stages of the two crops during the period when canopy density reaches its maximum.

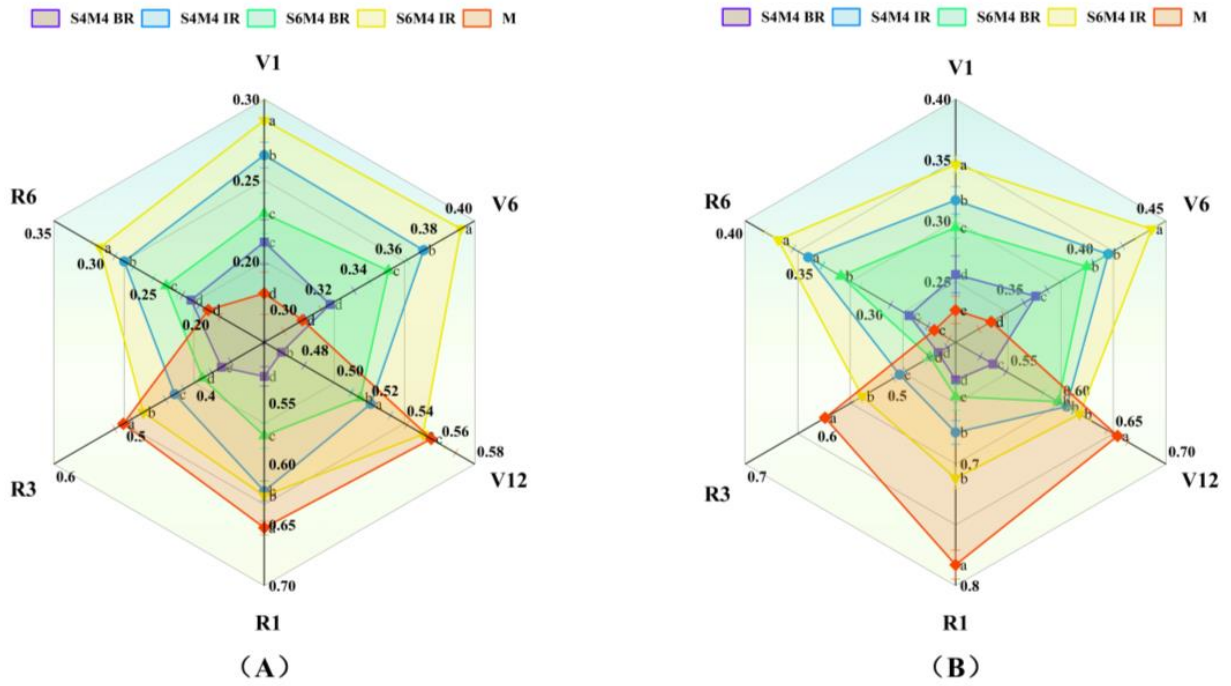


Figure 3. Dynamic Changes in Canopy Extinction Coefficient of *Maize* at Different Growth Stages under Different Cropping Patterns in 2024. Note: (**A**) Middle canopy; (**B**) Lower canopy. Different lowercase letters indicate significant differences among different row positions within the same canopy ($p < 0.05$).

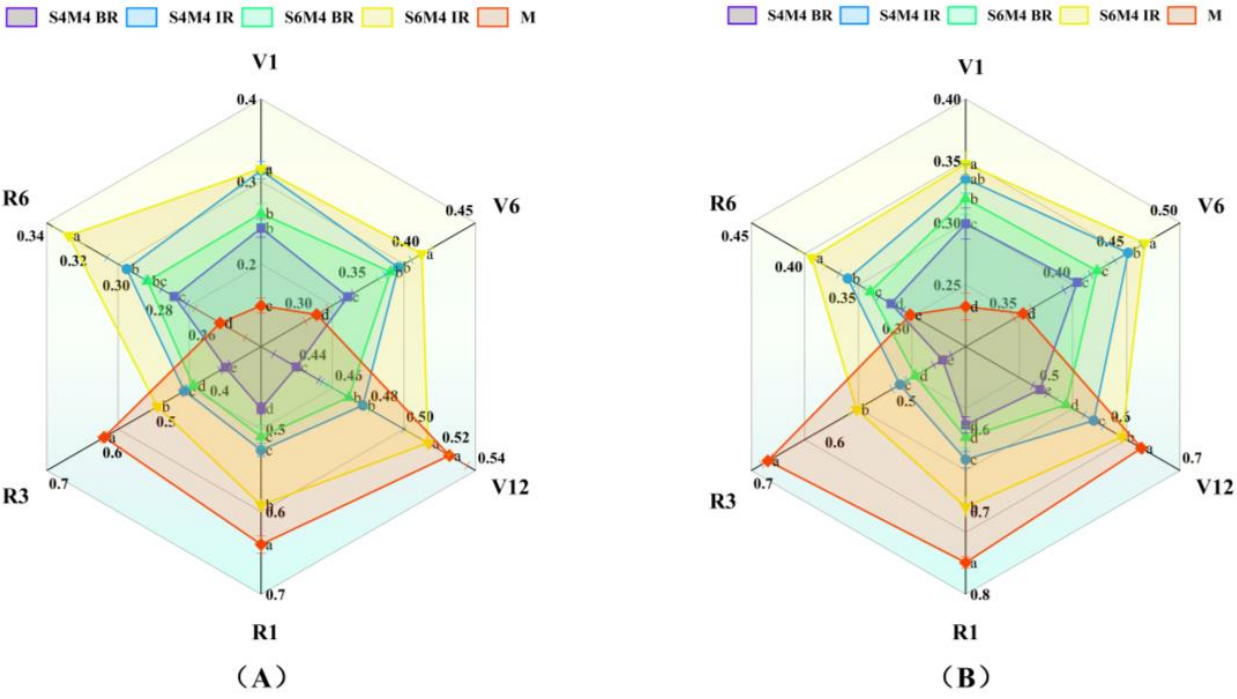


Figure 4. Dynamic Changes in Canopy Extinction Coefficient of *Maize* at Different Growth Stages Under Different Cropping Patterns in 2025. Note: (**A**) Middle canopy; (**B**) Lower canopy. Different lowercase letters indicate significant differences among different row positions within the same canopy ($p < 0.05$).

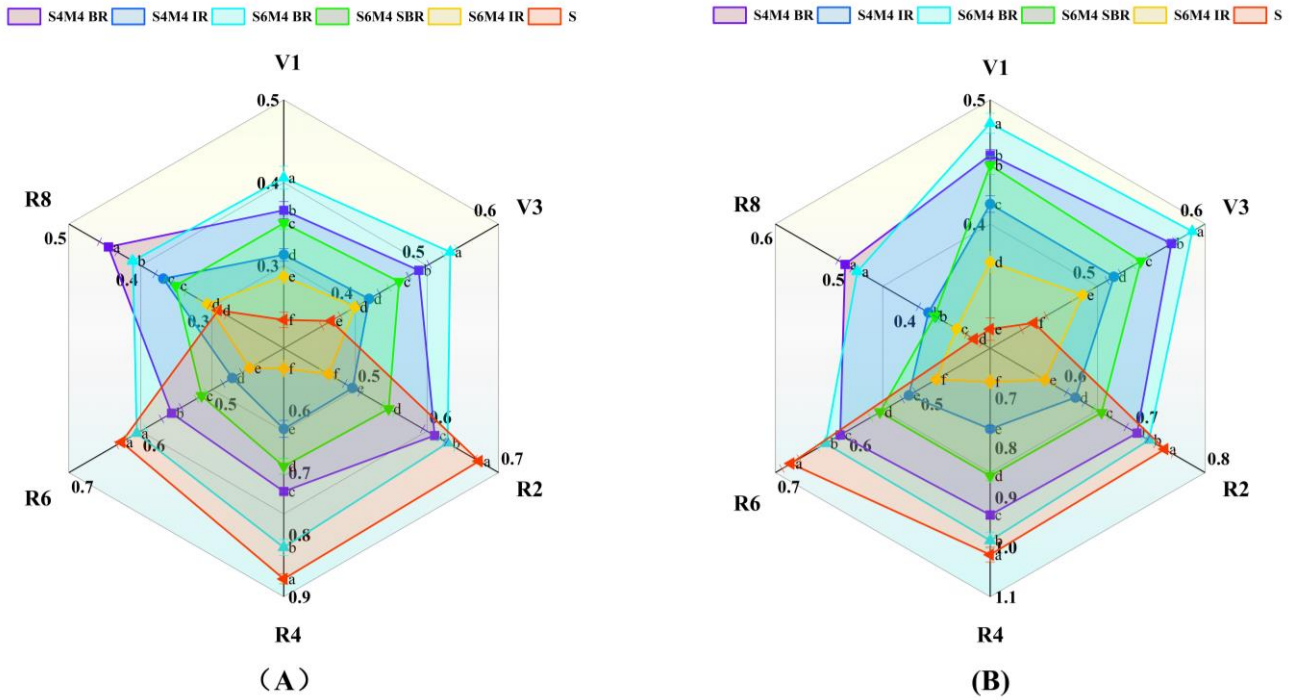


Figure 5. Dynamic Changes in Canopy Extinction Coefficient of *Soybean* at Different Growth Stages under Different Cropping Patterns in 2024. Note: (**A**) Middle canopy; (**B**) Lower canopy. Different lowercase letters indicate significant differences among different row positions within the same canopy ($p < 0.05$).

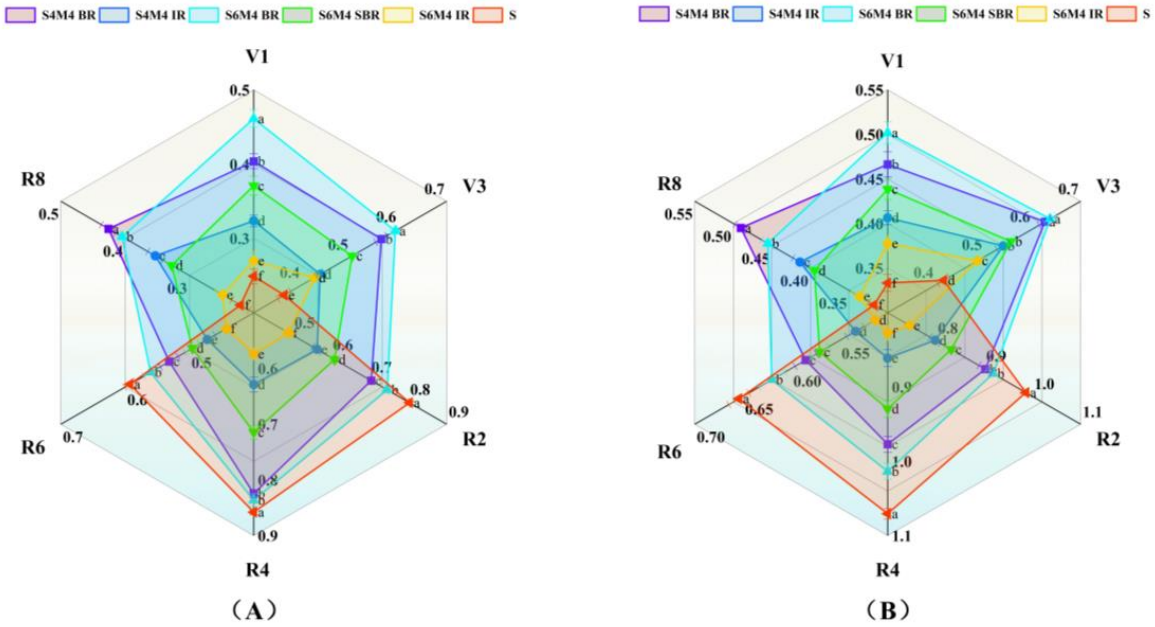


Figure 6. Dynamic Changes in Canopy Extinction Coefficient of *Soybean* at Different Growth Stages Under Different Cropping Patterns in 2025. Note: (**A**) Middle canopy; (**B**) Lower canopy. Different lowercase letters indicate significant differences among different row positions within the same canopy ($p < 0.05$).

Over two consecutive years of field trials, monocropped *maize* exhibited lower K values than intercropped *maize* at the V1, V6, and R6 stages. During all other growth stages, intercropped maize consistently had lower K values than monocropped *maize*. Across all growth stages and intercropping patterns, the K values of the BR were consistently lower than those of the IR, with the differences being statistically significant. When the

K of *maize* reached its peak, the K values of BR in the S4M4 intercropping pattern were reduced by 6.41–15.16% compared with IR, 11.86–21.80% compared with monocropping, and 11.86–18.76% compared with LCL. For the S6M4 pattern, the K values of BR exhibited a reduction of 7.90–14.01% relative to both IR and monocropping, while the K values of MCL were reduced by 7.81–14.37% compared with LCL. During the V1, V3, and V8 growth stages, the K values of monocropped *soybean* were lower than those of intercropped s*oybean*. In contrast, intercropped *soybean* exhibited lower K values than monocropped *soybean* across all other growth stages. Across different intercropping patterns and growth stages, the K values of *soybean* decreased with an increase in the interspecific distance between the two crops. With the exception of the R8 stage, the K values of *soybean* in the S4M4 intercropping pattern were consistently lower than those in the S6M4 intercropping pattern. When the K values of *soybean* reached its peak, the following results were observed: For the S4M4 intercropping pattern, the K values of BR were 11.88–23.75% higher than those of IR; compared with monocropping, the K values of intercropped *soybean* decreased by 14.15–21.94%; the K values of MCL were 19.86–20.93% lower than those of LCL. For the S6M4 intercropping pattern, the K values of BR were 8.31–15.91% higher than those of SBR and 18.37–35.07% higher than those of IR, respectively; compared with monocropping, the K values of intercropped *soybean* decreased by 13.73–21.82%; the K values of MCL were 18.63–23.30% lower than those of LCL. This finding demonstrates that *maize–soybean* intercropping confers distinct agronomic advantages, with a prominent BR advantage. Compared with monocropping, crops grown under the intercropping system receive greater light exposure throughout the growing season, which enhances their photosynthetic efficiency and delays crop senescence. Therefore, rational intercropping practices can effectively promote the efficient utilization of solar energy.

3.3. Dry Matter Accumulation in Maize–Soybean Intercropping Composite Population

Analysis of Figures 7 and 8 shows that, over the two consecutive years of field trials, the dry matter accumulation of all organs and the whole plant of intercropped *maize* is significantly higher than that of monocropped *maize*, with the BR exhibiting higher accumulation levels than the IR. During the vegetative growth stage, dry matter accumulation in stems and leaves increases continuously; it then declines gradually from the onset of the reproductive growth stage and eventually reaches a steady state. Dry matter accumulation in grains initiates at the start of the reproductive growth stage, followed by rapid and sustained accumulation from the R1 stage to R6. The R1 stage represents the transition period from vegetative to reproductive growth, during which dry matter accumulation in stems and leaves reaches its peak and grain formation begins. At the R1 growth stage, the following growth trait differences were observed in the S4M4 intercropping pattern: compared with IR, BR increased stem length by 3.06–9.82%, and intercropped maize exhibited a 6.97–10.36% increase in stem accumulation relative to monocropped *maize*; BR also increased leaf accumulation by 7.23–7.73%, while intercropped *maize* increased leaf accumulation by 5.56–5.64% compared with monocropped *maize*. At the R6 growth stage, BR increased grain accumulation by 3.14–7.97% compared with IR in intercropping systems, and intercropped *maize* increased grain accumulation by 5.65–8.07% compared with monocropped *maize*. At the R1 growth stage, the following differences were observed in the S6M4 intercropping pattern: compared with IR, BR increased stem accumulation by 3.74–10.54%, and BR also increased stem accumulation by 4.66–8.95% relative to monocropped *maize*; for leaf accumulation, BR exhibited an increase of 5.77–8.40% compared with IR and 9.98–10.41% compared with monocropped *maize*, respectively. Additionally, BR increased grain accumulation by 2.57–6.88% compared with IR, and intercropped *maize* increased grain accumulation by 3.88–5.35% relative to monocropped *maize*. Intercrop-

ping contributes more than 80% to the total dry matter accumulation of the system, whereas monocropping accounts for less than 80%. Additionally, intercropping maintains a longer leaf area duration (LAD), which establishes a "source-sink enhancement" relationship and thereby promotes the allocation of photosynthates to economic organs. The *maize–soybean* intercropping system effectively enhanced the photosynthate accumulation capacity of both individual maize plants and the entire population by optimizing the microenvironment within the crop canopy. Among all intercropping treatments, the S4M4 treatment exhibited the highest dry matter accumulation.

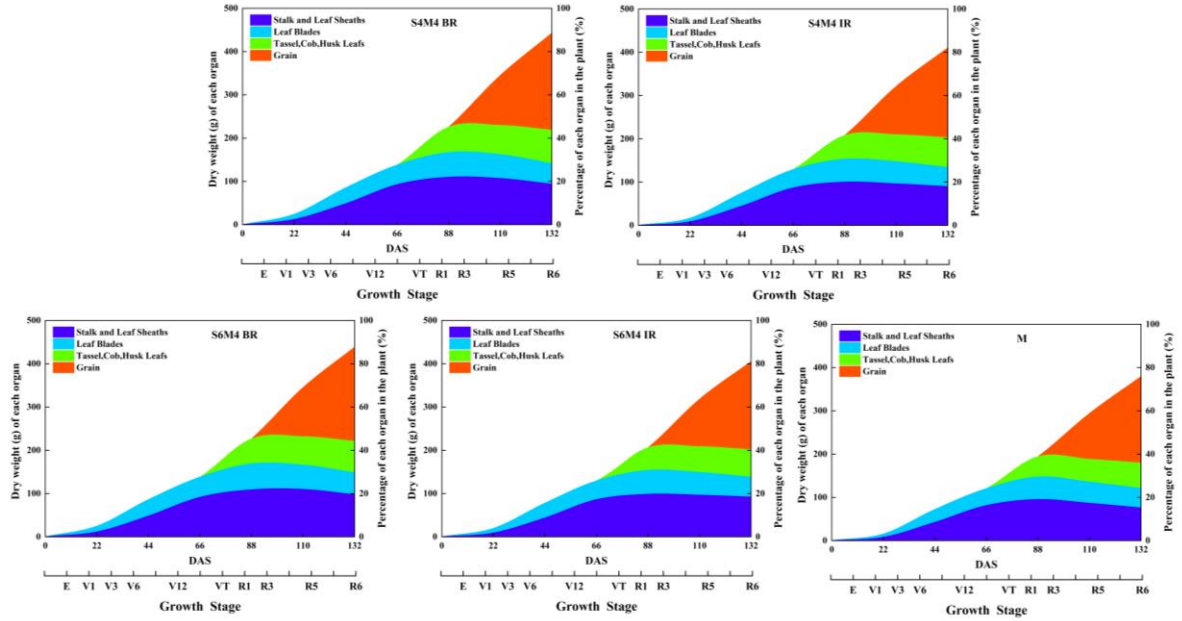


Figure 7. Dynamic of Dry Matter Accumulation in *Maize* under Different Intercropping Modes in 2024.

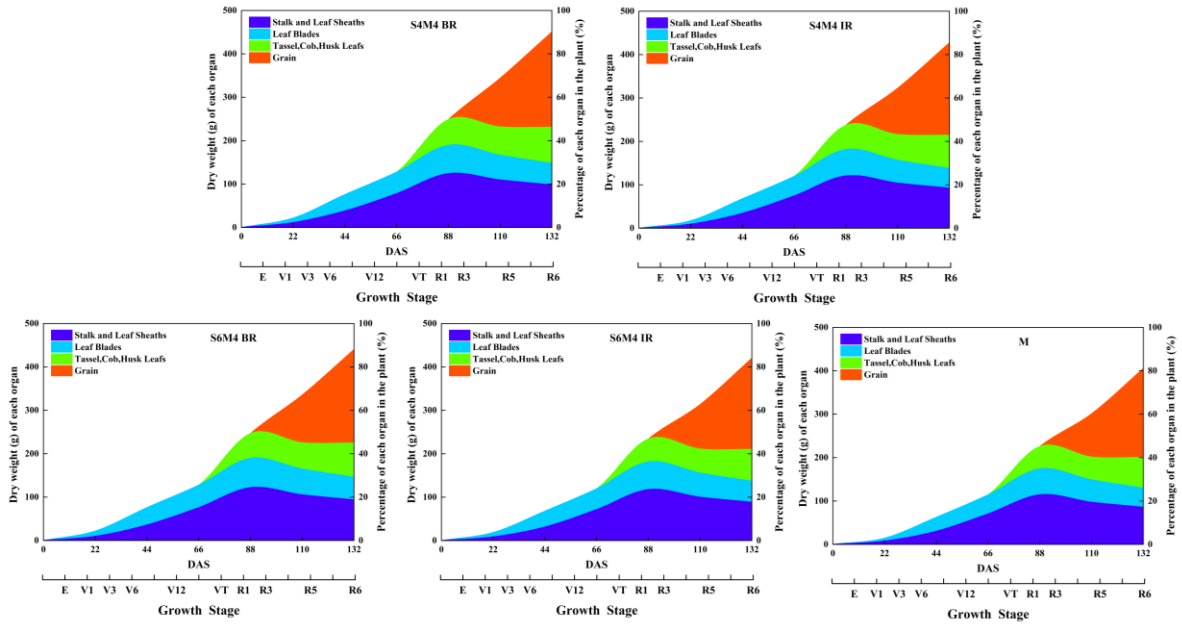


Figure 8. Dynamic of Dry Matter Accumulation in *Maize* under Different Intercropping Modes in 2025.

Analysis of Figures 9 and 10 shows that over two consecutive years of field trials, the dry matter accumulation of *soybean* exhibited four distinct characteristics: "early-stage

suppression, mid-stage compensation, preferential allocation to seeds, and prominent BR advantage". Throughout the entire growing season, the dry matter accumulation of *soybean* decreased with an increase in the interspecific distance between maize and *soybean*. During the V1 and V3 stages, the dry matter accumulation of intercropped *soybean* was lower than that of monocropped *soybean*; in contrast, intercropped *soybean* exhibited higher dry matter accumulation than monocropped *soybean* during all other growth stages. From the R4 growth stage onward, dry matter accumulation in *soybean* stems and leaves slows down or even declines, while the dry weight of pods and seeds begins to increase rapidly. This indicates a shift in dry matter allocation from vegetative organs to reproductive organs. At the R4 growth stage, the following differences were observed in the S4M4 intercropping pattern: compared with IR, BR increased stem accumulation by 5.37–10.53%, and intercropped *soybean* increased stem accumulation by 10.13–14.88% relative to monocropped *soybean*; for leaf accumulation, BR and intercropped *soybean* exhibited increases of 6.67–12.62% and 8.37–9.69% compared with IR and monocropped *soybean*, respectively. At the R8 growth stage, BR increased grain accumulation by 11.48–12.17% compared with IR in intercropping systems, and intercropped *soybean* increased grain accumulation by 24.89–26.66% compared with monocropped *soybean*. At the R4 growth stage, compared with SBR and IR, BR increased stem accumulation by 7.12–10.52% and 13.60–20.31%, respectively; in addition, intercropped *soybean* increased stem accumulation by 4.74–7.20% relative to monocropped *soybean*. Intercropped *soybean* increased leaf accumulation by 9.43–9.60%, 22.96–41.79%, and 8.99–9.58% compared with BR, SBR, and IR of monocropped *soybean*, respectively. At the R8 growth stage, BR increased grain accumulation by 8.23–8.74% compared with SBR and by 21.80–23.33% compared with IR; intercropped *soybean* increased grain accumulation by 12.66–13.56% relative to monocropped *soybean*. At the R8 growth stage, the dry matter content of *soybean* grain accounted for more than 80% of the total plant dry matter in intercropping systems, whereas this proportion was less than 70% in monocropping systems. The detailed data are provided in the online Supplementary Materials. Compared with intercropping, monocropped *soybean* exhibited lower leaf dry matter accumulation and a shorter leaf retention period. These characteristics led to insufficient plant "source" capacity and smaller "sink" size in monocropping, forming a "small source-small sink" relationship.

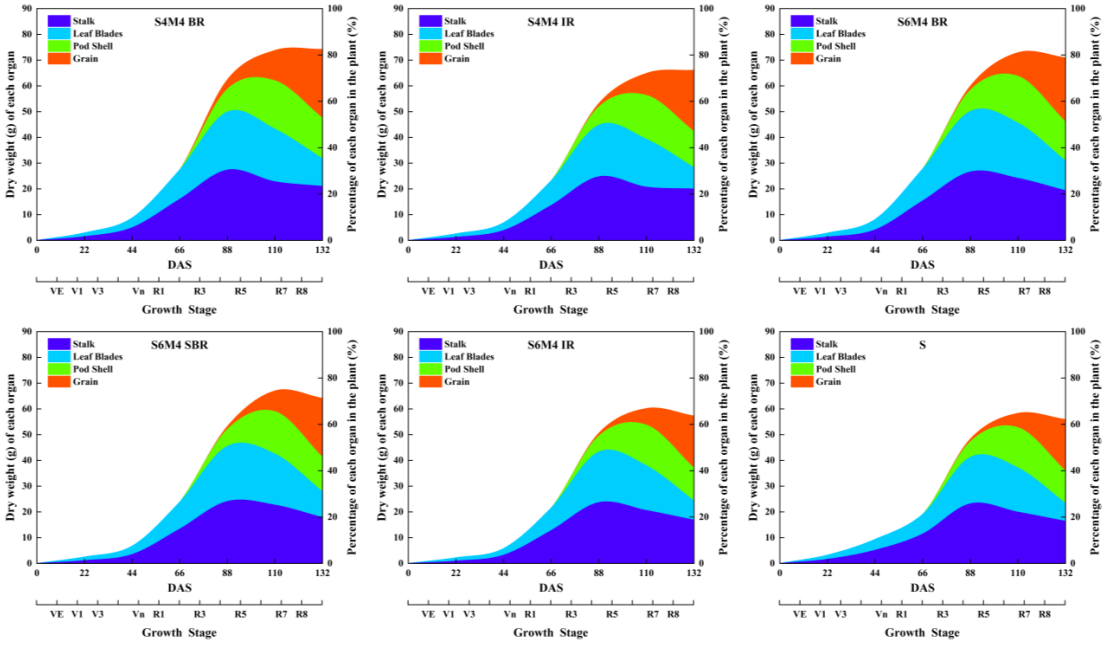


Figure 9. Dynamic of dry matter accumulation in *soybeans* under different intercropping modes in 2024.

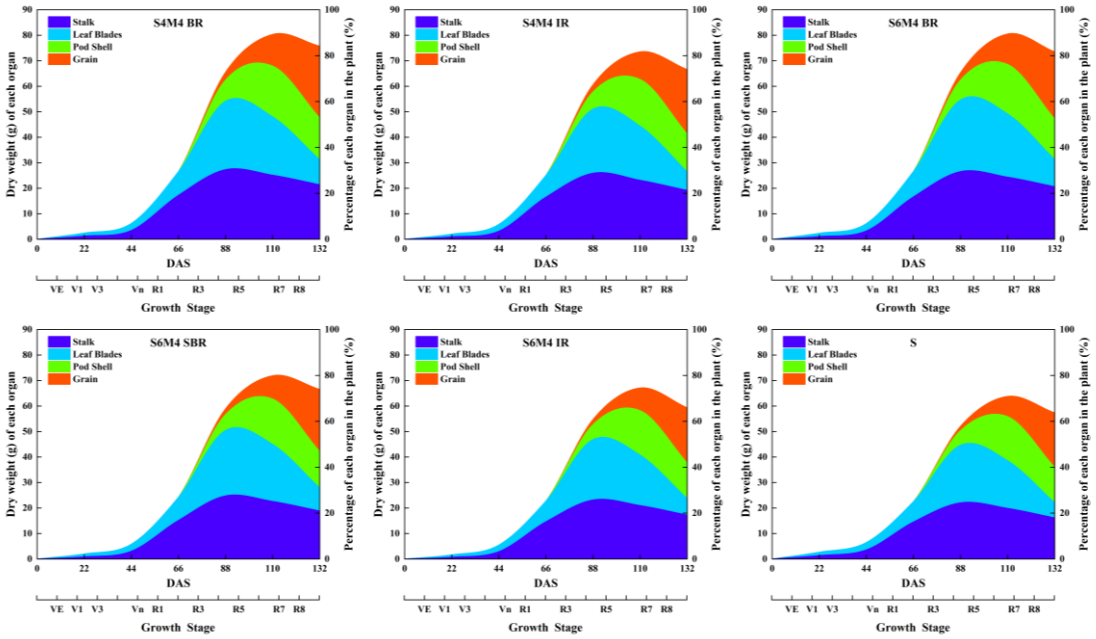


Figure 10. Dynamic of dry matter accumulation in *soybeans* under different intercropping modes in 2025.

3.4. Yields and Yield Advantages of Maize–Soybean Intercropping Composite Population

The yield of *maize–soybean* intercropping systems is jointly determined by the individual productivity of *maize* and *soybean* as well as their population density. The synergistic and competitive interactions between these two factors directly affect the final yield. Analysis of Table 2 shows that over two consecutive years of field trials, the S4M4 *maize–soybean* intercropping system achieved an average total yield of 12,437.07 kg·hm^{-2}, which was a 33.42% increase compared with the weighted average yield of 9322.02 kg·hm^{-2} in monocropping systems. The LER of this intercropping system was 1.27. Under the S6M4 *maize–soybean* intercropping system, the average total yield reached 10,016.12 kg·hm^{-2}, which was a 22.13% increase compared with the weighted average yield of 8201.00 kg·hm^{-2} in monocropping systems, and the LER was 1.16. The S4M4 intercropping system outperformed the S6M4 system in terms of total yield, LER, and yield increment relative to monocropping. Compared with monocropped *maize* or *soybean* at equivalent yields, *maize–soybean* intercropping systems conserved 12.54–32.25% of land resources. The IA values of the S4M4 system was 51.67% higher than that of the S6M4 system, and both IA values remained positive. Notably, the IA was significant, with the S4M4 system exhibiting greater benefits. These intercropping systems complement each other in the spatiotemporal utilization of light, temperature, water, and nutrient resources, thereby achieving a synergistic improvement in land productivity.

Table 2. The influence of different planting patterns on the yields and yield advantage indicators of corn and *soybeans*.

Year	Planting Pattern	Maize Yield/kg·hm^{-2}	Soybean Yield/kg·hm^{-2}	Intercropping Advantages	Land Equivalent Ratio
2024	S4M4	10,166.11 ± 177.86 b	1846.35 ± 45.44 b	0.31 ± 0.04	1.21 ± 0.06
	S6M4	7575.58 ± 91.31 c	2161.65 ± 112.02 b	0.21 ± 0.05	1.13 ± 0.08
	M	14,816.25 ± 47.41 a	——	——	——
	S	——	3539.88 ± 277.7 a	——	——

Table 2. *Cont.*

Year	Planting Pattern	Maize Yield/kg·hm^{-2}	Soybean Yield/kg·hm^{-2}	Intercropping Advantages	Land Equivalent Ratio
2025	S4M4	10,647.27 ± 170.14 ab	2214.4 ± 195.14 b	0.4 ± 0.33	1.32 ± 0.25
	S6M4	7780.69 ± 436.31 b	2514.33 ± 225.76 b	0.26 ± 0.22	1.19 ± 0.12
	M	15,037.97 ± 3878.79 a	——	——	——
	S	——	3893.96 ± 454.06 a	——	——

Note: The table contains different lowercase letters indicating the significance of the differences in corn and soybean yields between different planting patterns ($p < 0.05$).

4. Discussion

4.1. Dry Matter Accumulation and Yield of Maize–Soybean Intercropping Composite Population

In *maize–soybean* intercropping systems, the dry matter accumulation of both crops is attributed to the synergistic effects of interspecific competition and complementarity between the two species. Through the synergistic effects of "aboveground light stratification, underground root niche differentiation, and nitrogen mutual supply", interspecific competition is mitigated, thereby enhancing resource utilization efficiency and improving stress resistance. Compared with monocropping, intercropped *maize* exhibits the characteristics of "rapid mid-growth-stage accumulation, increased grain allocation ratio, and prominent BR advantage". The dry matter accumulation in *maize–soybean* inter-cropping is a dynamic process driven by resources including light, temperature, water, and nutrients. Through photosynthesis, the two crops fix carbon sources, which modulates their "resource acquisition efficiency" and "physiological metabolic activity", thereby achieving inter-specific competition and complementary effects. The differences in photosynthetic mechanisms between *maize* (a C4 crop) and *soybean* (a C3 crop) directly determine their resource utilization strategies and dry matter contribution to inter-cropping systems. In *maize–soybean* intercropping systems, the interspecific interactions between adjacent *maize* and *soybean* rows are stronger than those between non-adjacent rows a phenomenon known as the BR effect, which serves as a significant contributor to yield advantages [28,29]. Crop yield is closely associated with dry matter accumulation in plants and dry matter translocation to reproductive organs [30]. A study on *maize*–vegetable intercropping conducted by Gao Yunjie et al. [31] showed that the yield and aboveground dry matter of spring *maize* in BR were significantly higher than those in IR, with increases of 58.7% and 40.8%, respectively, compared with IR. Research by Zhao Deqiang et al. [32] indicates that the growth of *soybeans* in the first row under the 3M6S intercropping treatment (three rows of *maize*, six rows of *soybeans*) was not inhibited by *maize*, and the 3M6S inter-cropping pattern achieved the highest relative biomass and yield. Research by Wang Xiaohui et al. [33] indicates that *maize* yields in the BR of the 4:4 strip intercropping system consistently exceed those in the IR.

In this study, plants in the BR of the *maize–soybean* intercropping system received sufficient light exposure. Both *maize* and *soybean* plants in BR exhibited higher SPAD values and chlorophyll content, which enhanced the efficiency of photosynthetic pigments in capturing and converting light energy. This provided a material basis for dry matter accumulation, as the BR treatment showed significantly higher dry matter accumulation than the IR treatment. Consistent with previous studies, the percentage increase observed in this research was lower than that reported in prior works, which can be attributed to differences in the ecological niches of intercropped crops. Owing to the higher *soybean* row density in the S6M4 intercropping system, both the light intensity and ventilation conditions in IR were close to those in monocropping systems. The dry matter accumulation of soybeans in IR under this treatment exhibited a smaller difference compared with that in monocropping, while still maintaining an advantage. This indicates that a rational row

spacing configuration exerts a significant impact on the dry matter accumulation of *maize* and *soybean*. Compared with monocropping, *maize–soybean* intercropping simultaneously increases the proportion of dry matter allocated to leaves (source) and grain yield (sink), establishing a balanced source-sink relationship that serves as a critical foundation for achieving high yields. The S4M4 row spacing configuration is more rational, as it enhances positive interspecific interactions while alleviating interspecific competition. BR plants exhibited significantly higher dry matter accumulation than IR plants, accompanied by a marked increase in the capture of photosynthetically active radiation (PAR). This, in turn, promoted the synthesis and accumulation of photosynthates, ultimately leading to the formation of a typical "BR advantage".

4.2. SPAD Values and Extinction Coefficient of Maize–Soybean Intercropping Composite Population

SPAD values, an indicator of relative chlorophyll content, are key parameters reflecting crop nitrogen nutrition status and photosynthetic potential. Higher SPAD values are associated with higher chlorophyll content, sufficient nitrogen supply, stronger photosynthetic efficiency, and increased dry matter accumulation. This study indicates that the intercropping of the two crops significantly increased the SPAD values compared with monocropping, which reflects the IA. Additionally, the SPAD values decreased with an increase in the distance between the two crops, indicating a significant BR advantage. Intercropping significantly increased the SPAD values in the MCL and LCL of both *maize* and *soybean*, with the least pronounced increase observed in the UCL. This differential response is primarily attributed to the mitigation of shading on the lower *maize* canopy by intercropped *soybean*, while *maize* improved ventilation within the *soybean* stand. Furthermore, nitrogen fixation by *soybean* root nodules delivered substantial benefits to the MCL and LCL of both crops. Intercropping optimizes the overall chlorophyll content through rational resource allocation, providing a physiological basis for dry matter accumulation and high yields. This result indicates that the crop configuration is well-balanced: *maize* and *soybean* exhibit reduced competition for light, water, and nitrogen, thereby fully exerting the IA and BR advantage.

Light exposure is a critical environmental factor affecting the growth of *soybeans* in intercropping systems. Insufficient light exposure impairs photosynthetic capacity, thereby reducing photosynthate production. This disrupts the source-sink relationship of *soybeans* and restricts their growth [34]. *Maize* has a lower light K value in the upper canopy, which facilitates light transmission to the lower layers. Meanwhile, *soybean* leaves in the lower canopy generally exhibit a more horizontal distribution and a higher K value, enabling them to fully absorb the light energy transmitted to the lower leaves. Additionally, variations in light distribution can induce significant changes in crop traits, thereby affecting the light K value and consequently influencing light use efficiency [35]. When *maize* is planted with a two-row or four-row wide-narrow row spacing configuration with an increased proportion of BR, all rows exhibit greater advantages in light interception compared with other treatments [36]. In this study, the K value of *maize* was significantly lower under the BR treatment than under the IR treatment, higher under the LCL treatment than under the MCL treatment, and lower under intercropping than under monocropping. The reduction in *maize* K value indicates improved canopy light transmission, which not only ensures the photosynthetic efficiency of maize itself but also supplies more light to the *soybeans* in the lower canopy. For short-statured crops in intercropping systems, although the shading effect of tall-statured crops reduces their light interception, their light use efficiency may increase [13]. Wang Zhu et al. [37] found that wide-row planting significantly reduced interspecific competition among crops, alleviated shading stress on *soybeans*, and mitigated resource competition from *maize*. This practice increased biomass and yield in intercrop-

ping systems and particularly helped to minimize yield loss in *soybeans*. Cui et al. [38] found that *soybeans* in the 4:4 strip intercropping pattern (T4:4) exhibited edge effects on photosynthetic rate during the R4 and R6. With an increase in the number of *soybean* rows per unit area, the aboveground biomass and yield of *soybeans* also increase. From the light distribution pattern, it can be observed that the lower canopy of *soybean* plants is in a shaded environment. Although shading intensity decreases with an increasing number of rows, the light conditions in the lower canopy remain unchanged, while ventilation may deteriorate [39]. *Soybean* light use efficiency (LUE) is improved; however, this enhancement fails to compensate for the reductions in leaf area and total light interception, ultimately leading to a decrease in *soybean* yield [15]. In this study, the K value of *soybeans* showed significantly intercropping < monocropping, BR < IR, MCL < LCL. The K value of *soybeans* decreased as the distance from *maize* increased. Although the K value of *soybeans* in BR showed a relative increase, this phenomenon actually reflected an optimized photosynthetic structure and efficient light energy utilization under sufficient sunlight conditions, which in turn conferred robust light interception capacity. This ultimately formed a high-yielding canopy type characterized by strong light-harvesting capability. Based on the performance of various indicators, the adoption of ridge cultivation in intercropping systems effectively improves the resource use efficiency of *soybeans* in BR. This practice alleviates the suppressive effect of *maize* on *soybean* BR, thereby increasing the dry matter accumulation and yield of *soybeans*. Compared with monocropping, intercropping regulates the canopy structure to maintain higher SPAD values and more optimal K values in crops. This practice reduces light competition, enhances the accumulation of photosynthates, and thereby highlights the BR advantage and high-yield potential of intercropping systems. Given the significant variations in *maize–soybean* intercropping practices across different ecological zones in China [7], further refinement of the study locations and experimental duration is required to ensure applicability across a wider range of regions.

5. Conclusions

This study analyzed the edge-row effect on crop dry matter accumulation and light extinction coefficients under different row spacing configurations in *maize–soybean* intercropping systems. The results showed that with an increase in the interspecific distance between the two crops, the dry matter accumulation of both *maize* and *soybean* decreased, the K values of *maize* increased, those of *soybean* decreased, and the edge-row advantage became prominent. Under intercropping systems, both *maize* and *soybean* exhibited increased dry matter accumulation, reduced K values, LER > 1, and IA > 0. These beneficial effects were consistently verified across the treatments, with the S4M4 configuration outperforming the S6M4 configuration. The synergistic regulation of row spacing configuration and agronomic practices can fully exploit the BR advantage, alleviate interspecific competition, and enhance the overall productivity of the intercropping system. Following the verification of the crop rotation configuration, this planting technology should be promoted in line with local soil and climatic conditions. Future research could explore the molecular mechanisms underlying crop–crop interactions, analyze the long-term ecological effects of this planting model, advance smart agriculture, and further enhance the sustainable development of the agricultural sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture16030371/s1.

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