

Postprint: Dry Matter Accumulation Models and Characteristic Analysis of Different Soybean Varieties After Light Restoration in Strip Intercropping

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Abstract

To investigate the dry matter accumulation characteristics of high-yield type soybeans after re-illumination under intercropping, this study used 14 soybean varieties with high, medium, and low yield levels as materials to compare the differences in dry matter accumulation characteristics after re-illumination among different soybean yield types intercropped with maize. The results showed that: 1) The dry matter accumulation of high-yield type soybeans after re-illumination was $32.99 \text{ g} \cdot \text{plant}^{-1}$, which was 26.82% and 91.51% higher than that of medium- and low-yield types, respectively (two-year average). 2) The dry matter accumulation rate of different yield types of soybeans after re-illumination all exhibited a trend of initially increasing and subsequently decreasing; the maximum and average dry matter accumulation rates after re-illumination followed the order of high-yield type > medium-yield type > low-yield type; the time to reach maximum dry weight accumulation rate for high-yield type soybeans was approximately 41-42 days after re-illumination, whereas for medium- and low-yield types it was 33-37 days after re-illumination; the duration days, accumulation rate, and dry matter accumulation amount during the gradual increase phase, as well as the accumulation rates and amounts during the rapid and slow increase phases of high-yield type soybeans after re-illumination were all significantly higher than those of medium- and low-yield types. 3) Yield was significantly positively correlated with maximum dry matter accumulation rate, time to maximum dry matter accumulation rate, average dry matter accumulation rate, duration and dry matter increment of the gradual increase phase, average accumulation rate and dry matter increment of the rapid increase phase, and average accumulation rate and dry matter increment of the slow increase phase. This study indicates that the stronger dry matter accumulation advantage of

high-yield type soybeans after re-illumination under intercropping was mainly manifested in the gradual increase phase after re-illumination, and the stronger dry matter accumulation capacity during this phase was primarily attributable to its longer duration days.

Full Text

Preamble

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Dynamic Model and Characteristics Analysis of Dry Matter Production After Light Recovery of Different Soybean Varieties in Relay Strip Intercropping Systems*

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Abstract:

Maize-soybean relay strip intercropping is a widespread practice in soybean production areas in southwestern and southern China and has been the main mode of increasing total output of soybean in China. To provide a theoretical basis for the selection and breeding of high-yield soybean varieties for intercropping, this study used fourteen soybean varieties with different yield levels to analyze the characteristics of dry matter production after light recovery (after maize harvest) of different yield types of soybean varieties relay strip intercropped with maize. Results indicated that the average grain yield of high-yield soybean varieties was $1,408.17 \text{ kg} \cdot \text{hm}^{-2}$, which was 37.45% and 57.25% higher than those of medium and low-yield varieties, respectively. Dry matter accumulation of high-yield soybean varieties averaged $32.99 \text{ g} \cdot \text{plant}^{-1}$, which was 26.82% and 91.51% higher than those of medium and low-yield varieties, respectively. The Logistic equation was used to simulate the relationship between dry matter weight and days after light recovery for three types of soybean varieties ($R^2 = 0.960$). Paired t-test for independent samples showed no significant difference between the simulated and measured values. After light recovery, the rate of dry matter accumulation of three types of soybean varieties increased before declining. The order of maximum rate of dry matter accumulation and the mean rate of dry matter accumulation was high-yield type > medium-yield type > low-yield

type. The average time to maximum rate of dry matter accumulation after light recovery of the high-yield soybean varieties was 41–42 days, while that of both medium and low types was 33–37 days. The duration, accumulation rate, and accumulation amount of dry matter of the gradual increase stage; the accumulation rate and amount of dry matter accumulation of both fast increase and slow increase stages of high-yield soybean were significantly higher than those of the other two yield types of soybean. The yield had a significantly positive correlation with the maximum dry matter accumulation rate, time reaching the maximum dry matter accumulation rate, mean dry matter accumulation rate, duration of gradual increase stage, dry matter weight of gradual increase stage, dry matter accumulation rate and weight of both fast and slow increase stages. Two years of data indicated that leaf area index, light interception rate, population growth rate, and leaf area duration of high-yield soybean were $2.52 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $0.81 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $6.02 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, and $317.84 \text{ m}^2 \cdot \text{d} \cdot \text{m}^2$, respectively, which were significantly higher than those of both medium and low-yield types. Our results suggested that greater dry matter accumulation mainly occurred at the gradual increase stage after light recovery for high-yield soybean varieties, which was mainly attributed to the longer duration of the stage.

Keywords: Relay strip intercropping; Soybean; Yield level; Variety; Light recovery; Dry matter production

Introduction

Soybean (*Glycine max*) originated in China and has been cultivated for over five thousand years. Due to its excellent nutritional value, soybean is widely used in food, medicine, feed, and industrial raw materials, with demand increasing annually. However, affected by declining comparative benefits and import impacts, soybean production in China has decreased, and the supply-demand gap has expanded. In 2015, imports reached 81.69 million tons, a year-on-year increase of 14.4%. Intercropping soybean can not only fully utilize light, heat, and water resources but also increase the multiple cropping index, representing one of the main approaches to increase total soybean output and alleviate the supply-demand contradiction in China. Among these systems, the maize (*Zea mays*)-soybean relay strip intercropping pattern is an important representative model in southwestern and southern China.

In the maize-soybean relay strip intercropping system, soybean experiences two distinct growth stages: the co-growth period with maize and the solitary growth period after maize harvest. During the co-growth period, the lower-position soybean is shaded by the higher-position maize, and the shading signal significantly affects soybean morphology and physiology. Studies have found that under shaded environments, soybean exhibits smaller and thinner leaves, significantly increased stem length, and decreased stem diameter, photosynthetic rate, and aboveground biomass. With increasing shading degree, chlorophyll content

and chlorophyll a/b ratio in soybean seedling leaves decrease, photosynthetic accumulation reduces, and lodging becomes severe. Strong shade-tolerant varieties can maintain higher photosynthetic capacity and lodging resistance under moderate shading. During the solitary growth period after maize harvest, soybean obtains compensatory growth. Research has shown that in intercropping systems, after the harvest of the preceding crop, the growth of the succeeding crop recovers and compensates, with final yield reaching or exceeding that of corresponding monoculture. This indicates that in intercropping systems, later compensatory growth can compensate for earlier negative effects, mainly manifested as greater dry matter accumulation. Many scholars often use crop growth simulation equations to explain the relationship between dry matter accumulation and yield, but in intercropping systems, research has focused on analyzing interspecific interactions and nutrient accumulation, while studies describing crop compensatory growth are rarely reported. Therefore, this study used soybean varieties with different yield levels as materials to establish a dry matter accumulation model, analyze the dynamics of dry matter accumulation and light interception characteristics after light recovery in maize-soybean relay strip intercropping, clarify growth differences among soybean varieties with different yield levels after shading removal and light recovery, and provide a theoretical basis for screening suitable soybean varieties for intercropping.

1.1 Experimental Materials

The experiment selected 14 soybean varieties (lines) with different yield levels collected by our research group as experimental materials. High-yield varieties: ‘Nandou 021-1’ , ‘Texuan 13’ , ‘Nandou 12’ , and ‘Gongxuan 1’ , with an average yield of $1,408.17 \text{ kg} \cdot \text{hm}^{-2}$; medium-yield varieties: ‘Xiaohuangdou’ , ‘Caidou’ , ‘Guixia 3’ , ‘Dayuandou’ , and ‘Luoquanhuang’ , with an average yield of $880.7 \text{ kg} \cdot \text{hm}^{-2}$; low-yield varieties: ‘Qianshanwudou’ , ‘Nan 256-1’ , ‘Dahuangzhu’ , ‘Guang 15’ , and ‘Gongqiudou 04-2’ , with an average yield of $601.93 \text{ kg} \cdot \text{hm}^{-2}$.

1.2 Experimental Design

The experiment was conducted from 2013 to 2015 at the teaching and research farm of Sichuan Agricultural University in Ya’ an. The experimental soil contained total nitrogen $2.79 \text{ g} \cdot \text{kg}^{-1}$, total phosphorus $0.383 \text{ g} \cdot \text{kg}^{-1}$, total potassium $12.89 \text{ g} \cdot \text{kg}^{-1}$, available nitrogen $168.6 \text{ mg} \cdot \text{kg}^{-1}$, available phosphorus $81.3 \text{ mg} \cdot \text{kg}^{-1}$, available potassium $140.1 \text{ mg} \cdot \text{kg}^{-1}$, and organic matter $33.2 \text{ g} \cdot \text{kg}^{-1}$. A single-factor randomized block design was adopted using a maize-soybean (2:2) relay strip intercropping pattern (RSI) with 14 soybean varieties. The experiment had three replications, with a plot area of 12 m^2 ($2 \text{ m} \times 6 \text{ m}$). The maize variety in the relay strip intercropping treatment was ‘Zhenghong 505’ , which was seeded on March 28 and transplanted on April 9. During transplanting, two rows of maize formed one strip, with a row spacing of 0.5 m , hole spacing of 0.4 m , and two plants per hole. Each maize strip was spaced 1.5 m apart, with

a maize density of 50,000 plants · hm². Maize was harvested on August 9. On June 20, two rows of soybean were sown within the wide maize rows, with a row spacing of 0.5 m, hole spacing of 0.2 m, and two plants per hole, resulting in a density of 99,000 plants · hm². The fertilizer application rate for relay strip intercropping maize was pure nitrogen 240 kg · hm², P O 70 kg · hm², and K O 90 kg · hm², with nitrogen applied as base fertilizer; jointing fertilizer: ear fertilizer at a ratio of 2:3:5, and phosphorus and potassium applied as base fertilizer. Soybean received no fertilizer throughout the growth period, and normal field management for weeds, pests, and diseases was implemented.

1.3 Measurement Items and Methods

Sampling was conducted on the day of maize harvest and at 15, 30, 45, and 60 days after harvest. Before each sampling, PAR distribution was measured on sunny days between 11:00–13:00. Using a LI-1400 quantum sensor (Li-Cor, USA), natural light intensity (I) was measured 30 cm above the soybean canopy (with the probe facing horizontally upward) and light intensity (I) reaching the canopy bottom was measured to calculate light interception rate.

For each sampling, five plants with consistent growth were selected from each plot. After root removal, individual plants were separated into leaves, petioles, and stems. Leaves were scanned to obtain individual leaf area for calculating leaf area index. All parts were placed in paper bags, oven-dried at 105°C for 30 minutes, then at 75°C to constant weight, weighed, and used to calculate individual plant aboveground dry matter. At soybean maturity, continuous plants were selected from each plot.

1.4 Modeling and Validation

The Logistic equation was applied to fit the dry matter accumulation process after light recovery and calculate corresponding characteristic parameters for growth analysis. Regression analysis and paired t-tests were used for model validation; better consistency between simulated and observed values indicated more accurate simulation results. Modeling data were from 2013–2014, and model validation data were from 2015. The Logistic equation is:

$$W = \frac{A}{1 + Be^{-Ct}}$$

Where: t is days after light recovery (light recovery day is designated as $t = 0$); W is dry matter after light recovery (dry matter on light recovery day is W); A is theoretical maximum dry matter; B and C are shape parameters derived from first and second derivatives of the equation. Specific formulas are as follows:

Dry matter peak start date (t):

$$t_1 = \frac{\ln B - 1.317}{C}$$

Corresponding dry matter W at this time:

$$W_1 = \frac{A}{1 + e^{1.317}}$$

Dry matter peak end date (t):

$$t_2 = \frac{\ln B + 1.317}{C}$$

Corresponding dry matter W at this time:

$$W_2 = \frac{A}{1 + e^{-1.317}}$$

When dry matter after light recovery reaches 99% of A , it is considered the effective accumulation period, with calculation formula t :

$$t_3 = \frac{\ln B + 4.595}{C}$$

Corresponding dry matter at this time is W . Duration of gradual increase stage (T) is:

$$T_1 = t_1 - t_0$$

Dry matter increment during gradual increase stage (w) is:

$$w_1 = W_1 - W_0$$

Average accumulation rate during gradual increase stage (v) is:

$$v_1 = \frac{w_1}{T_1}$$

Duration of fast increase stage (T) is:

$$T_2 = t_2 - t_1$$

Dry matter increment during fast increase stage (w) is:

$$w_2 = W_2 - W_1$$

Average accumulation rate during fast increase stage (v) is:

$$v_2 = \frac{w_2}{T_2}$$

Duration of slow increase stage (T) is:

$$T_3 = t_3 - t_2$$

Dry matter increment during slow increase stage (w) is:

$$w_3 = W_3 - W_2$$

Average accumulation rate during slow increase stage (v) is:

$$v_3 = \frac{w_3}{T_3}$$

Time of maximum dry matter accumulation rate (T_{max}) is:

$$T_{max} = \frac{\ln B}{C}$$

Dry matter amount at maximum accumulation rate (W_{max}) is:

$$W_{max} = \frac{A}{2}$$

Maximum dry matter accumulation rate (R_{max}) is:

$$R_{max} = \frac{AC}{4}$$

Mean dry matter accumulation rate (v_{mean}) is:

$$v_{mean} = \frac{W_3}{t_3}$$

Population growth rate and leaf area duration calculation formulas are:

$$\text{Population growth rate (g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}) = \frac{W_2 - W_1}{t_2 - t_1}$$

$$\text{Leaf area duration (} \times 10^4 \text{ m}^2 \cdot \text{d} \cdot \text{hm}^{-2}) = 0.5 \times (L_1 + L_2) \times (t_2 - t_1)$$

Where: W and W are dry matter weights ($\text{t} \cdot \text{hm}^2$) measured at two consecutive times, t and t are the two consecutive measurement times (d), and L and L are leaf areas ($\text{m}^2 \cdot \text{hm}^2$) measured at two consecutive times.

Light interception rate calculation formula is:

$$\text{Light interception rate} = 1 - \frac{I}{I_0}$$

Where: I is light intensity reaching the canopy bottom, and I is light intensity at the canopy top.

1.5 Data Analysis and Processing

Experimental data were processed using SPSS 17.0 and Microsoft Excel 2013 software. Duncan's new multiple range test (SSR) was used for significance testing, Spearman test for correlation analysis, and linear regression analysis and paired t-tests for model validation.

Results

2.1.1 Comparison of Dry Matter Accumulation Amount

Dry matter accumulation after light recovery is a major factor affecting yield. [Figure 1: see original paper] shows that in 2013, dry matter accumulation after light recovery of high-yield soybean was $29.39 \text{ g} \cdot \text{plant}^{-1}$, which was 34.28% and 107.90% higher than medium- and low-yield soybeans, respectively. In 2014, dry matter accumulation after light recovery of high-yield soybean was $36.58 \text{ g} \cdot \text{plant}^{-1}$, which was 19.37% and 75.14% higher than medium- and low-yield soybeans, respectively.

2.1.2 Establishment and Validation of Dry Matter Logistic Model

The Logistic equation was further used to simulate the dry matter accumulation process, with days after light recovery (t) as the independent variable and dry matter (W) as the dependent variable. Two years of data showed that the determination coefficients of equation fitting were all above 0.960, indicating that the Logistic equation could well fit the dry matter accumulation process after light recovery of soybean (Table 1).

Linear regression analysis of simulated and measured values after light recovery for 'Texuan 13' (high-yield), 'Luoquanhuang' (medium-yield), and 'Guang 15' (low-yield) showed (Fig. 2 [Figure 2: see original paper]) that simulation accuracy (expressed as R^2) was 0.975, 0.988, and 0.943, respectively, with correlation coefficients all above 0.971 and extremely significant correlations between simulated and measured values. Paired t-tests between simulated and measured values found P-values of 0.909, 0.886, and 0.900, respectively, all greater than 0.05, indicating no significant difference. This demonstrates that the model can accurately reflect dry matter accumulation characteristics after light recovery of different soybean varieties.

2.1.3 Dry Matter Accumulation Characteristic Parameters

Table 2 shows that in 2013, the maximum dry matter accumulation rate (R_{max}) and mean dry matter accumulation rate (V_{mean}) of high-yield soybean were $0.847 \text{ g} \cdot \text{d}^{-1}$ and $0.462 \text{ g} \cdot \text{d}^{-1}$, respectively, both significantly greater than $0.553 \text{ g} \cdot \text{d}^{-1}$ and $0.331 \text{ g} \cdot \text{d}^{-1}$ of medium-yield soybean and $0.454 \text{ g} \cdot \text{d}^{-1}$ and $0.273 \text{ g} \cdot \text{d}^{-1}$ of low-yield soybean. High-yield soybean reached maximum dry matter accumulation rate at 30 days after light recovery, with maximum dry matter accumulation amount of $18.515 \text{ g} \cdot \text{plant}^{-1}$ at this time. In 2014,

high-yield soybean ‘Texuan 13’ showed significantly greater maximum dry matter accumulation rate (R_{max}), time to maximum rate (T_{max}), dry matter at maximum rate (W_{max}), and mean accumulation rate (V_{mean}) than medium- and low-yield types.

2.1.4 Dry Matter Accumulation Stages

Based on the Logistic curve, the dry matter accumulation process after light recovery was divided into gradual increase, fast increase, and slow increase stages (Table 3). For all three yield types, the duration of each stage followed the pattern: slow increase stage > fast increase stage > gradual increase stage. Dry matter accumulation rate showed a trend of first increasing then decreasing, with performance as: fast increase stage > gradual increase stage > slow increase stage, while dry matter accumulation amount was: fast increase stage > slow increase stage > gradual increase stage. High-yield soybean had the longest gradual increase stage duration, with a two-year average of 13.45 days, and slow increase stage duration of 40.54 days, both significantly higher than low-yield types, but with no significant difference in fast increase stage duration. High-yield type showed the greatest dry matter accumulation rate and amount in all three stages.

2.1.5 Correlation Analysis Between Dry Matter Accumulation Parameters and Yield

Correlation analysis between yield and dry matter accumulation parameters of three soybean types (Table 4) showed that yield was significantly positively correlated with maximum dry matter accumulation rate (R_{max}), time to maximum rate (T_{max}), dry matter at maximum rate (W_{max}), mean accumulation rate (V_{mean}), gradual increase stage duration (T), gradual increase stage increment (w), fast increase stage mean rate (v), fast increase stage increment (w), slow increase stage mean rate (v), and slow increase stage increment (w).

2.2 Population Matter Production at Maturity of Different Yield-Level Soybean Varieties

By calculating population matter production characteristics from light recovery day (0 d) to physiological maturity (45 d) (Table 5), in 2013, leaf area index, light interception rate, population growth rate, and leaf area duration of high-yield soybean were $2.45 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $0.80 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $5.55 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, and $366.77 \text{ m}^2 \cdot \text{d} \cdot \text{m}^2$, respectively, all greater than medium-yield types ($1.50 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $0.67 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $3.37 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $250.34 \text{ m}^2 \cdot \text{d} \cdot \text{m}^2$) and low-yield types ($1.11 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $0.45 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $2.74 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $205.87 \text{ m}^2 \cdot \text{d} \cdot \text{m}^2$). In 2014, high-yield soybean ‘Texuan 13’ showed leaf area index, light interception rate, population growth rate, and leaf area duration of $2.59 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $0.83 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, $6.50 \text{ g} \cdot \text{m}^2 \cdot \text{d}^{-1}$, and $268.92 \text{ m}^2 \cdot \text{d} \cdot \text{m}^2$, respectively, all significantly greater than medium- and low-yield soybean types.

Discussion

3.1 Establishment of Dry Matter Accumulation Model and Characteristic Parameters After Light Recovery of Different Soybean Varieties

Crop growth models can describe crop growth and development characteristics and have been reported for soybean, rice (*Oryza sativa*), maize (*Zea mays*), and other crops. Regarding soybean, Tang et al. analyzed the effects of different tillage methods on dry matter accumulation and distribution patterns of summer soybean based on the Logistic equation. Jiang et al. established soybean dry matter accumulation curves using the Logistic equation to forecast soybean yield. This study showed that dry matter after light recovery of three yield types of soybean was well fitted by the Logistic equation ($R^2 > 0.960$). Based on this, we analyzed dry matter production characteristics of different yield types of soybean varieties.

Previous studies based on crop growth models describing soybean dry matter production characteristics have focused mainly on monoculture soybean during the entire growth period, while research on dry matter production characteristics of intercropped soybean, particularly after light recovery in relay intercropping, is rarely reported. This study showed that dry matter accumulation rate after light recovery showed a trend of first increasing then decreasing, which could be divided into gradual increase, fast increase, and slow increase stages. High-yield soybean had a gradual increase stage duration of 13.45 days on average, significantly higher than medium- and low-yield types, with maximum dry matter accumulation rate occurring at 29 days after light recovery, and showed the greatest dry matter accumulation rate and amount in all three stages. Studies have shown that shading during soybean vegetative growth affects morphological characteristics and reduces biomass accumulation but does not affect grain yield, while shading during reproductive growth significantly reduces yield. Reports also indicate that light enrichment during soybean reproductive growth can increase yield, suggesting that enhanced light during reproductive growth is beneficial for yield improvement. Studies on shading at different growth stages found that shading during emergence to full flowering mainly affected main stem morphology and had little effect on yield formation, and light recovery before full flowering was beneficial for photosynthetic capacity recovery. According to soybean growth stages, high-yield soybean under relay intercropping had longer growth periods and was still in vegetative growth when light recovered, allowing more energy accumulation for reproductive growth, while medium- and low-yield soybean had already entered reproductive growth, and the shaded environment seriously affected yield formation. Correlation analysis also showed that gradual increase stage duration and increment were extremely significantly positively correlated with yield. This indicates that the greater dry matter accumulation after light recovery in high-yield soybean mainly came from its longer gradual increase stage and greater mean growth rate.

3.2 Differences in Population Photosynthetic Matter Production After Light Recovery of Different Soybean Varieties

Increasing matter production capacity during reproductive growth is an effective way to increase soybean yield. Leaf area index, light interception rate, leaf area duration, and population growth rate are important indicators characterizing population photosynthetic production capacity. Studies have shown that high-yield lines have significantly greater aboveground and belowground biomass during reproductive growth than medium- and low-yield lines. Other studies indicate that after light recovery, aboveground dry matter of soybean increases rapidly, with distribution patterns showing “less stem, more leaf,” and high-yield types have significantly greater aboveground dry matter, leaf area, and leaf dry weight proportion than low-yield types. Under our experimental conditions, high-yield soybean yield averaged $1,408.17 \text{ kg} \cdot \text{hm}^{-2}$, which was 37.45% and 57.25% higher than medium- and low-yield types, respectively. After light recovery, leaf area index, light interception rate, population growth rate, and leaf area duration were all significantly greater in high-yield types than in medium- and low-yield types. This indicates that high-yield soybean had larger leaf area, could intercept more light, and thus promoted more dry matter accumulation, laying the foundation for high yield.

High-yield soybean under relay intercropping was still in vegetative growth when light recovered, allowing more energy accumulation for reproductive growth. High-yield soybean showed significantly greater dry matter accumulation, leaf area index, light interception rate, population growth rate, and leaf area duration after light recovery than medium- and low-yield types. Its stronger matter accumulation advantage after light recovery was mainly manifested in the gradual increase stage, and the stronger matter accumulation capacity in this stage was mainly due to its longer duration.

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