Effects of Reduced Nitrogen Application and Soybean Intercropping on Carbon Balance Characteristics in Sugarcane Fields (Postprint)

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Abstract

To investigate the effects of nitrogen fertilizer input and legume crop intercropping on carbon sequestration in sugarcane fields, a two-year (2012–2013) field experiment was conducted using the input-output balance method (i.e., quantitative analysis of carbon input and carbon output during the crop growth period) to explore the characteristics of carbon input and output in sugarcane field ecosystems under two nitrogen application levels [300 kg · hm ^{2} (reduced nitrogen application) and 525 kg · hm ^{2} (conventional nitrogen application)] and four planting patterns (sugarcane monoculture, soybean monoculture, sugarcane||soybean 1:1 row ratio intercropping, and sugarcane||soybean 1:2 row ratio intercropping). The results showed that the carbon input of the sugarcane||soybean 1:2 row ratio intercropping pattern under both nitrogen treatments was significantly higher than that of sugarcane monoculture and sugarcane||soybean 1:1 row ratio intercropping pattern. In 2012, the carbon output of the sugarcane||soybean 1:2 row ratio intercropping pattern under reduced nitrogen treatment was significantly lower than that of sugarcane monoculture and sugarcane||soybean 1:1 row ratio intercropping pattern, while the difference was not significant in 2013; after sugarcane harvest, the soil carbon sequestration of both sugarcane||soybean intercropping patterns under reduced nitrogen treatment was significantly higher than that of sugarcane monoculture. Analysis of carbon budget and balance in the sugarcane||soybean intercropping ecosystem indicated that the net carbon fixation of the sugarcane||soybean 1:2 row ratio intercropping pattern under reduced nitrogen treatment was 2,956.35 kg · hm ^{2} in 2012 and 872.59 kg · hm ^{2} in 2013. The farmland carbon sequestration potential under the reduced nitrogen treatment with sugarcane||soybean 1:2 row ratio intercropping pattern was greater than that of other treatments, and from the perspective of sustainable agricultural development, this pattern possesses certain ecological rationality.

Full Text

Preamble

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Effects of Reduced Nitrogen Application and Sugarcane-Soybean Intercropping on Carbon Balance Characteristics in Sugarcane Fields*

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Abstract

Intercropping has an outstandingly long history in China. Studies have reported several advantages of cereal-legume intercropping systems, including increased yields, land use efficiency, natural resource utilization, and pest and disease control, which have significant potential to contribute to the sustainability of modern agriculture. As a cereal crop, sugarcane is a major economic crop used in sugar production in China. Its wide-row planting space and slow growth rate during the initial growth stage provide the required niche of space and resources for intercropping. However, long-term monocropping of sugarcane along with the overuse of nitrogen fertilizer has induced severe nitrous pollution in the environment and high agricultural production costs in South China. Sugarcane-soybean intercropping can reduce nitrogen application while maintaining high crop yield, thereby reducing the overall cost of farming, enriching soil fertility, and enhancing soil carbon sequestration in the field. However, few studies have investigated carbon balance under sugarcane intercropping and carbon sequestration in sugarcane intercropping fields. The objective of this study was to determine the effects of sugarcane and soybean intercropping under reduced nitrogen fertilizer on soil carbon balance. This study will further strengthen the scientific basis for nutrient uptake and utilization and the relationships among nutrition utilization and environmental factors under intercropping systems. To that end, a field experiment was conducted in 2012-2013 at South China Agricultural University. The study analyzed carbon balance and sequestration in farmlands in sugarcane-soybean intercropping systems with crop line ratios of 1:1, sugarcane-soybean intercropping systems with crop line ratios of 1:2, monocropped sugarcane (MS) under two nitrogen levels (N1, 300 kg · hm ^{2} and N2, 525 kg · hm ^{2}), and monocropped soybean under zero nitrogen supply during the crop growth season. Carbon balance and sequestration in farmland soils were investigated using Input-Output Analysis, where carbon input and output were quantified for the crop growth period to determine the intensity of the carbon sink. The results showed that carbon input under the sugarcane-soybean (1:2) intercropping system was significantly higher than that under monoculture sugarcane and sugarcane-soybean (1:1) intercropping under two nitrogen application levels. Compared with sugarcane-soybean (1:1) intercropping and monoculture sugarcane, carbon output under sugarcane-soybean (1:2) intercropping was significantly decreased with reducing nitrogen application in 2012, although there was no significant difference in 2013. After harvesting sugarcane, soil carbon storage under sugarcane-soybean intercropping systems with reduced nitrogen application was significantly higher than that under monoculture sugarcane. Carbon budget analysis for sugarcane-soybean intercropping systems showed that sugarcane-soybean (1:2) intercropping was a good net carbon sink with high carbon fixation of 2,956.35 kg • hm ^{2} in 2012 and 872.59 kg • hm ^{2} in 2013 under reduced nitrogen application conditions. It was noted that sugarcane-soybean (1:2) intercropping with reduced nitrogen application had better carbon storage potential. In addition, the land equivalent ratio (LER) of sugarcane-soybean intercropping systems exceeded 1.0 in 2012 and 2013, and the LER of the sugarcane-soybean (1:2) intercropping system with reduced nitrogen application was higher than 1.0. In conclusion, the sugarcane-soybean intercropping system (1:2) with reduced nitrogen application is a feasible production mode for the sustainability of modern agriculture.

Keywords: Sugarcane-soybean intercropping; Reduced nitrogen application; Carbon input; Carbon output; Carbon balance; Soil carbon sequestration

Introduction

Climate warming has become a global issue, and the increase in greenhouse gases caused by human activities is the primary driver of climate change. Consequently, reducing carbon emissions has become a common concern among scientists worldwide [1]. Farmland ecosystems possess substantial carbon sequestration potential [2–3], and different irrigation, tillage, and fertilization practices directly affect soil carbon cycling and ecosystem carbon balance, thereby influencing climate change. In agricultural ecosystems, carbon and nitrogen cycles are interdependent and closely linked processes, and nitrogen fertilizer application is intimately related to soil carbon cycling. Shi et al. [4] demonstrated through numerous long-term fertilization experiments that applying organic fertilizer alone, combined NPK chemical fertilizers, or combined organic and inorganic fertilizers can all increase soil organic carbon content. Additionally, Zhang et al. [5] found that fertilization treatments enhanced soil organic carbon levels compared with no-fertilizer treatments, which is beneficial for soil fertility improvement. Thorburn et al. [6] discovered that sugarcane (*Saccharum officinarum*) straw return can increase soil active organic carbon and total carbon content, with similar conclusions reported by Manna et al. [7] and Banger et al. [8].

Soils can act as either carbon sources or carbon sinks during land use changes.

Current research on carbon balance primarily focuses on how fertilization benefits soil carbon balance, yet few studies have examined carbon balance under excessive fertilization conditions, with most related research concentrating on environmental effects. In intercropping systems, the more efficient utilization of space and environmental resources by two crops increases the total amount of carbon fixed by crops compared with monoculture, thereby increasing total carbon input and enabling farmland ecosystems to reach a new carbon balance [9], which enhances farmland carbon sequestration capacity. Oelbermann et al. [10] demonstrated through studies on carbon sequestration potential in agroforestry systems that the carbon sequestration potential of agroforestry ecosystems cannot be ignored, a conclusion also supported by Albrecht et al. [11]. Furthermore, in farmland ecosystems, Zhang et al. [12] found that the rice-duck symbiotic system has greater carbon sequestration potential than conventional systems. However, current domestic and international research on carbon balance in farmland ecosystems primarily focuses on how fertilization promotes increases in soil organic carbon content [4–5] and soil respiration [13–14], with limited research on reasonable nitrogen application under excessive fertilization backgrounds or how crop intercropping affects farmland ecosystem carbon balance—an area that will represent an important future trend in farmland ecosystem carbon cycle research.

Sugarcane is China' s major sugar crop and an important source of income for farmers. Guangdong is one of China' s three major sugarcane production regions, with unique climatic conditions highly favorable for sugarcane industry development [15]. However, sugarcane cultivation in Guangdong lacks scientific guidance, with widespread partial and excessive nitrogen fertilizer application [16]. China has relatively high sugarcane production costs, with fertilizer inputs accounting for over 30% of total costs [17]. Excessive nitrogen application not only fails to increase sugarcane yield [18] but also causes a series of environmental problems [19]. Therefore, exploring scientific cultivation and management measures for sugarcane is particularly important. Sugarcane grows slowly during its early stage, requiring at least 90 days from planting to row closure, during which light, water, and other resources cannot be fully utilized by sugarcane. Previous studies have shown that intercropping enables more effective utilization of environmental resources than monoculture, with further complementary expansion of temporal and spatial niches between the two crops [20]. Research indicates that interspecific nitrogen complementary utilization mechanisms exist in legume-cereal intercropping systems, where cereal crops compete for soil nitrogen, thereby reducing soil nitrogen inhibition of nitrogenase activity and promoting biological nitrogen fixation in legume crops [21–23]. Therefore, intercropping sugarcane with soybean (*Glycine max*) is significant for reducing nitrogen fertilizer application in farmland management. Meanwhile, reasonable fertilizer management can not only improve soil fertility but also promote carbon sequestration in farmland ecosystems [24] and enhance carbon sink intensity [25]. The effects of reduced nitrogen application and soybean intercropping on farmland ecosystems have received increasing attention from scientists [26–

27], but few reports have documented studies on carbon budget and balance in sugarcane field ecosystems under reduced nitrogen application and soybean intercropping in China’ s sugarcane planting regions.

Investigating the carbon cycling balance status under different sugarcane planting systems and clarifying the carbon source-sink issues in sugarcane field ecosystems under typical planting systems are important for scientific fertilization and promoting sustainable and healthy agricultural development in South China. This study examined the effects of reduced nitrogen application and intercropping with soybean on carbon balance and cycling characteristics in sugarcane fields through field positioning experiments, aiming to provide scientific references for nitrogen optimization management in sugarcane planting in South China.

Materials and Methods

1.1 Study Area

The long-term positioning experiment on sugarcane-soybean intercropping and reduced nitrogen application began in 2009 and was conducted at the university farm of South China Agricultural University in Guangzhou (23°08 N, 113°15 E). The farm is located in a subtropical region with a typical subtropical monsoon oceanic climate, abundant light and heat resources, annual sunshine hours of 1,289–1,780 h, total solar radiation of 105.3 kJ · cm ^{2}, mean annual temperature of 21.9–22.8°C, and mean annual rainfall of 1,348–2,278 mm. Approximately 85% of precipitation occurs from April to August. Before the long-term experiment began in 2009, the test soil was determined to be lateritic red soil, with topsoil organic matter content of 14.81 g · kg ^{1}, alkaline hydrolyzable nitrogen of 41.30 mg · kg ^{1}, available phosphorus of 85.03 mg · kg ^{1}, and available potassium of 169.38 mg · kg ^{1}.

1.2 Experimental Materials and Design

1.2.1 Experimental Materials

The sugarcane variety used was ‘Yuetang 00-236’ , characterized by extremely early maturity, high sugar content, high yield, fast and uniform germination, high germination rate, strong tillering ability, and high stalk formation rate. The soybean variety used was ‘Maodou 3’ , an early-maturing variety with a growth period of approximately 100 days.

1.2.2 Experimental Design

The experiment employed a two-factor design with nitrogen application level and planting pattern. Based on local farmers’ conventional nitrogen application rates, two nitrogen levels were established: conventional nitrogen application at 525 kg · hm ^{2} and reduced nitrogen application at 300 kg · hm ^{2}. Four planting patterns included three sugarcane planting patterns (sugarcane monoculture, sugarcane||soybean 1:1 row ratio intercropping, and sugarcane||soybean 1:2 row ratio intercropping) and one unfertilized soybean monoculture control, totaling seven treatments . The experiment used a randomized block design with three replications, with each replication constituting one plot. Each plot measured 5.5 m in length and 4.8 m in width (26.4 m^2). Sugarcane row spacing was 120 cm, with four rows planted per plot, each containing 38 double-bud segments. Soybean row spacing was 30 cm, with plant spacing of 20 cm; soybean monoculture consisted of 16 rows with 25 holes per row, with two plants per hole during the seedling stage.

In the sugarcane||soybean 1:1 and 1:2 intercropping patterns, sugarcane was planted in four rows, with soybeans planted in four and eight rows, respectively [Figure 1: see original paper].

The 2012 field experiment sowed sugarcane on February 25, planted soybeans on March 10, harvested soybeans on June 3, and harvested sugarcane on December 16. Basal fertilizer was applied on February 24, consisting of potassium chloride (150 kg · hm ^{2}), calcium superphosphate (1,050 kg · hm ^{2}), and compound fertilizer (N-P-K=15-15-15, 750 kg · hm ^{2}). Tillering fertilizer was applied on May 3, with potassium chloride (300 kg · hm ^{2}) and urea (225 kg · hm ^{2} for conventional nitrogen treatment, 113 kg · hm ^{2} for reduced nitrogen treatment). Stem elongation fertilizer was applied on June 27, with urea (672 kg · hm ^{2} for conventional nitrogen treatment, 295 kg · hm ^{2} for reduced nitrogen treatment). The 2013 experiment sowed sugarcane on March 9, planted soybeans on March 16, harvested soybeans on June 3, and harvested sugarcane on December 8. Basal fertilizer was applied on March 8, tillering fertilizer on May 5, and stem elongation fertilizer on June 30. Except for different sowing and fertilization dates, other field management practices and fertilizer amounts remained the same as in 2012.

The experimental design was identical to that of Zhang et al. [19]. Sugarcane-soybean intercropping adopted a ridge-furrow pattern, with soybeans planted on ridges (90 cm wide) and sugarcane planted in furrows (30 cm wide). Basal fertilizer was applied in the sugarcane furrows and covered with 5 cm of soil; subsequent topdressing was also applied in the sugarcane furrows before hilling. Soybeans received no fertilizer throughout their growth period. After soybean harvest, leaves and stems were returned to the sugarcane rows and covered with soil, with ridges eventually becoming furrows to facilitate drainage. Other field management practices were consistent with local sugarcane cultivation.

1.3 Sample Collection and Analysis Methods

1.3.1 Crop Carbon Content Determination

On June 3, 2012, five soybean plants were randomly selected from each plot. Soybean stems, leaves, pods, and roots were separated, killed at 105°C for 30 minutes, dried at 80°C for 48 hours to constant weight, and total carbon content was determined [29]. Carbon content in soybean stems, leaves, and roots was included in the straw return portion of carbon input, while pod carbon content was included in the soybean harvest portion of carbon output. On December 16, three representative sugarcane plants were continuously selected from each plot. After sampling, plants were killed at 105°C for 30 minutes, dried at 80°C for 60 hours to constant weight, and total carbon content was determined [29]. The same methods were used in 2013.

1.3.2 Litter Carbon Input Determination

Sugarcane leaves were stripped on September 2, 2012. Leaves from three plants per plot were collected, dried, ground, and total carbon content was determined [29], included as litter input. In 2013, leaves were stripped on September 18, with the same procedures as in 2012.

1.3.3 Soil Carbon Pool Determination

On February 24, 2012 (pre-experiment) and December 17, 2012 (post-experiment), soil samples were taken from the sugarcane-soybean intercropping zone 20 cm from sugarcane plants. Sampling depth was 0–30 cm from the surface, with three points mixed per zone. Fresh soil was air-dried, ground, and sieved for total carbon content determination [29]. In 2013, sampling occurred on March 8 (pre-experiment) and December 9 (post-experiment).

1.3.4 Chemical Fertilizer Carbon Calculation

Chemical fertilizer carbon content was estimated using the "total carbon" analysis method of West et al. [30]: Chemical fertilizer carbon content = fertilizer application rate × 0.8956. Carbon input from fertilizers for each treatment is shown in .

1.3.5 Seed Carbon Calculation

According to planting requirements, each plot required 16 sugarcane seed pieces (6,000 pieces per hectare). Based on an average carbon content of 443.30 g per harvested sugarcane plant, sugarcane seed carbon was 2,659.80 kg per hectare. In sugarcane-soybean intercropping mode, 3.03×10 soybean seeds were required per hectare, while soybean monoculture required 6.06×10 seeds. Ten soybean seeds were dried and ground to determine carbon content at 477.89 g · kg ^{1}. Carbon in soybean seeds was 651.67 kg · hm ^{2} for sugarcane||soybean 1:1 intercropping, 1,303.34 kg · hm ^{2} for 1:2 intercropping, and 2,606.67 kg · hm ^{2} for soybean monoculture.

1.3.6 Gas Collection and Analysis

Starting from sugarcane planting, greenhouse gas emissions were measured every 14 days (adjusted for rainy weather) using the static chamber-gas chromatography method. Two sampling points were established at the base of sugarcane and soybean plants in each plot, with three plots per treatment and two sampling points per plot. Field static chambers followed the method of Dyer [31], using circular PVC tubes (diameter 11 cm, length 25 cm) inserted 10 cm into the soil. The chamber top was covered with a PVC cap (diameter 11 cm) with a 2 cm sampling hole sealed with a rubber stopper. A 10 cm long, 6 mm diameter ventilation tube was installed beside the sampling hole to balance air pressure inside and outside the chamber. On clear days between 9:00–11:00 AM, three gas samples were collected at t=0, t=15 min, and t=30 min. A 50 mL syringe was inserted into the sampling port, and the piston was moved back and forth three times to mix the gas before collection. Collected gas samples were immediately placed in sealed bags, transported to the laboratory, and analyzed using a TRACE GC 2000 gas chromatograph (Italy). The CO detector was an ECD at 300°C; the CH detector was an FID at 300°C; oven temperature was 80°C; carrier gas was high-purity N . Greenhouse gas emission flux was calculated following the method of Wan et al. [32], with cumulative emissions weighted across the growth period. The calculation formula was:

$$F = \frac{V \times M_0}{A} \times \frac{C_2 - C_1}{t_2 - t_1} \times \frac{273.15}{T}$$

Where:
F = gas emission flux (mg · m ^{2} · h ^{1}), positive for emission and negative for absorption
A = chamber base area (m^2)
V = chamber volume (m^3)
M = molecular mass of the measured gas
m , m = gas mass in the chamber at closing and opening (mg)
t , t = start and end times of measurement
C , C = gas volume concentrations at closing and opening
T , T = temperatures in the chamber at closing and opening (K)

1.3.7 Land Equivalent Ratio

Land Equivalent Ratio (LER) is commonly used to measure intercropping advantages, calculated as:

$$\text{LER} = \frac{Y_{is}}{Y_{ss}} + \frac{Y_{ib}}{Y_{sb}}$$

Where Y and Y_b are yields of intercropped sugarcane and soybean (t · hm ^{2}), and Y and Y_b are yields of monocropped sugarcane and soybean (t · hm ^{2}). LER > 1.0 indicates intercropping advantage, while LER < 1.0 indicates disadvantage [33].

1.4 Data Processing and Statistical Methods

The long-term positioning experiment began in 2009, while the carbon balance experiment began in 2012. Therefore, LER data from 2009-2013 were used, while other data were from 2012 and 2013. Microsoft Excel 2003 was used for tables, and SPSS 13.0 for statistical analysis. Duncan' s new multiple range test was used for multiple comparisons among treatments. Data in tables and figures are presented as mean ± standard error.

Results

2.1 Land Equivalent Ratio of Different Cropping Systems

The land equivalent ratios (based on crop yield) of sugarcane-soybean intercropping systems from 2009–2013 are shown in [Figure 2: see original paper]. During 2009–2013, LER values for all intercropping patterns ranged from 1.10 to 1.84, all exceeding 1.0, indicating that sugarcane-soybean intercropping improves land use efficiency per unit area and provides certain yield advantages. Under N1 (reduced nitrogen) level, the LER of SB2 (sugarcane||soybean 1:2 intercropping) was significantly higher than SB1 (sugarcane||soybean 1:1 intercropping) annually from 2009–2013. Under N2 (conventional nitrogen) level, SB2 LER was significantly higher than SB1 only in 2013. Overall, five-year data indicated that SB2-N1 treatment had the highest LER values among all planting patterns without significant interannual variation, showing the most obvious and stable intercropping advantage. This demonstrates that reduced nitrogen application under sugarcane||soybean 1:2 intercropping provides yield advantages in farmland ecosystems. From cost-saving and sugarcane yield maintenance perspectives, sugarcane||soybean 1:2 intercropping under reduced nitrogen application is feasible.

2.2 Changes in Farmland Soil Carbon Pool Under Different Cropping Systems

As shown in , in 2012, soil carbon sequestration in sugarcane-soybean intercropping systems was higher than in sugarcane monoculture, and in 2013, it was higher than monoculture except for SB2-N2. Two-year results showed that soil carbon sequestration under SB1-N1 and SB2-N1 treatments was significantly higher than under sugarcane monoculture. However, due to soybean symbiotic nitrogen fixation, MB treatment soil carbon sequestration was significantly higher than all other treatments. In 2013, soil carbon sequestration under MS-N1, MS-N2, SB1-N2, and SB2-N2 treatments was negative, indicating that farmland soil carbon pools became carbon sources after sugarcane harvest.

2.3 Total CO and CH Emissions from Farmland Soil Under Different Cropping Systems

Seasonal emissions of CO and CH from sugarcane-soybean intercropping farmland soil are shown in . In 2012 under N1 level, SB2 pattern had significantly lower cumulative CO emissions than SB1 and MS patterns, while in 2013, SB2 showed a similar trend but without significant differences. Under N2 level in 2012, no significant differences in cumulative CO emissions were observed among treatments. Two-way ANOVA indicated that the interaction between intercropping pattern and nitrogen level had extremely significant effects on cumulative CO emissions, while different intercropping patterns had significant effects. In 2013 under N2 level, SB1 pattern had significantly lower cumulative CO emissions than SB2 pattern, but nitrogen level and intercropping pattern had no significant effects. All treatments showed negative cumulative CH emissions, indicating that sugarcane-soybean intercropping farmland soil is a weak CH absorption sink, with no significant effects from intercropping pattern or nitrogen level.

2.4 Carbon Cycling in Sugarcane Fields Under Different Cropping Systems

As shown in , carbon input, output, and return varied among sugarcane-soybean intercropping, sugarcane monoculture, and soybean monoculture systems. System carbon input primarily consisted of chemical fertilizers, sugarcane seeds, soybean seeds, and litter. In 2012 under N1 level, SB2 pattern had significantly higher carbon input than SB1 pattern and sugarcane monoculture, increasing by 11.25% and 25.11%, respectively. The same pattern was observed in 2013, with increases of 11.68% and 21.74%, respectively. Additionally, under N2 level, SB2 pattern had significantly higher carbon input than sugarcane monoculture in both years. All intercropping patterns had significantly higher carbon input than soybean monoculture, primarily because soybean seeds were the main carbon source in soybean monoculture. System carbon output mainly consisted of carbon removed by soybean pod harvest, sugarcane harvest, and soil greenhouse gas CO emissions. All treatments showed negative cumulative CH emissions, indicating that dryland farmland absorbs CH . In 2012, SB2-N1 treatment had carbon output of 4,859.46 kg · hm ^{2}, which was 28.87% and 41.5% lower than MS-N1 and SB1-N1 treatments, respectively. In 2013 under reduced nitrogen application, no significant differences in carbon output were observed among treatments, but SB2-N2 treatment had significantly higher carbon output than SB1-N2 and MS-N2 treatments, increasing by 36.23% and 43.59%, respectively. Carbon returned to the system consisted of soybean stems, leaves, and roots after harvest. Due to different soybean row numbers in different intercropping patterns, MB treatment had significantly higher carbon return than all intercropping patterns, with no significant differences among intercropping patterns.

2.5 Carbon Budget and Balance in Farmland Soil Under Different Cropping Systems

The carbon budget and balance of sugarcane field ecosystems include inputs from chemical fertilizers and seeds, soil carbon sequestration, soybean harvest returns, CH and CO emissions, and carbon removed by crop harvest. Total input includes input, soil carbon sequestration, and return, while total output includes CH and CO emissions and carbon removed by crop harvest. As shown in , in 2012, MS-N1, SB1-N1, and MB treatments had output greater than input, acting as carbon sources, while other treatments acted as carbon sinks, with SB2-N1 treatment having the highest net carbon fixation at 2,956.35 kg · hm ^{2}. In 2013, MS-N1, MS-N2, and SB2-N2 treatments had output greater than input (carbon sources), while other treatments were carbon sinks, with SB2-N1 treatment having the greatest carbon sequestration potential at 872.59 kg · hm ^{2}.

Two-year results consistently showed that SB2-N1 pattern had the greatest soil carbon sequestration potential.

Discussion and Conclusion

The ultimate purpose of nitrogen fertilizer application is to ensure high crop output, while nitrogen management aims to achieve high yield without environmental damage, thereby achieving coordinated economic and environmental benefits [34]. Sugarcane-soybean intercropping can rationally utilize environmental resources such as light while reducing chemical nitrogen application in sugarcane fields. In this study, compared with farmers' conventional nitrogen application rate of 525 kg · hm ^{2}, reduced nitrogen application (N 300 kg · hm ^{2}) did not affect sugarcane yield, and the sugarcane||soybean 1:2 intercropping pattern under reduced nitrogen showed the most obvious and stable interannual variation over five years, demonstrating that reduced nitrogen application while maintaining sugarcane yield is feasible. Yong et al. [35] also found that in a maize-soybean intercropping system, compared with conventional nitrogen application (240 kg · hm ^{2}), reduced nitrogen application (180 kg · hm ^{2}) significantly improved yield, economic coefficient, and nutrient uptake and utilization efficiency of both maize and soybean. Zhang et al. [36] proposed that evaluating nitrogen use rationality requires examining not only yield increase effects but also residual inorganic nitrogen levels in soil. Therefore, initial soil inorganic nitrogen and net mineralization levels may be important factors affecting final nitrogen application rates, and rational nitrogen application must consider soil conditions in different regions with different fertility levels.

Studies have shown that nitrogen application promotes soil CO emissions, possibly by stimulating microbial activity [37–38]. In this study, two-way ANOVA indicated that nitrogen application had significant effects on CO emissions in 2012, but no such effect was observed for cumulative CO emissions in 2013, possibly due to influences from rainfall and other weather conditions and sampling times. Additionally, this study found that soil acted as a weak CH sink based on cumulative emissions, with no significant treatment effects on CH emissions. Chen et al. [39] proposed that different fertilizer types, application methods, and rates affect CH emissions, with fertilized treatments showing significantly higher CH emissions than unfertilized treatments, possibly because long-term fertilization promotes microbial activity, increasing average greenhouse gas emission flux [40].

In the sugarcane-soybean intercropping ecosystem, carbon input in sugarcane||soybean 1:2 intercropping pattern was significantly higher than in sugarcane||soybean 1:1 intercropping and sugarcane monoculture at the same nitrogen level, primarily due to increased soybean seeding rate. Carbon brought in through crop seeds is the main carbon source in farmland ecosystems, and different nitrogen application modes bring different carbon amounts through fertilizers. In this experiment, carbon from reduced nitrogen application was far lower than from conventional nitrogen application, with conventional nitrogen rates far exceeding crop nitrogen demand. Farmland carbon output mainly includes carbon removed by aboveground crop harvest, CO emission losses, and CH emission losses. Under the same intercropping pattern, conventional nitrogen application in sugarcane||soybean 1:2 intercropping had significantly higher carbon output than reduced nitrogen application, mainly because increased nitrogen use promoted CO emissions, consistent with Dick [41]. However, in sugarcane||soybean 1:1 intercropping, conventional nitrogen application had lower CO emissions than reduced nitrogen application, consistent with Burton et al. [42] and DeForest et al. [43], possibly because nitrogen application reduced soil extracellular enzyme activity and fungal communities, decreasing CO emissions. Both phenomena appeared in this experiment, and besides the aforementioned reasons, specific mechanisms require further long-term positioning studies. Additionally, carbon output from sugarcane harvest in 2013 was much higher than in 2012, possibly because sugarcane has a long growth period and field experiments are highly susceptible to weather factors. In 2012, sugarcane was severely affected by typhoon lodging during late growth, directly affecting later growth and causing large differences in carbon output between the two years, consequently resulting in large differences in net carbon fixation.

Yin et al. [9] found that fertilization affects not only topsoil organic carbon content but also its storage, with fertilization promoting carbon fixation in fluvo-aquic soils. Huang et al. [44] showed that organic-inorganic fertilizer combination (NPKM) in wheat-maize systems acted as atmospheric CO sinks. This study found that all sugarcane-soybean intercropping patterns except SB2-N2 acted as carbon sinks, while SB2-N2 and sugarcane monoculture acted as carbon sources, possibly because SB2-N2 had significantly higher CO emissions than other treatments, and sugarcane monoculture systems had no straw return as all sugarcane was harvested as product. Among all treatments, SB2-N1 had the greatest carbon sequestration potential, with net carbon fixation of 2,956.35 kg · hm ^{2} (2012) and 872.59 kg · hm ^{2} (2013). Li et al. [45] reported farmland ecosystem carbon sequestration of 6,829.1–8,950.2 kg · hm ^{2}, significantly higher than this study’ s results, mainly due to different calculation methods and monitoring durations. Additionally, differences in regional natural conditions, crop types, planting patterns, and field management measures also contributed to these estimation differences.

Nitrogen application can promote carbon fixation; however, excessive nitrogen application not only fails to increase yield but also affects the healthy cycling of soil nutrients in farmland ecosystems. This study demonstrates that intercropping and reduced nitrogen application can significantly improve system land equivalent ratio, and under SB2-N1 planting pattern, soil maintains good carbon sink status. Therefore, reasonable reduced nitrogen application and intercropping are considered feasible sustainable agricultural development measures.

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