

*Original Research*

# Effects of Different Intercropping Methods on Soil Organic Carbon and Aggregate Stability in Sugarcane Field

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## Abstract

In order to maintain soil stability, improve soil productivity and optimize planting patterns, the distribution characteristics of soil aggregates in sugarcane fields under different intercropping methods were studied. We investigated the differences in organic carbon content of different particle size aggregates and the effects of intercropping on soil organic carbon, aggregates stability, sugarcane water content and nutrients content. The results showed that intercropping could effectively improve soil physicochemical properties, increase soil organic carbon (SOC) content, but such an approach had little effect on soil stability. After intercropping, the content of SOC, readily oxidized organic carbon (ROC), dissolved organic carbon (DOC) in soil increased significantly. The content of SOC increased with the decrease in aggregate size, and the organic carbon is more stable in the aggregates with the particle size of  $R > 2$  mm and  $R < 0.154$  mm. The selection of soybean and mucuna pruriens as intercropping crops in both OS//M and OM treatments was less damaging to soil stability and soil performance was significantly improved than the other groups, making them more suitable for intercropping in sugarcane fields. Intercropping increased the water content and N, P and K content of sugarcane plants.

**Keywords:** sugarcane field, intercropping, soil organic carbon, aggregate, mucuna pruriens

## Introduction

Soil is a terrestrial carbon pool and an important part of the global carbon cycle [1]. The concentration of organic carbon in soil is highly affected by soil microorganisms, fertilization and other tillage activities [2]. The increase of organic carbon content can improve soil quality, and improve soil productivity [3]. Organic carbon is an important cementing material for soil aggregates [4]. Aggregates play a protective role for the stabilization of SOC [5], and their ability to protect organic carbon varies among particle sizes [6]. Therefore, comparing the organic carbon content in soils with different particle sizes is an important method to study SOC.

ROC is the organic carbon that is easily oxidized and decomposed in the organic carbon pool. Compared with other variables in soil, ROC can sensitively reflect the small differences between soil samples of each group [7]. DOC is not only an important source of organic carbon [8], but an indicator of the availability of soil microorganisms [9]. DOC may be fixed through complex interactions with soil surface [10]. The changes of ROC and DOC content are also important for the study of soil organic carbon.

Straw returning to the field can increase soil organic carbon content, and increase crop yield [11, 12]. The application of chemical fertilizer can change the distribution of organic carbon in aggregates [13, 14], and also improve the soil organic carbon content [15]. The research results of Tan et al. [16] showed that the application of potassium fertilizer in soil and straw returning to the field can improve the content of available potassium in soil.

Guangxi is the largest sugarcane planting base in China, its sugar output accounts for more than 60 percent of the country's total output [17], and the soil of sugarcane field is widely distributed in Guangxi. However, the perennial planting of sugarcane reduces the soil quality and fertility. Intercropping refers to a planting method where two or more crops are planted in branches on the same field in the same growth period. Intercropping can not only improve land use efficiency and soil biodiversity [18] but also make better use of environmental resources [19]. Many studies have shown that soya-grain intercropping can improve soil performance [20]. Intercropping of deep-rooted and shallow-rooted plants can reduce nitrate leaching [21]. Intercropping and nitrogen application can improve the function and diversity of rhizosphere soil microbial community [22].

We hypothesize that compared with mono-cropping, intercropping will improve soil physicochemical properties, effectively protected soil stability, and increased water content of sugarcane plants and N, P and K content in plants. In this study, soybeans, mucuna pruriens, and watermelons were selected for intercropping following the sugarcane crop cycle to evaluate the effects of different co-cultivation

intercropping methods on the soil physicochemical properties, organic carbon, aggregate stability and plant nutrient element content of sugarcane fields. We aimed to provide a theoretical basis for soil improvement and optimization of intercropping in sugarcane fields.

## Materials and Methods

### Overview of the Study Area and Test Materials

The study area is located in Nala Tun, Duchong Village, Dongluo Town, Fusui County, Chongzuo City, Guangxi Zhuang Autonomous Region (107°39'29"-107°40'17"E, 22°20'50"-22°20'36"N), which has a subtropical monsoon climate with an average annual temperature of 20.8°C and an average annual rainfall of 1400 mm, 80% of rainfall is concentrated in March-September. The test soil is red soil. The test sugarcane variety is Gui sugar 42, the soybean variety is Gui spring 3, the watermelon variety is black beauty, and the mucuna pruriens is provided by Guangxi Academy of Agricultural Sciences, which is a local specialty crop in Guangxi, and no variety is introduced.

### Experimental Design

The experiment was conducted on a representative sloping arable field with a sloping field surface. There were four treatments from the top to the bottom of the slope. The O treatment was optimized fertilization and artificially transplanted from the harvested cane leaves of the previous season, with an area of 513 m<sup>2</sup>. The OM treatment was optimized fertilization + straw return + mucuna pruriens, mucuna pruriens were planted at the beginning of sugarcane elongation (late May/early June), at 2 m spacing in the middle of wide rows of sugarcane, the area of this treatment was 447 m<sup>2</sup>. The OS//M treatment was optimized fertilization + straw return + soybean + mucuna pruriens. Soybean was planted with three rows at a spacing of 50 cm × 20 cm between wide rows, mucuna pruriens were grown in the same way as before, the area of this treatment was 553 m<sup>2</sup>. The OW//M treatment was optimized fertilization + straw return + watermelon + mucuna pruriens. Watermelon was planted with at a spacing of 1.5 m between wide rows of sugarcane, the area of this treatment was 893 m<sup>2</sup>. Both soybean and watermelon were planted at the sugarcane seedling stage on March 7 and harvested in late May. Many studies have shown that when the experimental area has reached a large area, no repetition can be set [23-26]. In consideration of the large area of each treatment in this study and the uniform plowing of the land, the treatment method is relatively rigorous. Therefore, no repeated experiment was set in this experiment. The planting method was wide and narrow rows with row spacing of 1.5 m + 0.5 m, that is, wide row spacing of 1.5 m and narrow row spacing

of 0.5 m. The planting system was 1 year of new planting and 2 years of perennial root, and the trial year was the first year of perennial root. The amount of straw returned to the field was the full amount of sugarcane stems and leaves.

The fertilizer inputs for each treatment were 376.0 kg/hm<sup>2</sup> of pure N, 135 kg/hm<sup>2</sup> of P<sub>2</sub>O<sub>5</sub>, and 240 kg/hm<sup>2</sup> of K<sub>2</sub>O. Fertilizer was applied in 2 times, seedling fertilizer and elongation fertilizer, with nitrogen and potassium fertilizer in the ratio of seedling fertilizer: elongation fertilizer 3:7 and phosphorus fertilizer in the ratio of seedling fertilizer: elongation fertilizer 1:1. The first seedling fertilizer was applied on March 7, 2019, and the second elongation fertilizer was applied on June 5, 2019, both by spreading in the sugarcane planting rows. Sugarcane was harvested on December 26.

### Sample Collection and Treatment Soil Sample Collection

Soil samples were collected from 0-30 cm soil layer by soil auger method after the sugarcane harvest. Six sampling points were randomly selected in the S-shape for each treatment. The soil samples were placed in sealed bags, numbered and brought back to the laboratory. After removing plant and animal residues and gravel, the soil samples were dried naturally and placed in a dry place for subsequent experiments.

### Determination Method

Soil water-stable aggregates were measured by wet screen method [27]. 100 g air-dried soil samples were placed on a sieve group composed of 2, 1, 0.5, 0.25, 0.196 mm and put into an aggregator analyzer equipped with deionized water. The analyzer was operated for 40 min (the upper and lower amplitude is 38 mm, vibration 30 times per minute), the soil components on each screen were collected, their constant mass was measured after drying, and used to calculate the stability indexes of soil aggregates. The pH was measured by a pH meter (water and soil ratio 2.5:1), the available K was determined by CH<sub>3</sub>COONH<sub>4</sub> extraction method, the available P was determined by NaHCO<sub>3</sub> extraction - molybdenum antimony anti-spectrophotometric method, the SOC content was determined by K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> oxidation-spectrophotometric method and the soil was screened into 2, 0.9, 0.45, 0.03, 0.2, by dry sieve method. The organic carbon content of aggregates with different particle sizes was determined by K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> oxidation-spectrophotometric method after grinding through 60 mesh sieve. The ROC was determined by 330 mmol/L KMnO<sub>4</sub> oxidation method. The field capacity of the air-dried soil samples was kept at about 60% and cultured in a light incubator with deionized water added every day. After 7 days, the content of DOC was measured by TOC total organic carbon analyzer. The contents of N, P and K in sugarcane plants were measured by Kjeldahl

method, vanadium and molybdenum yellow colorimetry and flame photometric method.

### Data Processing

The stability indexes of soil aggregates include mean weight diameter (MWD), geometric mean diameter (GMD), large water-stable aggregates (WR<sub>0.25</sub>), and fractal dimension (D) [28, 29, 30].

The formula for calculating the mean weight diameter is as follow:

$$MWD = \sum_{i=1}^n \bar{d}_i \omega_i \quad (1)$$

The formula for calculating the geometric mean diameter is as follows:

$$GMD = \exp\left(\sum_{i=1}^n \omega_i \ln \bar{d}_i\right) \quad (2)$$

The formula for calculating the large water-stable aggregates is as follows:

$$WR_{0.25} = \frac{M_{r>0.25}}{M_T} \times 100\% \quad (3)$$

The formula for calculating the fractal dimension is as follows:

$$\frac{M(R < \bar{d}_i)}{M_T} = \left(\frac{\bar{d}_i}{\bar{d}_{\max}}\right)^{(3-D)} \quad (4)$$

Where:  $\bar{d}_i$  is the average diameter of each particle size of aggregates (mm),  $\omega_i$  is the weight percentage of each particle size.  $WR_{0.25}$  is the aggregate content (%) of particle size  $R > 0.25$  mm aggregate content (%),  $M_{r>0.25}$  is the weight of aggregates with particle size  $R > 0.25$  mm,  $M_T$  is the total weight of aggregates (g).  $M(R < \bar{d}_i)$  is the aggregate particle size smaller than the cumulative mass sum of aggregates, and  $\bar{d}_{\max}$  is the average diameter of the maximum particle size of aggregates.

Excel 2019 and SPSS25.0 were used for statistical analysis of the data. One-way analysis of variance (ANOVA) were used to compare the differences among different treatments, significance level ( $P < 0.05$ ) and use Origin2019 to draw.

## Results

### Physical and Chemical Properties of Soil under Different Intercropping Methods

The physical and chemical properties of soil under different intercropping methods were shown in Table 1. The content of SOC of available P and available K

Table 1. Soil physical and chemical properties under different intercropping methods.

Intercropping methods	pH	Conductivity (S·m <sup>-1</sup> )	Available P (mg·kg <sup>-1</sup> )	Available K (mg·kg <sup>-1</sup> )	SOC (g·kg <sup>-1</sup> )
O	4.51±0.02a	34.70±0.21d	43.10±2.66d	56.73±0.98c	6.89±0.87d
OM	4.02±0.07c	55.60±1.11b	234.81±4.37b	85.97±2.32b	15.38±0.48b
OS//M	4.28±0.08b	65.90±1.82a	257.68±10.31a	103.90±1.54a	22.98±2.40a
OW//M	4.54±0.12a	41.10±2.01c	171.05±6.72c	82.02±1.95b	9.67±0.63c

Note: Data in the table are mean standard deviations and different lowercase letters indicate significant differences under different intercropping methods ( $P < 0.05$ ).

in soil under the four treatment methods were OS//M, OM, OW//M, O in descending order. Among them, available P, available K and SOC content in OS//M were the highest, and the difference was significant with other intercropping methods. Compared with O, the SOC content of available P and available K in OS//M, OM, OW//M, were significantly increased, and the available P content increased by 498.00%, 444.93%, 296.96%, respectively; The content of available K increased by 83.15%, 51.54%, 44.58%, respectively; SOC content increased by 233.33%, 123.19% and 44.93%, respectively.

#### Distribution Characteristics of Soil Aggregates under Different Intercropping Methods

The composition of soil aggregates was shown in Fig. 1. The number distribution of soil aggregates under different intercropping methods was basically the same. The contents of aggregates with different particle sizes under the same intercropping method were different. The aggregate composition of the four intercropping modes were mainly  $R > 2$  mm aggregates. Its content was much higher than other particle sizes, and the content was between 34.57% and 46.66%. The aggregates content of  $R < 0.196$  mm particle size was the second, which ranged from 19.61% to 27.86%. The OS//M and OM intercropping methods had the lowest soil aggregate content of 0.196 mm~0.25 mm particle size, and the O and OW//M intercropping methods had the lowest soil aggregate content of 0.5 mm ~ 1 mm particle size. The content of aggregates with the same particle size was different in different intercropping methods. Under the particle size of  $R > 2$  mm, the aggregate content was the highest in O, and the lowest in OM. When the particle size was  $R < 0.196$  mm, the aggregate content was the highest in OM and the lowest in O.

The indexes of aggregates under different intercropping modes were shown in Table 2.  $WR_{0.25}$  varies from 0.64 to 0.73 under the four intercropping modes. The range of MWD was 1.06~1.22. The range of GMD was 0.68~0.82. The range of the three indexes from large to small was O, OS//M, OW//M, OM. The variation range of D was 2.18~2.36, and from large to small, it was OM, OW//M, OS//M, O. Comparing the indicators of agglomerates, the values of MWD,

GMD,  $WR_{0.25}$  of O treatment were the highest, and the value of D was the lowest; while the values of MWD, GMD,  $WR_{0.25}$  of OM were the lowest, and the value of D was the highest.

#### Characteristics of Soil Organic Carbon under Different Intercropping Methods

##### Characteristics of Soil Active Organic Carbon under Different Intercropping Methods

As can be seen from Fig. 2, soil DOC content was significantly affected by different intercropping methods, and the order of DOC content from high to low was OS//M, OM, OW//M, O. DOC content in OS//M was significantly higher than that in other three intercropping methods. Compared with O, the soil DOC content of the OS//M, OM, and OW//M intercropping methods increased by 75.38%, 124.61%, and 283.07%, respectively. Soil ROC content is different under different intercropping methods. The ROC content of the four intercropping methods in descending order was OW//M, OM, O, OS//M. Compared with O, OW//M

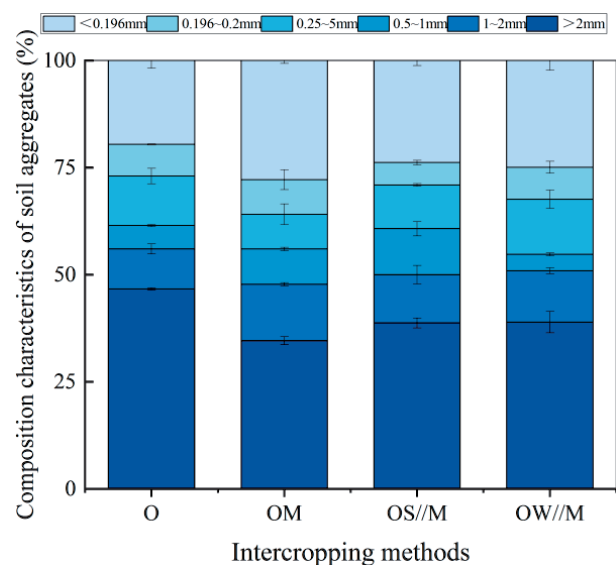


Fig. 1. Composition characteristics of soil aggregates under different intercropping methods.

Table 2. Indexes of aggregates under different intercropping methods.

Intercropping methods	MWD	GMD	D	WR <sub>0.25</sub>
O	1.22±0.01a	0.82±0.04a	2.18±0.19a	0.73±0.07a
OM	1.06±0.02b	0.68±0.03a	2.36±0.07a	0.64±0.03a
OS//M	1.12±0.06ab	0.76±0.06a	2.27±0.11a	0.71±0.04a
OW//M	1.10±0.07ab	0.72±0.07a	2.32±0.09a	0.68±0.06a

Note: Data in the table are mean standard deviations and different lowercase letters after data in the same column which indicates that there is no significant difference under different intercropping methods (P<0.05)

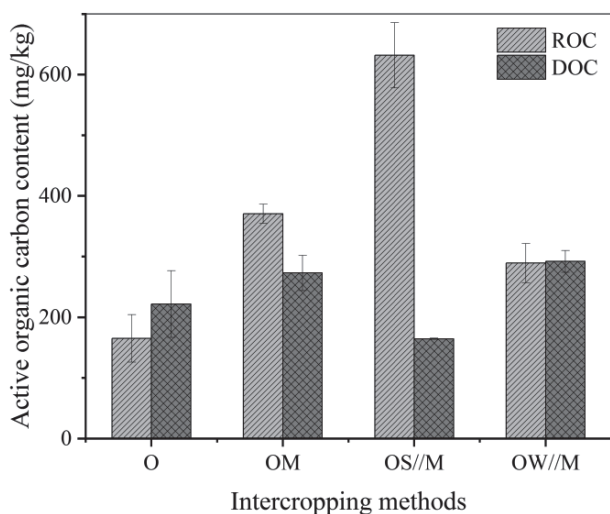


Fig. 2. Soil easily oxidized organic carbon soluble organic carbon content under different intercropping methods.

and OM increased by 31.69% and 23.12% respectively; OS//M decreased by 25.83%.

*Characteristics of Organic Carbon of Different Particle Sizes under Different Intercropping Methods*

According to the distribution characteristics of organic carbon of different particle sizes in Fig. 3, intercropping increased the content of organic carbon in aggregates of different particle sizes. As the particle size decreased, the content of SOC in aggregates showed an increasing trend. The organic carbon content of agglomerates with R<0.196 mm under the four intercropping methods was the highest among all the agglomerates of particle size. Among them, the organic carbon content of different particle sizes of O increased in turn with the decrease of the aggregate size. The change trend of OW//M organic carbon content with the decrease of aggregate size is not obvious.

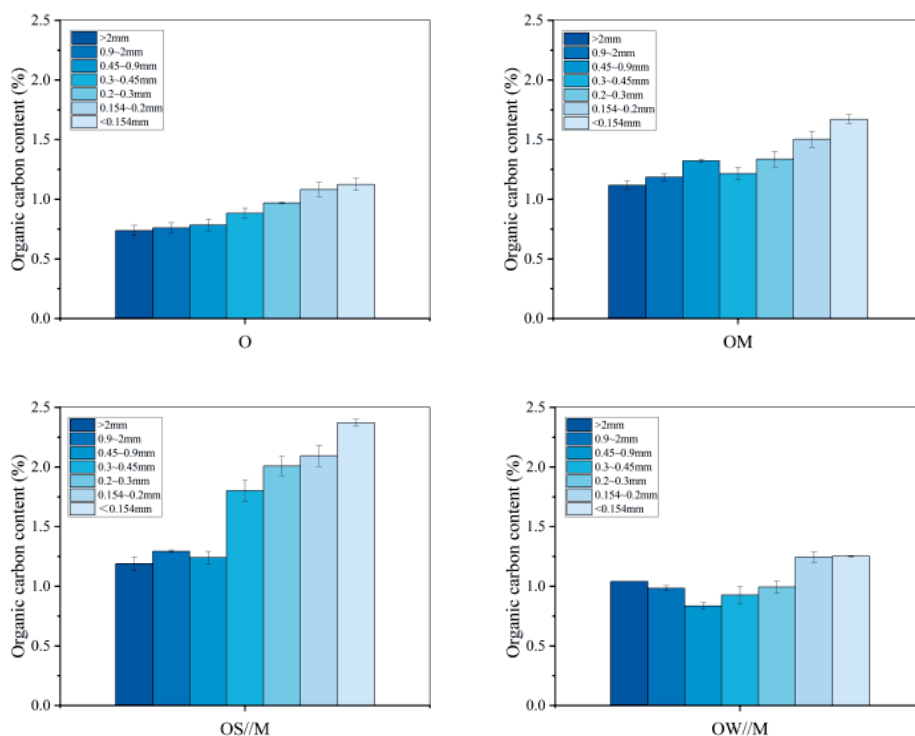


Fig. 3. Soil organic carbon content of different grain sizes under different intercropping methods.

Table 3. Sugarcane yield under different intercropping methods.

Intercropping methods	O	OM	OS//M	OW//M
Sugarcane production (kg/hm <sup>2</sup> )	70668.45a	60595.20b	57550.50c	60627.30b
Sugarcane leaves production (kg/hm <sup>2</sup> )	11831.13a	9653.01c	10978.47b	9232.29d

Note: Data in the table are mean standard deviations and different lowercase letters after data in the same column which indicates that there is no significant difference under different intercropping methods ( $P < 0.05$ ).

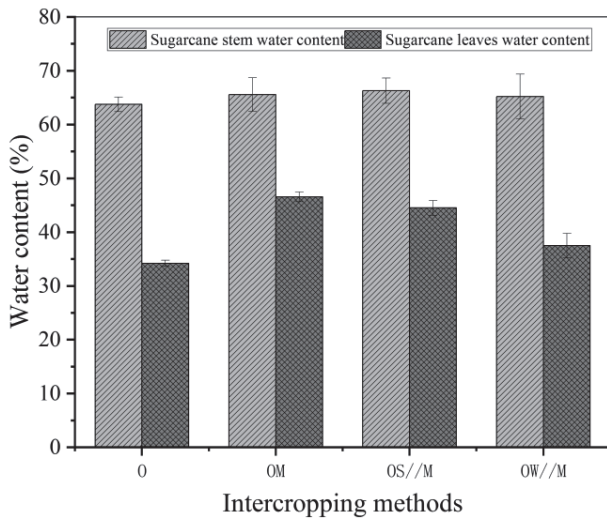


Fig. 4. Water content of sugarcane plants under different intercropping methods.

### Sugarcane Yield under Different Intercropping Methods

As can be seen from Table 3, in 2019 sugarcane production showed  $O > OM > OW//M > OS//M$ . Compared with O, OM, OW//M, and OS//M sugarcane production decreased by 14.25%, 16.57%, and 21.64%, respectively. Sugarcane leaves production showed  $O > OS//M > OM > OW//M$ , compared with O, OS//M, OM, and OW//M sugarcane leaves yield decreased by 9.24%, 18.41%, and 26.92%, respectively.

### Water Content of Sugarcane Plants under Different Intercropping Methods

There were differences in water content of sugarcane plants under different intercropping methods. The water content in sugarcane stems under the four treatments was OS//M, OM, OW//M, and O in descending order. Compared with O, the water content in sugarcane stems increased by 4.00%, 2.87%, and 2.31% for OS//M, OM, and OW//M, respectively. The water content in sugarcane leaves in descending order was OM, OS//M, OW//M, O. Compared to O, the water content in OM, OS//M, OW//M sugarcane leaves increased by 36.11%, 30.12%, and 9.65%, respectively.

### N, P and K Contents in Sugarcane Plants under Different Intercropping Methods

The N, P, and K contents of sugarcane plants differed significantly among different intercropping methods. Under the four treatments, the N content of sugarcane stems was OS//M, OM, O and OW//M in descending order; the P and K contents were OM, OS//M, O and OW//M in descending order. Compared to O, P content in OM sugarcane stems increased by 25.00% and K content increased by 53.33%; N content in OS//M sugarcane stems increased by 1.96% and K content increased by 4.44%; N content in OW//M cane stems decreased by 7.84, P content decreased by 25% and K content decreased by 15.56%. The N, K contents of sugarcane leaves were OM, OS//M, OW//M, and O in descending order; the P contents were OS//M, OM, OW//M, and O in descending order. compared with O, the N, P, and K contents of OM sugarcane leaves

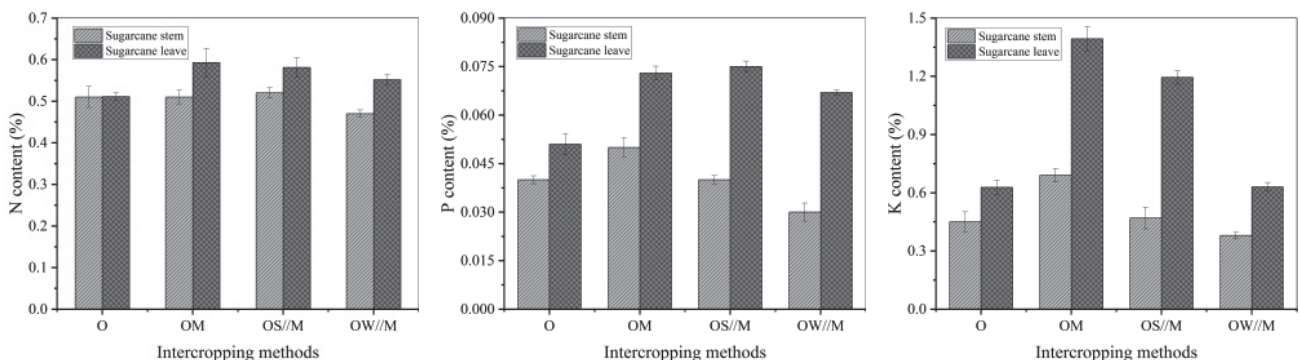


Fig. 5. N, P, K content of sugarcane plants under different intercropping methods.

increased by 16.05%, 43.14%, and 121.82%, respectively; the N, P, and K contents of OS//M sugarcane leaves increased by 13.70%, 47.06%, and 90.13%, respectively; and N, P, and K content in OW/M sugarcane leaves increased by 8.02%, 31.37%, and 0.32%, respectively.

## Discussion

### Effects of Different Intercropping Methods on Soil Fertility

Compared with sugarcane monocropping, the three intercropping treatments significantly increased the content of soil available K, available P and organic carbon in sugarcane field, and the SOC in OS//M increased the most. This is due to legumes such as soybeans and mucuna pruriens fix  $N_2$  in the atmosphere, and planting legume plants increased the content of litters. Such high-quality organic matter from legume plants and improved nitrogen utilization rate accelerated the decomposition of organic residues [31], thus increasing the organic carbon content. At the same time, intercropping can improve the  $H^+$  concentration and phosphatase activity in rhizosphere soil, thus promoting the activation of P and increasing the content of available [32, 33].

Intercropping soil in different ways, leads to the differences between organic carbon of soil exogenous input [34]. In this study, ROC content of the three intercropping treatments is significantly increased comparing with monocropping. In OS//M, soybeans and mucuna pruriens have developed root systems. The dead leaves of plants return to the soil, and the fallen leaves are easy to decompose. The amount of external input carbon is relatively high, so the ROC content in this treatment is high. The O crop is single, and the amount of external carbon input is small, so the ROC in O is the lowest among all intercropping methods.

In this study, compared with monocropping, OW//M, OM increased DOC content, while OS//M reduced DOC content. This shows that OS//M reduced soil DOC loss and is conducive to soil carbon sequestration. To sum up, the intercropping method of OS//M can well improve soil performance and reduce the loss of DOC.

### Effects Of Different Intercropping Methods On Soil Aggregate Stability

The higher the values of  $WR_{0.25}$ , MWD and GMD is, the more stable the soil structure [35]. The smaller the D value is, the smaller the soil aggregates dispersion and the stronger the soil aggregate effect is. Among all intercropping treatments, the stability of soil aggregates in O treatment is the best, OS//M is the second, and OM is the worst. O treatment as sugarcane monocropping has a certain protective effect on the stability of soil aggregates, which may be because

tillage affects the number and type of aggregates [36], thus changing the stability of aggregates. Monocropping can protect the stability of aggregates to some extent. The number of plant residues is an important factor to form and stabilize the structure of aggregates. Plant roots and residues are the main organic skeleton, which bond soil particles together to form aggregates [37]. Legumes such as soybeans and mucuna pruriens have well-developed root systems which can fix plants to absorb nutrients and water through soybeans. In the study of April Stainsby et al. [38], legumes improved the stability of aggregates, which is consistent with the results of this study. In OW //M treatment, compared with legumes, watermelon has a weaker role of plant roots and a greater damage to soil stability. Under the four intercropping methods, OS//M treatment has a smaller impact on soil stability and the soil condition is relatively stable.

### Effects of Different Intercropping Methods on the Organic Carbon of Aggregates with Different Particle Sizes

Under different intercropping treatments, soil organic carbon content in different particle size aggregates are significantly increased, showing that intercropping can improve soil organic carbon content. This is because, on the one hand, intercropped crops are organic carbon sources that can directly supplement the organic carbon in aggregates; on the other hand, the organic carbon can be wrapped in aggregates or exist in pores in the form of particles to reduce the decomposition of organic carbon. The roots of leguminous plants can promote the formation of aggregates, reduce the decomposition of organic carbon, and thus increasing the content of organic carbon. The content of organic carbon in aggregates generally increases with the decrease of aggregate size. Studies have shown that the stability of soil aggregate organic carbon generally increases with the decrease of aggregate size [39, 40]. Huang et al. [41] found that after the straw is returned to the field, the new carbon would be preferentially stored in the soil aggregates of 2 mm, which is consistent with the increasing trend of organic carbon of aggregates with  $R > 2$  mm particle size in each treatment in this study. The organic carbon content of  $R > 0.45$  mm aggregates continued to increase, while the organic carbon content of 0.45~2 mm aggregates decreased to different degrees, which indicated that straw returning and intercropping can improve organic carbon content in  $R > 2$  mm and  $R < 0.45$  mm aggregates. The content of organic carbon in  $R < 0.154$  mm aggregate is the highest in each intercropping methods. At the same time, the organic carbon content in  $R > 2$  mm and  $R < 0.45$  mm aggregates are higher than the organic carbon content of 2~0.45 mm aggregates. This shows that the aggregates with  $R > 2$  mm and  $R < 0.45$  mm are more stable and can protect organic carbon.

### Effect of Different Intercropping Methods on Sugarcane Yield

The results showed that sugarcane yield was better in the mono-cropping treatment than in each intercropping treatment, which can be attributed to interactive competition [42]. The decrease in sugarcane yield may be due to the intense competition between intercropping plants and sugarcane, and may also be attributed to the difference in planting time between crops, for example, soybean and watermelon were planted at the beginning of sugarcane seedling stage, and the growth of soybean and watermelon used a lot of soil nutrients resulting in a decrease in sugarcane yield, while cat bean was planted at the beginning of sugarcane elongation, leaving enough space for sugarcane growth in the early stage, resulting in a smaller decrease in sugarcane yield.

### Effects of Different Intercropping Methods on Water Content, N, P, K Contents of Sugarcane

Plant water content is an important indicator to characterize physiological processes such as photosynthesis and respiration [43]. Once the water metabolism of plants is out of balance, it will disrupt the normal physiological activities of the plant, and in severe cases, it can cause plant death. The water content in sugarcane stems and leaves was significantly increased in the intercropping treatments compared with mono-cropping, with OM and OS//M treatments being more effective in increasing the water content in sugarcane stems and leaves, indicating that these two intercropping methods can fix the water in sugarcane well and protect the growth of sugarcane.

Plant nutrient uptake is the basis of its growth and development, and different intercropping treatments exerted significant effects on sugarcane stems and leaves N, P and K nutrient uptake. In the intercropping system, the nutrient uptake advantage was mainly derived from the complementary effect of combined crops on resources in time and space [44]. Rhizobium infects legumes to form nodules, nitrogen in the atmosphere is reduced to ammonia for plant absorption and utilization [45]. In this study, the N content in sugarcane stems and leaves under intercropping is higher than that of mono-cropping sugarcane, which is due to the biological nitrogen fixation of legumes [46], and also indicated that intercropping improved the rate of soil nitrogen fixation, resulting in the change of N content in sugarcane plants. During the intercropping of sugarcane and soybean, Yang et al. [47] found that the nitrogen uptake of crops under intercropping increased to a certain extent compared with the monocropping model, which is consistent with the results of this study.

At the same time, P content in sugarcane stems and leaves under intercropping is significantly higher than that of mono-cropping sugarcane. This is because legumes can significantly acidify the rhizosphere

of plants, which is conducive to the activation and absorption of insoluble soil P, and thus increasing the P content in sugarcane plants. Similar research results have also been reported. For example, in the study of Li et al. [48], intercropping between corn and broad bean increased phosphorus content in corn plants.

Sugarcane plants under different intercropping treatments not only increased nitrogen and phosphorus content, but also changed potassium content. The potassium content of OS//M and OM sugarcane stems and leaves are higher than that of sugarcane mono-cropping, while the potassium content of OW//M is slightly lower than that of sugarcane mono-cropping. It has been shown that key transporters for root nitrogen and potassium uptake are regulated by the same set of protein phosphorylation mechanisms, and there is also synergistic regulation between nitrogen and potassium [49, 50]. This shows that intercropping can increase the potassium content in crop plants. In summary, both OS//M and OM treatments significantly increased water content and N, P, K content in sugarcane plants, indicating that these two intercropping treatments are helpful to increase plants water content and utilization of N, P, and K in the soil.

### Conclusion

In this study, different intercropping treatments were applied to sugarcane soils and the effects of different treatments on soil physicochemical properties, aggregates distribution characteristics, soil stability, active carbon fraction, sugarcane yield and sugarcane water content and N, P and K content were compared. The results showed that two intercropping methods, OS//M and OM, using soybean and mucuna pruriens as sugarcane intercrops, significantly improved soil physicochemical properties, effectively protected soil stability, and increased water content of sugarcane plants and N, P and K content in plants, indicating that these two intercropping methods are feasible agricultural practices.

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### Conflict of Interest

The authors declare no conflict of interest in this paper.

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