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Continuous Straw Returning Combined with Nitrogen Application Improve Soil Properties and Yield of Double Cropping Maize in Subtropical Regions

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Abstract: This study aimed to investigate the impact of straw returning (SR) combined with appropriate N application rates on soil properties and maize yield for a double cropping maize system in South China. From 2021 to 2022, a two-year field experiment was conducted (the perennial orientation study began in 2018) with two nitrogen application rates, 0 kg ha^{-1} (N0) and 250 kg ha^{-1} (N250), under various straw treatments (SR and traditional planting). The findings revealed that SR, along with the nitrogen application of 250 kg ha^{-1} (N250), increased soil total nitrogen (TN), soil total phosphorous (STP), and the soil total potassium (STK) content besides soil organic carbon (SOC) and labile organic carbon (LOC); similarly, their interaction improved SOC and LOC in the 0–20 cm soil layer. In addition, within the 20–40 cm soil layer, SR and N250 also increased the soil TN, SOC, LOC, STP, and STK content. Notably, these soil properties exhibited a decrease with increasing soil depth. Furthermore, SR and N250 led to improvements in the grain yield and yield component of maize. Combining SR with N250 led to a significant 101.53% increase in SOC content from 2018 to 2022. Our research indicates that implementing N rates of 250 kg ha^{-1} under SR is an effective method to boost maize grain yield, enhance soil chemical characteristics, and ensure safe and productive maize cultivation.

Keywords: straw returning; nitrogen application; soil chemical properties; maize grain yield

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1. Introduction

An increase in crop yield significantly increases crop straw yield [1]. A previous study revealed that the yield of straw in Southwest China reached 800 million tons in one year, but only part of it was used, and the remaining straw was disposed of by abandonment and incineration [2]. According to Su et al. [3], this not only wastes resources but also increases the emission of air pollution and pollutes the environment. The diverse nutrient profile of crop straw, including nitrogen (N), phosphorus (P), and potassium (K), makes it a versatile organic resource for sustainable agriculture practices. Specifically, the N levels in rice, wheat, and maize are 16.1, 10.7, and 14.5 g kg^{-1}, respectively [4]. This nutrient richness suggests that, up to a certain level, crop straw has the potential to serve as a viable alternative to chemical fertilizers [5]. Moreover, straw returning (SR) emerges as the simplest and most effective method for utilizing crop straw as a fertilizer [6]. In addition to supplying nutrients to crops, SR has been shown to reduce greenhouse gas emissions [7]. Prior research has demonstrated that the practice of SR can lead to a decrease in greenhouse gas emissions, resulting in an annual reduction of approximately 7.089 million tons [4]. Previous studies have shown that SR benefits the soil by forming large pores and a suitable soil aggregate structure. This reduces the upward movement of underground capillary water, thereby decreasing water loss and enhancing soil water retention capacity, which ultimately promotes plant growth [8,9]. Additionally, the continued implementation of SR may support the achievement of optimal crop yields while decreasing reliance on NPK fertilizer applications [10]. However, despite its benefits, SR also presents some shortcomings, for example, insufficient straw decomposition impact on nutrient supply [11,12].

Ding et al.'s [13] research showed that N is a crucial component of growth and development. The deficiency of N in crops can lead to detrimental effects such as premature senescence and a decrease in yield [14]. However, it is evident that the widespread adoption and extensive use of N fertilizer, driven by the imperative to ensure crop yield, has resulted in the pervasive issue of excessive N fertilizer application [15]. This overuse of the N fertilizer poses significant risks regarding soil, water, and air pollution [16]. Consequently, there is an urgent need to reduce N application in a manner that is both rational and environmentally sustainable.

The breakdown of straw was impacted by a range of factors including soil conditions, microbial conditions, as well as other environmental elements [17]. At the beginning of straw incorporation, a significant amount of N is needed for the microbial breakdown of straw. When there is a deficiency of N in the soil, microorganisms may end up in competition with crops for N in the soil. This competition can impact the typical growth and progress of crops [18]. SR, combined with an appropriate N fertilizer, can meet the needs of microorganisms for N, increase microbial biomass and their activity, and accelerate straw decomposition [7]. Consequently, determining the optimal N application rate following SR has emerged as an imperative challenge requiring urgent resolution.

To investigate the impacts of SR in conjunction with N on soil properties, including the maize yield in subtropical regions, and ultimately to improve the overall quality of the soil, a two-year four-season field trial was carried out (2021–2022) in Guangxi (the perennial orientation study started from 2018), China (a humid subtropical region). The purpose of this study was (1) to explore the effect of SR combined with N application in the soil nutrient content of one-year double-cropping maize and (2) to evaluate the impact of combining SR with N application on the yield of one-year double-cropping maize, and to explore the relationship between soil nutrients and yield.

2. Material and Methods

2.1. Site Description and Field Management

The experimental study conducted at Guangxi University (22°50′ N, 108°17′ E) in China from 2021 to 2022 was part of the perennial orientation study initiated in 2018. The experimental site has a subtropical monsoon climate, with an average annual temperature of 21.6 °C and an average annual rainfall of 1304.2 mm (Table 1). The soil at the site is classified as clay loam, with basic properties such as soil organic carbon (SOC), total nitrogen (TN), soil total phosphorus (STP), soil total potassium (STK) contents, and pH values recorded at 9.84, 1.68 g, 0.42, 18.6 g kg^{-1}, and 6.3, respectively, in the 0–20 cm soil layer. Before sowing in 2018, the SOC and TN contents in the same soil layer were measured at 8.47 and 0.79 g kg^{-1}, respectively.

Table 1. Monthly average temperature (°C) and rainfall (mm) from March to November during 2021–2022.

	Years	March	April	May	June	July	August	September	October	November
Temperature	2021	19.7	21.7	28.9	29.6	30.9	30.3	29.3	24.5	19.6
	2022	22.8	24.6	25.4	29.8	31.1	30.2	29.1	25.2	24.6
Rainfall	2021	16.4	103.4	83.8	307.4	247.0	129.8	147.2	115.0	14.6
	2022	59.0	27.8	180.6	232.0	196.4	220.0	41.8	14.0	12.8

The experiment employed a split-plot design, encompassing the following two factors: straw treatments and N application rates. Straw treatments included straw returning (SR; after the maize harvest, all above-ground straw was smashed and mixed into the 0–20 cm soil layer by rotary tillage) and traditional planting (TP; after the maize harvest, all the straw was transported out manually). Two N rates were used, including pure N 0 kg ha^{-1} (N0) and 250 kg ha^{-1} (N250), where N250 was the optimal N level in Guangxi according to the results of perennial orientation research [10]. To conduct the experiment, a total of 12 plots were established by implementing four different treatments, each replicated three times. Each plot had dimensions of 4.2 m × 4.2 m, with a row spacing of 0.6 m and a plant spacing of 0.3 m, resulting in a planting density of 55,556 plants ha^{-1}. The N fertilizer used was Urea (N = 46.4%), while the phosphate fertilizer utilized was a calcium magnesium phosphate fertilizer (P_2O_5 = 18%), and the potassium fertilizer was potassium sulfate (K_2O = 60%). Both P_2O_5 and K_2O were applied as the base fertilizer at the rate of 100 kg ha^{-1}. The N fertilizer was split into 2/3 as the base fertilizer and left 1/3 as topdressing (applied at the large bell stage). The spring maize was sown on 4 March 2021 and 6 March 2022 and harvested on 5 July 2021 and 9 July 2022, respectively, using the Zhengda-169 maize variety. The autumn maize was sown on 8 August 2021 and 8 August 2022 and harvested on 26 November 2021 and 26 November 2022, respectively. Each plot underwent all required farming practices, such as herbicide and insecticide applications, in accordance with the traditional agronomic methods specific to the region throughout the entirety of the experimental periods.

2.2. Samples Collecting and Analyzing

In the maturity period (R6), 0–20 and 20–40 cm soil layer samples were selected by the "S"-shaped sampling method. All soil samples were naturally dried, fully mixed, ground, sieved (0.149 mm mesh), and used for the determination of soil total nitrogen (TN), soil organic carbon (SOC), labile organic carbon (LOC), soil total phosphorus (STP), and soil total potassium (STK). TN was measured by the semi-automatic Kjeldahl method [19], and SOC was determined by the $K_2Cr_2O_7$-H_2SO_4 external heating method [20]. LOC was measured by the potassium permanganate-oxidation method [21], while STP and STK were measured using sodium hydroxide alkali fusion-molybdenum–antimony anti-spectrophotometry [22] and flame photometry [23], respectively. During the R6 growth stage, two square meters of maize ears were selected at random from each plot. Following natural air drying, measurements were taken for grain number (GN), thousand grain weight (TGW), and grain yield.

2.3. Statistical Analysis

Statistical analyses were carried out utilizing SPSS version 25 (IBM SPSS Statistics software, Chicago, IL, USA). Mean discrepancies were identified with an LSD test at a significance threshold of $p \leq 0.05$. Relationship evaluations among TN, SOC, LOC, STP, STK, and grain yield were completed through correlation analysis in R v.3.63. Graphs were produced with OriginPro2021 (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Soil TN Content

Figure 1 shows that the TN content was notably impacted by the rates of N application and SR treatment in both soil depths (0–20 and 20–40 cm), with statistical significance ($p < 0.05$). The soil TN content of TP-N0, TP-N250, SR-N0, and SR-N250 treatments were 1.53, 1.75, 1.62, and 1.86 g kg^{-1}, respectively (0–20 cm soil layer). In comparison to the TP treatment, the soil TN content (0–20 cm soil layer) increased significantly by 7.03% (2021) and 5.48% (2022) under the SR treatment ($p < 0.05$). Correspondingly, in the 20–40 cm layer, the soil TN content displayed a notable rise of 5.42% (2021) and 6.40% (2022) under SR treatment ($p < 0.05$). Additionally, the soil TN content (0–20 cm soil layer) exceeded that of the 20–40 cm layer by 61.30%. In summary, the average TN concentration in the soil was higher during the spring compared to the autumn.

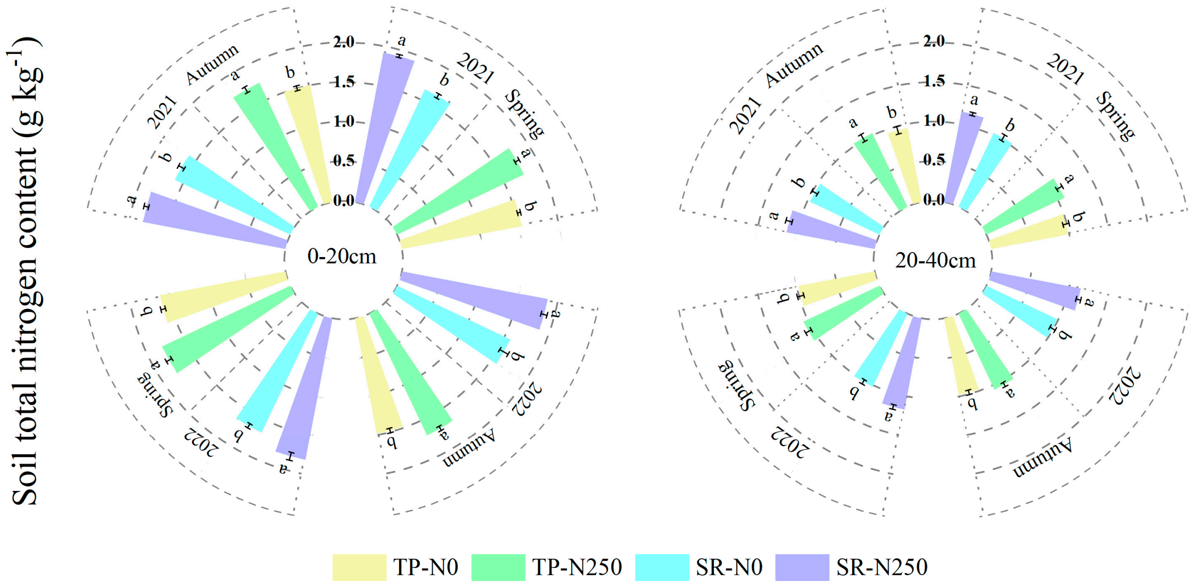

Figure 1. Soil total nitrogen content of 0–20 cm and 20–40 cm layers under straw return and nitrogen application. TP, traditional planting; SR, straw returning; N0 and N250 indicate nitrogen applications of 0 kg ha^{-1} and 250 kg ha^{-1}. The bars represent the SE, and different lowercase letters indicate significant differences at $p < 0.05$.

3.2. Soil SOC Content

Significant effects on SOC were observed at depths of 0–20 and 20–40 cm due to N application rates and SR (Figure 2; $p < 0.05$). The N application rates × SR interaction was found to be significant in the 0–20 cm soil layer ($p < 0.05$). The SOC content of the 0–20 cm soil layer under the TP-N0, TP-N250, SR-N0, and SR-N250 treatments were 10.16, 14.06, 11.86, and 17.09 g kg^{-1}, respectively. Comparatively, the SOC content showed a notable increase of 21.18% (2021) and 17.89% (2022) under the SR treatment (0–20 cm soil layer), as opposed to the TP treatment ($p < 0.05$). Similarly, at a 20–40 cm depth, the SOC content was 8.67% higher in 2021 and 10.24% in 2022 under the SR treatment compared to the TP treatment. Additionally, the N application led to a significant increase in the SOC content in the 0–20 cm soil layer when compared to the N0 treatment ($p < 0.05$). The SOC content of TP-N0 and TP-N250 has no significant difference at 20–40 cm ($p > 0.05$). Overall, higher SOC content was observed in the spring season compared to the autumn, with an average SOC content of 10.85 and 11.51 g kg^{-1} in 2021 and 2022, respectively.

3.3. Soil LOC Content

In both soil depths (0–20, 20–40 cm), the rate of N application significantly affected soil LOC contents (Figure 3; $p < 0.05$). However, the SR and SR × N interaction application rates only had significant ($p < 0.05$) effects on the soil LOC content of the 0–20 cm layer. The soil LOC content of TP and SR were 2.58, 3.16 g kg^{-1} (0–20 cm soil layer) and 1.36, 1.46 g kg^{-1} (20–40 cm soil layer). Relative to TP, the SR significantly ($p < 0.05$) promoted the soil LOC content of the 0–20 cm soil layer by 19.52% and 25.38% in 2021 and 2022, respectively. Similarly, in 2021 and 2022, SR treatment significantly ($p < 0.05$) increased the soil LOC content of the 20–40 cm soil layer by 6.01% and 8.70% compared to the TP treatment, respectively. The highest soil LOC content in both soil layers (0–20 and 20–40 cm) was observed for the N250 treatment. Additionally, the soil LOC content of the 0–20 cm soil layer was higher than that of the 20–40 cm soil layer.

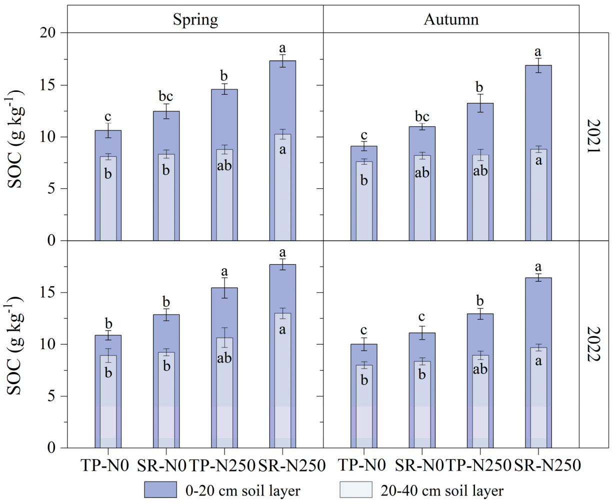

Figure 2. Soil organic carbon (SOC) content of 0–20 cm and 20–40 cm layers under straw return and nitrogen application. TP, traditional planting; SR, straw returning; N0 and N250 indicate nitrogen applications of 0 kg ha^{-1} and 250 kg ha^{-1}. The bars show the SE, and different lowercase letters indicate significant differences at $p < 0.05$.

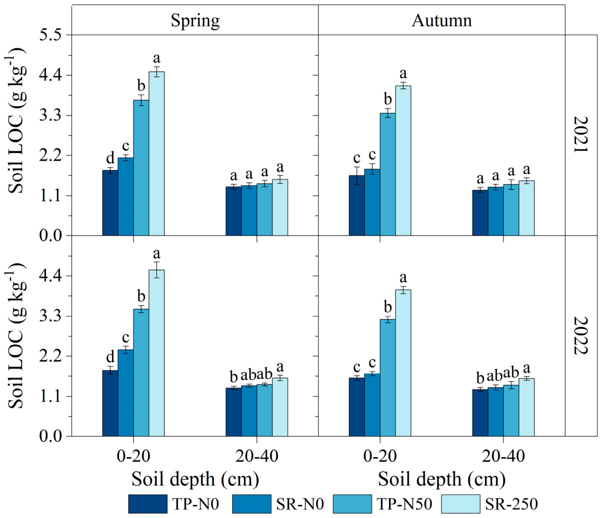

Figure 3. Soil labile organic carbon (LOC) content of 0–20 cm and 20–40 cm layers under straw return and nitrogen application. TP, traditional planting; SR, straw returning; N0 and N250 indicate nitrogen application 0 kg ha^{-1} and 250 kg ha^{-1}. The bars show the SE, and different lowercase letters indicate significant differences at $p < 0.05$.

3.4. STP Content

SR led to a notable increase in the STP content (0–20 cm soil depth), with a statistically significant difference (Table 2; $p < 0.05$). The average STP contents (0–20 cm soil depth) were 0.50 g kg^{-1} (2021) and 0.51 g kg^{-1} (2022) under the SR treatment. Within mean values of 0.41 g kg^{-1} in 2021 and 0.42 g kg^{-1} in 2022, the average value (STP content) of the SR treatment was considerably greater ($p < 0.05$) than that under the TP treatment. In the 20–40 cm soil layer, the variation in STP between different straw treatments was less pronounced. While the N250 treatment showed a significantly higher STP content than the N0 treatment in the 0–20 cm soil layer, there was no significant difference between the N0 and N250 treatments in the 20–40 cm soil layer under the same straw treatments ($p > 0.05$). Additionally, the STP content in the 0–20 cm soil layer depth was significantly greater than that at a 20–40 cm soil depth ($p < 0.05$).

Table 2. Soil total phosphorus (STP, g kg−1) content of 0–40 cm layers under straw returning and nitrogen application (N).

Years	Seasons	Treatments	0–20 cm Soil Layer	20–40 cm Soil Layer
2021	Spring	TP-N0	0.37 ± 0.04 c	0.23 ± 0.03 a
		TP-N250	0.50 ± 0.04 b	0.24 ± 0.05 a
		SR-N0	0.43 ± 0.05 bc	0.24 ± 0.04 a
		SR-N250	0.62 ± 0.05 a	0.27 ± 0.04 a
	Autumn	TP-N0	0.33 ± 0.03 c	0.20 ± 0.03 b
		TP-N250	0.45 ± 0.02 b	0.23 ± 0.04 a
		SR-N0	0.39 ± 0.05 b	0.22 ± 0.03 ab
		SR-N250	0.57 ± 0.04 a	0.24 ± 0.05 a
2022	Spring	TP-N0	0.37 ± 0.04 d	0.24 ± 0.04 a
		TP-N250	0.52 ± 0.04 b	0.26 ± 0.02 a
		SR-N0	0.44 ± 0.05 c	0.26 ± 0.04 a
		SR-N250	0.63 ± 0.04 a	0.27 ± 0.04 a
	Autumn	TP-N0	0.31 ± 0.03 d	0.21 ± 0.03 a
		TP-N250	0.48 ± 0.03 b	0.23 ± 0.03 a
		SR-N0	0.38 ± 0.02 c	0.22 ± 0.03 a
		SR-N250	0.60 ± 0.04 a	0.24 ± 0.03 a
			p value	
		Straw return	0.0309	0.1917
		N	0.0001	0.0927
		Straw return × N	0.0994	0.8511

TP, traditional planting; SR, straw returning; N0 and N250 indicate nitrogen application 0 kg ha^{-1} and 250 kg ha^{-1}. The mean ± SE. Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

3.5. STK Content

In Table 3, a clear trend is shown for the STK content, with SR-N250 > TP-N250 > SR-N0 > TP-N0 observed at both soil depths (0–20 and 20–40 cm). Specifically, within the 0–20 cm soil depth, SR notably enhanced the STK content by 8.31% (2021) and 8.36% (2022) compared to other treatments. Interestingly, there was no significant difference in the STK content between straw treatments under the same N application at a 20–40 cm soil depth. Furthermore, the STK content exhibited an upward trajectory with increasing N application rates within the 0–20 cm soil depth, although no significant variation ($p < 0.05$) was detected between the N0 and N250 treatments at a 20–40 cm soil depth. Notably, the average STK content at a 0–20 cm soil depth was substantially higher (17.42%) compared to the 20–40 cm soil depth, emphasizing the disparities in soil fertility at different layers.

3.6. Grain Yield and Yield Component

Table 4 shows that both SR and N application rates significantly increased TGW and GN ($p < 0.05$), resulting in a significant impact on the grain yield. The grain yield exhibited a consistent trend of SR-N250 > TP-N250 > SR-N0 > TP-N0 across both years. Specifically, compared to the TP treatment, the SR treatment led to a significant ($p < 0.05$) increase in grain yield by 18.27% and 17.27% in 2020 and 2021, respectively. In addition, N250 had a significantly ($p < 0.05$) increased grain yield compared to N0 under the same straw treatments in both study years. Both GN and TGW showed a similar trend of SR-N250 > TP-N250 > SR-N0 > TP-N0. Under the SR treatment, the GN was significantly higher than TP ($p < 0.05$), with increases of 18.80% and 16.27% in 2021 and 2022, respectively. Similarly, TGW showed significant ($p < 0.05$) increases of 4.96% and 6.51% in SR, respectively, in 2021 and 2022. Furthermore, the TGW and GN of N250 s were significantly higher than that of N0 under the same straw treatment.

Table 3. Soil total potassium (STK, g kg^{-1}) content of 0–40 cm soil layers under straw returning and nitrogen application (N).

Years	Seasons	Treatments	0–20 cm Soil Layer	20–40 cm Soil Layer
2021	Spring	TP-N0	17.19 ± 0.48 c	16.47 ± 0.29 a
		TP-N250	21.75 ± 0.89 ab	17.44 ± 1.15 a
		SR-N0	19.88 ± 0.65 b	16.92 ± 0.48 a
		SR-N250	22.55 ± 0.70 a	17.56 ± 0.58 a
	Autumn	TP-N0	16.36 ± 0.58 b	15.37 ± 0.57 a
		TP-N250	19.47 ± 0.51 a	16.10 ± 0.65 a
		SR-N0	18.44 ± 0.68 ab	15.68 ± 0.49 a
		SR-N250	20.13 ± 0.42 a	16.34 ± 0.41 a
2022	Spring	TP-N0	16.56 ± 0.42 b	16.11 ± 0.26 a
		TP-N250	20.73 ± 0.69 a	17.06 ± 0.69 a
		SR-N0	17.80 ± 0.60 b	16.56 ± 0.79 a
		SR-N250	21.89 ± 0.68 a	17.52 ± 1.35 a
	Autumn	TP-N0	16.46 ± 0.67 b	15.99 ± 0.55 a
		TP-N250	20.78 ± 0.71 a	16.46 ± 0.65 a
		SR-N0	18.41 ± 0.65 b	16.20 ± 0.79 a
		SR-N250	22.66 ± 0.47 a	17.08 ± 0.29 a
			p value	
		Straw return	0.0062	0.4252
		N	0.0003	0.0918
		Straw return × N	0.2219	0.9856

TP, traditional planting; SR, straw returning; N0 and N250 indicate nitrogen application 0 kg ha^{-1} and 250 kg ha^{-1}. The mean ± SE. Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

Table 4. Grain yield and yield component of maize under straw return and nitrogen application (N).

Years	Seasons	Treatments	Grain Number (ear^{-1})	Thousand Grain Weight (g)	Grain Yield (kg ha^{-1})
2021	Spring	TP-N0	240 ± 14.95 b	255.74 ± 1.04 d	2366 ± 72.65 d
		TP-N250	508 ± 4.50 a	306.31 ± 0.20 b	6000 ± 144.34 b
		SR-N0	307 ± 12.81 c	268.99 ± 0.38 c	2916 ± 83.33 c
		SR-N250	533 ± 6.53 a	311.63 ± 1.65 a	6666 ± 83.33 a
	Autumn	TP-N0	113 ± 8.62 d	222.90 ± 0.99 d	1750 ± 144.34 d
		TP-N250	508 ± 1.54 b	276.06 ± 0.30 b	5666 ± 83.33 b
		SR-N0	255 ± 5.00 c	245.25 ± 1.49 c	2666 ± 83.33 c
		SR-N250	532 ± 2.80 a	287.77 ± 0.74 a	6416 ± 83.33 a
2022	Spring	TP-N0	205 ± 7.17 d	251.47 ± 3.61 d	2283 ± 88.19 d
		TP-N250	436 ± 1.04 b	290.37 ± 1.53 b	5950 ± 76.38 b
		SR-N0	259 ± 6.01 c	263.60 ± 4.87 c	2866 ± 44.10 c
		SR-N250	509 ± 5.70 a	304.67 ± 3.71 a	6700 ± 86.60 a
	Autumn	TP-N0	218 ± 6.70 d	217.47 ± 0.86 d	2583 ± 44.10 d
		TP-N250	364 ± 6.18 b	262.83 ± 2.51 b	6300 ± 104.08 b
		SR-N0	251 ± 1.83 c	236.40 ± 3.33 c	1733 ± 16.67 c
		SR-N250	403 ± 14.59 a	284.03 ± 2.84 a	5766 ± 88.19 a
				p value	
		Straw return	0.0073	0.0015	0.0003
		N	0.0001	0.0001	0.0001
		Straw return × N	0.0260	0.0884	0.7483

TP, traditional planting; SR, straw returning; N0 and N250 indicate nitrogen application 0 kg ha^{-1} and 250 kg ha^{-1}. The mean ± SE. Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

3.7. Correlation Analysis

Correlation coefficients were utilized to evaluate the correlation between the characteristics of the soil and the yield of the grain (Figure 4). The results indicated a positive correlation among TN, SOC, LOC, STP, STK, GN, TGW, and grain yield. Specifically, grain yield exhibited significant ($p < 0.01$) and strong positive correlations with TN, SOC, LOC, STK, GN, TGW, and STP ($p < 0.05$) with correlation coefficients of 0.97, 0.95, 0.98, 0.98, 0.99, 0.99, and 0.74, respectively. Moreover, SOC, LOC, STK ($p < 0.01$), and STP ($p < 0.05$)

showed significant and positive correlations with TN. Furthermore, GN and TGW ($p < 0.05$) significantly and positively correlated with grain yield.

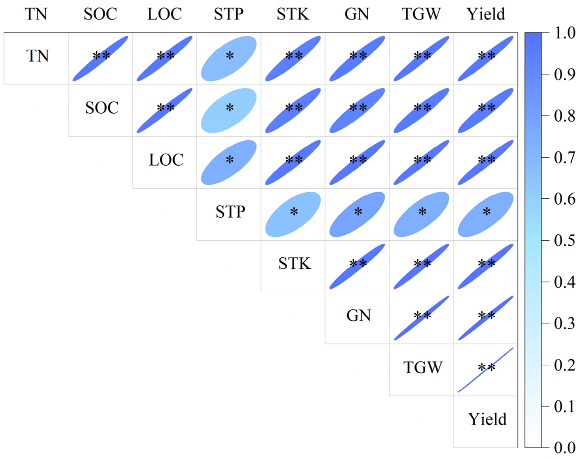

Figure 4. The correlation analysis of total nitrogen (TN), soil organic carbon (SOC), labile organic carbon (LOC), soil total phosphorus (STP), soil total potassium (STK) stem, grain number (GN), thousand-grain weight (TGW), and grain yield during 2021–2022. * $p < 0.05$ and ** $p < 0.01$.

3.8. Relationship between Years and SOC Content during 2018–2022

The linear regression showed a significant ($p < 0.01$) positive correlation between years and SOC content, and the correlation coefficient (R^2) under the different straw treatments was higher than 0.85 (Figure 5). From 2018 to 2022, the SOC content increased as the year increased. Furthermore, the SOC content of SR increased more rapidly compared with the TP, and the SOC content under the SR was higher than TP during the same years.

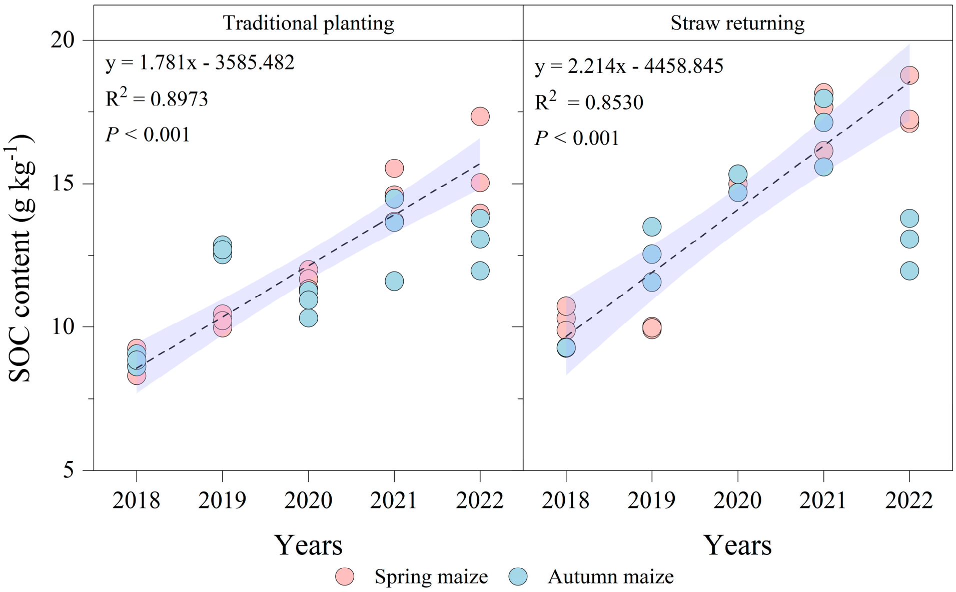

Figure 5. Regression analysis between years and soil organic carbon (SOC) content under the different straw treatments during 2018–2022. The black line represents the linear regression line; the light purple shaded area delimits the 95% confidence band.

4. Discussion

4.1. SR and N Application Increase Soil N and C (Carbon) Pool

According to earlier research, SR enhances the chemical and physical characteristics of soil [24]. SR has the potential to enhance crop production's SOC, LOC, and MBC content [25]. As such, it may be crucial for the advancement of sustainable agriculture.

Over time, adding straw to a field can boost agricultural yield by stimulating the formation of crop roots, minimizing soil water evaporation, increasing soil water storage capacity, and creating perfect water conditions for crop growth [8]. Common agronomic practices include applying nitrogen, and higher N fertilization can boost crop yields [26].

TN encompasses both organic and inorganic N, emerging as a key factor impacting soil characteristics [27]. Our findings showed that TN content was significantly influenced by appropriate rates of N application and SR (Figure 1; $p < 0.05$). This phenomenon has been validated by various studies, including those conducted by Zhao et al. [28,29] and Jin et al. [30]. This link can be ascribed to the N application's capacity to manage the soil's C/N ratio post-SR, hence producing an environment suitable to microbial diversity and straw residue breakdown [31]. Moreover, elevated N transformation and biological processes contribute to the enhancement of soil TN levels [27]. Greater quantities of residues heightened biological activities increased N mineralization, and subsequent enrichment in the soil TN content was observed [32]. These findings align with prior research studies [33], which also suggest that soil fertility is higher in spring maize compared to autumn maize, likely due to the optimal conditions for straw decomposition in the soil (e.g., water, temperature).

The most dynamic element of the soil C reservoir is LOC, which is highly responsive to external C additions [34]. The findings of this investigation indicate that SR coupled with suitable N application rates increases the soil LOC content (Figure 3). Our study showed that compared with TP, SR increased the LOC content by 14.92% in 2021 and 19.53% in 2022. This observation can be attributed to the enhanced cellulase activity after SR, which is helpful in increasing LOC content and straw decomposition [35]. Ndzelu et al. [36] found that some labile organic components like LOC are released into the soil after SR. In addition, the increasing microbial activity, which was improved by crop straw, facilitates the transformation of plant residue-C into LOC [37]. Our results showed that only in the 0–20 cm soil layer did the SR have a significant effect on LOC content. This may be due to the fact that compared with the 20–40 cm soil layer, the upper layer (0–20 cm soil layer) demonstrated better physical characteristics, such as porosity and water storage characteristics, which can support microbial activities [37].

Several studies have shown that SR, combined with N application, could increase the soil SOC content, which is consistent with our results [38,39] (Figure 2). According to Zhang et al. [40], SOC often correlates to climate, cropping system, and tillage management. After SR, a large number of LOCs are released by straw residue decomposition, increasing SOC content [41]. These LOCs can stimulate microbial growth and increase soil microbial biomass [42]. After that, increasing microorganisms can accelerate straw decomposition [43]. N application significantly increases the aboveground and root biomass, which improves the input of the soil C pool [44]. Moreover, N application facilitates straw decomposition and mineralization to provide sufficient N [45]. Our experimental investigation revealed that SR-N250 exhibited higher levels of TN, LOC, and SOC compared to other treatments, indicating the beneficial impact of combining SR with N application for the accumulation of these three components. Interestingly, we observed that the 0–20 cm soil layer had higher concentrations of TN, LOC, and SOC in our study. This occurrence can be attributed to the following two primary factors: (i) favorable soil temperature and higher water content in the 0–20 cm soil layer promoting straw decomposition [45]; (ii) crop residues are obtained in large quantities due to fertilization, primarily in the form of belowground biomass [46].

4.2. Effect of SR and N Application on STP and STK Content

Table 2 shows that STP content increased after SR and N application, as reported by Niu et al. and Huang et al. [47,48]. Zhuang et al. [4] showed that maize straw was one of the contributors to the STP content. The underlying reason for the increase in STP content may be that SR provides more energy to soil microorganisms, optimizes microbial activities, and stimulates the secretion of soil P enzymes [49]. Throughout the study, a progressive decline in STP concentration was noted as the soil depth increased. This decrease can be ascribed to various factors, including the uptake of phosphorus by plant roots in the deeper soil layers and the restricted movement of phosphorus, thereby limiting its leaching ability from the topsoil [9].

The results indicate that SR and N applications can significantly affect STK content (Table 3). Previous research has extensively shown that the application of soil replenishment (SR) can enhance potassium (K) uptake and is beneficial for maintaining soil K levels in agricultural fields [50]. According to Xiong et al. [51], SR has the potential to increase the percentage of small pores (<69.2 μm) and medium pores (69.2–500 μm) in the soil, facilitating water absorption by plant roots. In turn, this allows for the movement of K to the roots of crops, promoting their growth. Our study indicates a gradual decline in STK levels with increasing soil depth, supporting the findings from Zhao et al. [52] and Wang et al. [22].

4.3. Impact of SR and N Application on Grain Yield and Yield Component

The present research examined the impact of applying SR and N on the yield of maize and its components (Table 4; $p < 0.05$). In addition, experimental results revealed that the yield and the yield component of SR-N250 were higher than those of SR-N0. This may be due to the soil C/N content, which increases in the early stage of SR, and microorganisms compete with crops for N in the soil. Therefore, SR combined with an appropriate N application rate can give full play to the benefits of straw [18]. Furthermore, the results also indicated that N250 significantly increased the GN, TGW, and grain yield of spring and autumn maize ($p < 0.05$). Hu et al. [27] suggested that the increasing N application rate could enhance maize yield to a certain point, beyond which the yield may plateau or even decline. Throughout the two-year experiment, the yield component and yield of spring maize exceeded those of autumn maize. This may be attributed to the fact that autumn maize is sown in August, during a period of high temperatures, which can negatively impact the seedling stage of maize. Additionally, the light intensity and temperature decrease after the flowering stage of autumn maize affects its photosynthesis during the critical period and subsequently impacts grain dry matter accumulation [53].

4.4. Correlation Analysis between Soil Properties and Grain Yield

The presence of soil nutrients is vital for maize growth and yield. Enhancing soil nutrient levels through the use of SR and nitrogen can create a better soil environment, facilitating the growth and development of crops [7]. As shown in Figure 4, there were noticeable correlations between maize yield and various soil nutrients, including GN, TGW, TN, SOC, LOC, STP, and STK. Research by Liu et al. [2] indicated that the synergy between SR and N boosts the absorption of soil nutrients by plants, leading to the increased accumulation of dry matter in maize and, ultimately, higher grain yields. The study unveiled that soil nutrient levels were significantly higher under the SR-N interaction compared to those under TP conditions and N0 treatment, resulting in a notably increased grain yield ($p < 0.05$).

4.5. Effect of Continuous SR on SOC Content

Microbial development primarily relies on SOC as its main energy and nutrient source [28]. Research by Banger et al. [54] further supports the fact that SOC originates from integrated crop residues and organic matter deposited by plant roots. Incorporated waste degrades quickly and replenishes the field with significant amounts of C, improving soil quality and increasing fertility [55]. Five-year study results showed that the SOC content under the TP treatment was lower than those of the SR treatment for the same year and increased as the year increased. In comparison to TPs, SRs are better at enhancing SOC levels, as seen in studies by Liu et al. [2] and Yang et al. [31]. This could be attributed to the higher straw incorporation, promoting the breakdown and release of straw remnants and boosting soil nutrient levels [7]. Root leftovers from crops play a vital role in SOC accumulation within agricultural settings [56]. The rise in the SOC content within the

TP over time might be attributed to effective farming practices that stimulate crop root development, consequently boosting the root residue and enhancing SOC intake [57].

5. Conclusions

Our experimental results indicate that incorporating SR with a suitable N application rate could notably enhance the soil SOC and LOC levels within the 0–20 cm soil layer ($p < 0.05$). SR and suitable N application rates significantly promoted the soil TN, SOC, LOC, STP, and STK content in the 0–20 cm soil layer ($p < 0.05$). The content of soil TN, SOC, LOC, STP, and STK decreased with soil depth, as indicated by higher levels in the 0–20 cm soil layer compared to the 20–40 cm soil layer. In addition, SR and suitable N application rates significantly increased the grain yield and yield component of maize ($p < 0.05$). From 2018 to 2022, the SOC content under the SR continued to increase, indicating that SR was beneficial to the accumulation of SOC. The theoretical foundation is provided for enhancing maize yield in the subtropical areas of Southwest China through the efficient use of straw and nitrogen applications.

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