The Crop Residue Removal Threshold Ensures Sustainable Agriculture in the Purple Soil Region of Sichuan, China

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Abstract: Sichuan, a hilly area in southwestern China, is recommended as a bioethanol production base because of its abundant crop residue resources. However, removing the crop straw for bioethanol may negatively affect soil fertility and productivity due to the local purple soil vulnerability. To explore the impact of crop residue removal on soil fertility and productivity and meet the needs of sustainable agriculture, we conducted a crop residue removal experiment by measuring the soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) contents, and crop yield in the purple soil region in southwest China. Soil erosion was also simulated by Revised Universal Soil Loss Equation version 2 (RUSLE 2). The results showed that soil erosion increased with the increase of the straw removal rate. Compared with 0% removal treatment, the SOC content reduced at other removal rate treatments, especially for long-term residue removal. The effect of residue removal on soil TN and TP was not consistent within one year. After two years, residue removal greater than 25% caused a decrease in TN by 1.6–3.7%, and straw removal greater than 50% caused a TP decrease by 8.5–9.3%. More than 25% of the residue removed reduced maize and canola yields, and TN and TP content. However, all crop residue removal treatments resulted in SOC content reduction and soil erosion deterioration. In conclusion, crop residue removal was not recommended due to agricultural sustainability in Sichuan, China.

Keywords: purple soil; residue removal; soil productivity; sustainable agriculture

1. Introduction

The Sichuan Basin, with its rich biodiversity and complex landscapes in southwestern China, is the main agricultural production region in the upper reaches of the Yangtze River [1]. The primary soil type in this region is purple soil, which is often neutral or alkaline [2]; rich in mineral nutrients [3]; and prone to weathering, erosion, and leaching [4]. Sichuan was recommended as a bioethanol production base because of its adequate straw resources (the annual straw production accounts for approximately 12% of the country’s total annual straw production) [5]. Therefore, it is foreseeable that the utilization of straw resources will happen at a large scale in the near future [6]. However, ignoring the effect of residue removal on soil physical and chemical properties may not suitable for sustainable agriculture [7]. Although making full use of residue resources is essentially in line with sustainable agriculture requirements, there are more aspects to consider, such as soil erosion control, fertility loss, and productivity deteriorating.

Crop residue plays a vital role in reducing soil erosion [8]. Crop residue retention can provide a physical protective layer for the soil, reduce the direct impact of raindrops on the soil surface, reduce the soil surface and infiltration runoff, and effectively reduce soil hydraulic erosion [9], especially in high rainfall areas. Nelson et al. [10] found through the Revised Universal Soil Loss Equation version 2 (RUSLE 2) model that the removal of...
straw under different soil types and planting systems in the Central Plains of the United States caused significant soil erosion and organic matter loss. Therefore, residue removal impaction on soil loss in the purple soil area prone to erosion is worthy of attention.

Moreover, crop residue is critical to maintaining and improving soil fertility [11–14]. Straw retention provides a significant amount of organic matter to the soil, thereby affecting soil organic carbon (SOC). Many studies showed that although crop residue removal led to decreased SOC content, the degree of decline in SOC content varied for different climates and soil conditions [15–19]. A decreased SOC content adversely affects soil fertility; fertilizer nutrient utilization; and, therefore, crop yield [20]. In addition, crop residue removal changes the nutrient content in the soil. After a comprehensive analysis of 156 published studies worldwide, Wang et al. [21] concluded that the return of straw to the field directly promoted the accumulation of the total nitrogen (TN) in the soil by investing a large amount of organic and inorganic N. Meanwhile, Damon et al. [22] confirmed by using a model that the application of crop straw with low P concentration to the field did not significantly contribute to increasing the soil P content. However, some studies showed that the application of soybean and wheat straw would increase the availability of P because the content of P in plant biomass significantly increased when soybean and wheat straw were returned to the field [23,24]. The impact of straw management on soil fertility also depends on the climate and soil type [25]. However, the impact of straw management on soil fertility in the purple soil area has rarely been reported, and further research is needed.

Crop straw is essential in maintaining soil productivity and crop growth. Maintaining the crop residue in the field could keep the soil at a high moisture level, reduce the penetration resistance and promote crop root growth [23]. Straw retention could slow down the N fertilizer movement into the deep soil, thereby improving the absorption of N by crops and promoting crop growth [26]. During the decomposition of crop residue, a series of low molecular weight organic acids may be released, improving the availability of P in soil and promoting crop growth by reducing the nutrient-adsorption capacity of clay minerals [12]. Furthermore, some studies showed that keeping straw in the field could increase crop yield [8,27].

Soil and crop responses to crop residue removal are site-specific, as different responses are observed for different climates and soil conditions [25]. Few studies have been conducted on crop residue management in China’s hilly regions, particularly in regions with purple soil [2]. Therefore, one must explore the impact of crop residue removal on soil productivity and crop growth in purple soil to ensure sustainable agriculture.

To investigate the effects of crop residue removal on the purple soil properties and productivity, we conducted an on-farm experiment in purple regions and used the RUSLE 2 model to simulate soil erosion under various residue removal levels. The objectives of this study were (1) to explore the impact of different crop residue removal rates on the soil chemical properties and erosion loss, (2) to assess the soil productivity by measuring crop yields under different residue removal conditions, and (3) to determine the maximum residue removable rate in the researched area.

2. Materials and Methods
2.1. Site Description
An on-farm field experiment began in 2018 in Chengdu City, Sichuan Province, China (30°29’11” N, 104°38’42” E). The research plot is located in the middle of the hilly region of the Sichuan Basin, which is elevated at 430 m above sea level. The experimental site was characterized as having a subtropical monsoon climate with abundant rainfall (annual rainfall is 1190 mm) and high summer temperature (25°C). The rainfall and temperature data of the trial during the experiment are shown in Figure 1. The soil type is purple soil, and the international classification is Purple-Udic Cambisols [28]. The soil texture was classified as clay loam (42% sand, 26% silt, and 32% clay) with initial properties of 12.8 g kg\(^{-1}\) soil organic carbon (SOC), 29.1 g kg\(^{-1}\) soil inorganic carbon (SIC), 420 mg kg\(^{-1}\) total phosphorus (TP), 115 mg kg\(^{-1}\) total nitrogen (TN), and pH 8.14.
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2.3. Soil Sampling

The field had been in the “summer maize–winter canola” rotation for 70 years before the experiment. The summer maize growing period spanned from May to August each year, following a fallow period from August to October. The winter canola planting period lasted from October to May of the following year. Each experimental plot was 5 m × 5 m in size. The experimental design was a complete randomized block with 5 treatments and 4 replicates. The treatments included crop residue removal at 5 rates (i.e., 0%, 25%, 50%, 75%, and 100% of the total crop straw in the field) after harvest. After each crop harvest, the corresponding amount of straw was removed according to the different removal rates, following which the remaining straw was evenly spread on the soil surface (see Figure 2).

Figure 2. Field scene after crop residue removal at various rates (taken on 11 May 2019).

Although crop residue removal was performed according to our experimental design, the local producers implemented other agricultural management measures to restore the actual agricultural practices. Moderate tillage (tumble and loosen 0–10 cm soil on the surface) was conducted after crop residue removal. Urea was applied as an N fertilizer...
for 825 kg ha\(^{-1}\) every year. The main component of the phosphate fertilizer was superphosphate (P\(_{2}\)O\(_{5}\)), which accounted for more than 12%, and was applied 1500 kg ha\(^{-1}\) every year. During the summer maize planting period (April to August every year), urea was applied at a rate of 450 kg ha\(^{-1}\), and the phosphate fertilizer was applied twice at the rates of 225 kg ha\(^{-1}\) (maize seedling period) and 525 kg ha\(^{-1}\) (maize heading period). During the winter canola growing season (October to April of the following year), urea and phosphate fertilizer were applied once at the rates of 375 kg ha\(^{-1}\) and 750 kg ha\(^{-1}\), respectively.

2.3. Soil Sampling

The experiment began in April 2018. The soil was sampled during April 2018, August 2018, December 2018, April 2019, August 2019, November 2019, and April 2020. The specific field operation time is presented in Table 1. A total of 3 kg of soil was randomly sampled from 0–10 cm depth from each experimental plot. The soil sample collected from each plot was evenly mixed and air-dried, following which the soil samples were subjected to chemical analysis (SOC, TN, and TP).

Table 1. Specific field operations from 29 April 2018 to 1 May 2020.

| Time             | Experimental Duration 1 | Field Operation                      |
|------------------|-------------------------|--------------------------------------|
| 29 April 2018    |                         | Initial soil sampling                 |
| 15 May 2018      |                         | Canola residue removal                |
| 27 May 2018      |                         | P fertilizer application              |
| 21 June 2018     | 3 m                     | Soil sampling                        |
| 21 August 2018   |                         | Maize harvesting                     |
| 28 August 2018   |                         | N and P fertilizer application        |
| 1 December 2018  | 7 m                     | Soil sampling                        |
| 21 December 2018 | 23 April 2019           | Maize residue removal                |
| 21 August 2018   | 28 August 2018          | Soil sampling and canola harvesting  |
| 11 May 2019      | 12 m                    | Soil sampling and canola harvesting  |
| 24 May 2019      |                         | Canola residue removal                |
| 18 June 2019     |                         | P fertilizer application              |
| 18 August 2019   | 15 m                    | N and P fertilizer application        |
| 27 August 2019   |                         | Soil sampling                        |
| 25 November 2019 | 18 m                    | Maize residue removal                |
| 28 April 2020    | 24 m                    | Soil sampling and canola harvesting  |
| 1 May 2020       |                         | Canola residue removal                |

1 Experimental duration represents the time elapsed since the first straw removal.

2.4. RUSLE 2

Rainfall erosivity factor \(R\) is a function of rainfall intensity and runoff. The \(R\) factor was calculated by using the daily rainfall [29] as follows:

\[
R = \sum_{m=1}^{24} R_m
\]

\[
R_m = \alpha \sum_{j=1}^{k} P_j^\beta
\]

\[
\alpha = 21.586\beta^{-7.1891}
\]

\[
\beta = \frac{0.8363 \times 18.177 + 24.455}{P_{d12}}
\]

where \(R\) is rainfall erosivity (MJ mm hm\(^{-2}\) h\(^{-1}\) a\(^{-1}\)), \(R_m\) is the rainfall erosivity (MJ mm hm\(^{-2}\) h\(^{-1}\) a\(^{-1}\)) in the m-th half-month period, \(k\) is the number of days in the half-month period, \(P_j\) is the erosive daily rainfall (mm) on day \(j\) in a half-month period, \(\alpha\), \(\beta\) are the model parameters, \(P_{d12}\) is the average daily rainfall of 12 mm and above, and \(P_{y12}\) is the average annual rainfall with a daily rainfall of 12 mm and above; our calculation result was 7936.0 MJ mm hm\(^{-2}\) h\(^{-1}\) a\(^{-1}\).
Soil erodibility factor $K$ characterizes the difficulty of soil erosion. In this study, the $K$ factor was calculated on the basis of soil mechanical composition and soil organic matter [30]. Soil mechanical composition and other soil physical properties had been reported in other literature [31]. The $K$ factor was calculated as follows:

$$K = \left(0.2 + 0.3e^{-0.0256SAN(1 - \frac{SAN}{100})}\right) \times \left(\frac{SIL}{CLA + SIL}\right)^{0.3} \times \left[1 - 0.25C + e^{(3.72 - 2.95C)}\right] \times \left[1 - 0.7SN_1 + e^{(22.9SN_1 - 5.51)}\right]$$

where $SAN$ is the sand content (%), $SIL$ is the silt content (%), $CLA$ is the clay content (%), and $C$ is the content of soil organic matter (%); our calculation result was $0.045$ t h MJ$^{-1}$ mm$^{-1}$.

The slope of cultivated land in the Sichuan hilly area is mainly from $0^\circ$ to $15^\circ$ [32]. Thus, we selected five slopes of $0^\circ$, $2.5^\circ$, $5^\circ$, $10^\circ$, and $15^\circ$ to simulate soil erosion. In this study, the slope length of the slope was $5$ m in order to be consistent with the size of our test plot. $C$ and $P$ are the factors that characterize coverage management and soil and water conservation measures, respectively. $C$ and $P$ factors were estimated through the establishment of field rotation patterns in the model. Firstly, we established a summer corn-winter rape rotation system, field crop yields in each period, and the conversion of the added amount of corn stalks at each removal rate. Then we import rotation patterns to the management sub-module of the RUSLE 2 (version 2.6.1.9) model to estimating the $C$ and $P$ factors during the rotation period [33].

2.5. Measurement of Soil Properties

2.5.1. Soil Organic Carbon

The combustion–oxidation nondispersive infrared absorption method was used to determine the SOC content [34]. The soil was air-dried and passed through a $0.097$ mm sieve to obtain an experimental soil sample. Subsequently, $0.0500$ g of the soil sample was put in a quartz cup with a small amount of glass wool. After that, a $3\%$ phosphoric acid solution was added to the quartz cup until no bubbles evolved. The quartz cup was then put into a total organic carbon analyzer to measure the SOC content of the sample as follows:

$$w_{oc} = \left(\frac{A - A_0 - a}{b \times m}\right)$$

where $w_{oc}$ is the SOC content (g kg$^{-1}$) of the soil sample; $A$ and $A_0$ are the sample and blank sample response value of total organic carbon analyzer, respectively; $a$ is the intercept of the standard curve; $b$ is the slope of the standard curve; and $m$ is the quality (g) of the dry matter in the soil sample.

2.5.2. Soil TN

The TN content of the soil was measured by the modified Kjeldahl method [35]. The soil was air-dried and passed through a $0.25$ mm sieve to obtain an experimental soil sample. Subsequently, $0.2000$–$1.0000$ g of the soil sample was digested in a Kjeldahl digestion bottle. The digestion solution was then distilled in the Kjeldahl distillation unit. The liquid obtained after distillation was titrated with hydrochloric acid ($0.01$ mol L$^{-1}$) until the solution color changed from blue-green to purple-red, and the volume of the hydrochloric acid solution used was recorded. The TN content was calculated as follows:

$$w_N = \frac{(V_1 - V_0) \times c_{HCl} \times 14.0 \times 1000}{m \times w_{dm}}$$

where $w_N$ is the TN content (mg kg$^{-1}$) in the soil sample; $V_1$ and $V_0$ are the volume (mL) of the hydrochloric acid solution consumed by the sample and blank, respectively; $c_{HCl}$ is
2.5.3. Total Phosphorus Content in Soil

The TP content in the soil was calculated according to the amount of a standard hydrochloric acid solution. To that end, a 0.2500 g air-dried soil sample was obtained from each research plot and then passed through a 0.149 mm diameter sieve, following which the TP content was determined by using the Mo–Sb anti-spectrophotometric method [36]. The soil sample and NaOH were put in a nickel crucible and burned in a high-temperature muffle furnace. After the sodium hydroxide was melted, all the phosphorus-containing minerals and organic phosphorus compounds in the soil sample were converted to soluble orthophosphate. The soluble orthophosphate was then converted to a solution by pickling. Under acidic conditions, orthophosphate reacted with the Mo–Sb anti-coloring agent to produce phosphorus molybdenum blue, and the absorbance was measured at 700 nm wavelength by using a spectrophotometer. Within a specific concentration range, the total phosphorus (TP) content and absorbance value in the sample complied with the Lambert–Beer law, and the TP content in the soil was calculated by measuring the absorbance. The TP content was calculated as follows:

\[ w = \left( \frac{[A - A_0] - a}{b \times m \times w_{dm} \times V_2} \right) \times V_1 \]  

where \( m \) is the TP content (mg kg\(^{-1}\)); \( A \) and \( A_0 \) are the absorbances of the soil sample and blank test, respectively; \( b \) is the slope of the standard curve; \( m \) is the quality of the soil sample; \( w_{dm} \) is the dry matter content of the soil sample (%); and \( V_1 \) and \( V_2 \) are the sample constant volume and sample volume (mL), respectively.

2.6. Crop Harvest and Residue Removal

Crops from an area of 2 m\(^2\) were sampled for production statistics. The collected crop samples were oven-dried at 56 °C for 7 d. After drying, the crop grains were peeled off and weighed to calculate the total crop sample grain weight of each plot, and then the total grain weight of each plot was calculated. After crop harvesting, the corresponding amount of straw was removed according to different removal rates, and the remaining straw was evenly spread on the soil surface.

2.7. Statistical Analysis

The one-way analysis of variance (ANOVA) was conducted to examine the impacts of residue removal rates on the SIC, SOC, TN, and TP contents and crop yield. The two-way ANOVA was conducted to examine the impacts of treatment, time, and their interactions on the SIC, SOC, TN, and TP contents. Significant differences between treatments and between times were calculated by Duncan’s test via SPSS (version 25). Treatments and time were considered different when \( p < 0.05 \).

3. Results
3.1. ANOVA of Treatment Effects

The results of the ANOVA are presented in Table 2. The results showed that the crop residue removal rate, duration, and interaction significantly \( (p < 0.05) \) affected the SOC and TP contents. The yield of each crop was only compared across removal rates, and the results were significant. However, there were no significant effects of the crop residue removal rate and duration on the TN contents in the short term.
Table 2. Effects of the crop residue removal and time on the soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) contents and yield.

| Variable     | SOC | TN | TP | Yield |
|--------------|-----|----|----|-------|
| Treatment    | *   | -  | *  | *     |
| Duration     | *   | -  | *  | na    |
| Trt × Du     | *   | -  | *  | na    |

Symbols indicate statistical significance: - = no significance; * = significant at \( p \leq 0.05 \); na = no comparison.

3.2. RUSLE 2

Figure 3 shows soil erosion modulus A under different residue removal rates and cultivated land slope conditions. In general, the soil loss increased with the increase of straw removal rate under all different slopes. At a 0° slope, the soil losses under lower removal rates were relatively limited except that the soil loss under 100% removal treatment exceeded 10 t hm\(^{-2}\) a\(^{-1}\). When the slope was 2.5°, the soil loss under different residue removal rates was still small, and the soil loss under soil loss 0% removal rate was only 8.1 t hm\(^{-2}\) a\(^{-1}\). When the cultivated land slope increased to 5°, the soil loss under the complete removal treatment exceeded 100 t hm\(^{-2}\) a\(^{-1}\). When the slope increased from 5° to 10°, the soil loss under different straw removal rates rose sharply, and the increments were 124.1%, 125.4%, 129.3%, 128.9%, and 129.6% as the residue removal rate increased from 0% to 100%. When the slope reached 15°, the soil loss at each removal rate exceeded 100 t hm\(^{-2}\) a\(^{-1}\) except for the 0% removal treatment.

Figure 3. Simulation of soil erosion modulus A (t hm\(^{-2}\) a\(^{-1}\)) under different residue removal rates and cultivated land slope conditions.

3.3. SOC Content

Figure 4a shows the change in the SOC content under various residue removal rates at each sampling period. Generally, the crop residue removal resulted in a decrease in the SOC content in this study. The reduction in the SOC content caused by residue removal became more evident as the experimental period prolonged. Within one year of residue removal, the SOC content did not show a consistent change. Only the SOC at 50% and 75% removal rate in the third month showed a significant decrease relative to 0% removal treatment. After one year, relative to 0% removal treatment, residue removal caused a significant SOC reduction, and the SOC contents under 50% removal rate were always minimum.
Figure 4. SOC content in the soil. (a) Comparison of the SOC contents at various crop residue removal rates for the same sampling period. (b) Comparison of the SOC contents across different sampling periods at the same residue removal rate. Treatments with different letters indicate significant differences at the $P=0.05$ level. The absence of letters indicates no significant differences.

Figure 4b shows changes in the SOC content across different sampling periods at the same residue removal rate. In general, the SOC content at each removal rate fluctuated over time. Within one year from when the experiment was initiated, the SOC content under each removal rate did not show consistent changes over time, but the SOC content eventually increased from 3rd month to the 12th month. After more than one year of straw removal, the SOC content at each removal rate first decreased and then increased over time. Compared between the 3rd month to the 24th month, the SOC contents at all removal rates reduced, but only the complete removal treatment was significant.

3.4. TN Content

Figure 5a compares the soil TN content change at various residue removal rates for the same sampling periods. Generally, the effect of residue removal rate on the soil TN content was not evident in the short term, but a long-term high rate removal reduced TN significantly. There was no significant difference in the TN content under each removal rate within one year of residue removal. As the removal period increased, the TN under high residue removal treatments gradually decreased. After 24 months of straw removal, the TN content at 50% and above removal rates decreased significantly relative to 0% removal.
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Figure 5b shows the soil TN content change across different sampling periods at the same residue removal rate. Generally, at each removal rate, the TN under each removal rate showed an increasing trend over time. Under each residue removal rate, the TN content showed different changes with time within one year of residue removal. However, after more than one year of residue removal, the TN content under each residue removal rate gradually increased with time. From the 3rd month to the 24th month, the TN content under each removal rate increased, but only the increase under the 100% removal rate was not significant.

3.5. TP Content

Figure 6a shows the change in the soil TP content at various residue removal rates for the same sampling period. Generally, the TP content did not consistently change with the straw removal rate at each sampling time. When the residue removal time did not exceed one year, the maximum TP content always appeared at high removal rates. However, as time went on, this situation began to change, and the TP content at low removal rates raised. After 24 months of residue removal, the TP content at 50% and 75% removal rates decreased significantly compared to other removal rates.

Figure 5. TN content in the soil. (a) Comparison of the soil TN contents at various crop residue removal rates for the same sampling period. (b) Comparison of the soil TN contents across different sampling periods at the same residue removal rate. Treatments with different letters indicate significant differences at the $p = 0.05$ level. The absence of letters indicates no significant differences.

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Figure 6b shows the soil TP content change across different sampling periods at the same residue removal rate. Overall, the straw removal at a lower rate was beneficial to the accumulation of TP. At 0% and 25% removal rates, the TP content increased with time, generally showing an increasing trend. On the other hand, at other removal rates, no consistent changes were observed. After 24 months of straw removal, the TP content under each removal rate increased relative to the third month, but the 75% and 100% removal rate was not significant. Generally, after two years of straw removal, the TP content of 50% removal rate and below accumulated, and the TP content under other removal rates did not change significantly.

Figure 6. TP content in the soil. (a) Comparison of the soil TP contents at various crop residue removal rates for the same sampling period. (b) Comparison of the soil TP contents across different sampling periods at the same residue removal rate. Treatments with different letters indicate significant differences at the $p = 0.05$ level. The absence of letters indicates no significant differences.

3.6. Yield

Figure 7 shows the crop yields under different straw removal rates for the same sampling time. For all harvesting, the maximum yield was obtained at 0% removal treatment. Both the canola yields decreased with the increase of residue removal rate, and the yields at 75% and 100% removal rates decreased significantly relative to 0% removal treatment. For canola in 2019, the yield ranged from 1540 to 2732 kg ha$^{-1}$, while the yield ranged from 2922 to 3855 kg ha$^{-1}$. The order of the yield of maize in 2018 at different removal rates was 0% > 25% > 100% > 75% > 50%. The yields at 50%
3.6. Yield

Figure 7 shows the crop yields under different straw removal rates for the same sampling period. Treatments with different letters indicate significant differences at the \( p = 0.05 \) level. The absence of letters indicates no significant differences. Maize 2018 represents the maize yield in 2018 (August 2018), Canola 2019 the canola yield in 2019 (April 2019), Maize 2019 the maize yield in 2019 (August 2019), and Canola 2020 the canola yield in 2020 (April 2020). Because the maize and canola varieties were different, their yields were not compared with each other, and the yields here were crop grain yields.

Table 3 presents the harvest index (HI) index at each removal rate. No significant difference was observed in the HI index at each removal rate. The HI of maize was between 0.51 and 0.57, and that of canola was between 0.24 and 0.25.

Table 3. Harvest index (HI) at each removal rate.

|        | 0%    | 25%   | 50%    | 75%    | 100%   |
|--------|-------|-------|--------|--------|--------|
| Maize 2018 | 0.53  | 0.52  | 0.54   | 0.51   | 0.57   |
| Canola 2019 | 0.24  | 0.25  | 0.25   | 0.25   | 0.24   |
| Maize 2019 | 0.52  | 0.51  | 0.53   | 0.53   | 0.52   |
| Canola 2020 | 0.25  | 0.24  | 0.25   | 0.24   | 0.25   |

4. Discussion

4.1. Impact of Residue Removal on Soil Erosion

Soil erosion is always considered an essential factor in reducing agricultural productivity [9]. Our results showed that soil loss increased with the increasing straw removal rate. Crop residue mulch reduced the direct impact of raindrops by providing surface protection and reduced water flow by increasing the surface roughness of the soil, thereby reducing runoff [37]. Therefore, after removing the straw, the impact of raindrops on the soil and the runoff increased, resulting in more significant soil erosion. Park et al. [37] also reported the same conclusion. The decrease in SOC (see Figure 4) caused by straw removal may also
be the reason for the increased soil erosion. The decrease of SOC content that can be used as the binder of soil aggregates affected the stability of soil aggregates [38]. In the previous report of this study, it was also reported that the stability of soil aggregates decreased after straw removal [31], which was related to the decrease of SOC content. The reduced stability of soil aggregates led to more significant soil loss.

The purple soil in the southwest hilly areas had a high degree of weathering and low water and fertilizer retention capacity. Xu et al. reported [39] that the soil erosion intensity of purple soil was second only to that of yellow earth, and returning straw to the field was considered an effective management practice to reduce soil erosion and N losses from purple soils. Studies [40] showed that in order to maintain expected field productivity, the annual topsoil loss should not exceed 0.092 cm, meaning the allowable soil loss is 11.04 t hm$^{-2}$ a$^{-1}$. When the slope was 0$^\circ$, the soil loss under each straw removal rate could maintain the field productivity except for the 100% removal treatment. However, under other slopes in this study, only the slope of arable land was 2.5$^\circ$ at 0% removal rate met the minimum standards for maintaining purple soil productivity and fertility. In the Sichuan hilly areas, it is not advisable to consider 0$^\circ$ cultivated land under actual production conditions. Thus, we do not recommend straw removal when the slope of the cultivated land reaches 2.5$^\circ$ in Sichuan purple soil region.

4.2. Impact of Residue Removal on SOC, TN, and TP

The SOC content is governed by the dynamic balance of the C input and output [17]. Agreeing with other studies, our results showed that a high straw removal rate decreased the SOC content, especially for a long experimental duration [11,14,20]. The crop residue removal reduces the input of C into the soil, thereby reducing the SOC content. As for C output, the increase in straw removal increased soil erosion and thus increased C output (Figure 7). Therefore, the crop residue removal reduced the SOC content by reducing C input and increasing C output. Naab et al. [20] found that after returning all the straw to the field, the SOC storage of 0–20 cm soil was significantly increased. However, in our research, returning all straw to the field (0% removal rate) for two years did not increase the accumulation of SOC but only maintained the SOC content of the soil. This result may be attributed to a large amount of soil erosion in the test area with abundant rainfall and purple soil, which was prone to erosion.

Some studies showed that straw removal reduced the N content of soil [21,41]. Our results showed that residue removal did not significantly change the TN content (see Figure 5) within one year. This observation may be attributed to the short experimental period, residue nutritional properties, and the nature of purple soil, which is rich in nutrients [3]. One reason why residue removal did not change soil TN content in the short term is that the C/N ratio of maize and canola straws is more than 120 [42]. Meanwhile, a large amount of N fertilizer was used in the field every year, making the soil TN content stable. However, with the increase in the experimental period, a high removal rate treatment tended to decrease the TN content.

The precipitation pattern was also one reason for changes in soil TN and TP content. From the 3rd month to the 12th month, the test area had little rainfall (Figure 1). Therefore, the difference in soil erosion under different removal rates was small, and there was no significant difference in TN content as well. However, from the 12th month to the 18th month, the rainfall was heavy (Figure 1), and the effect of straw to reduce soil erosion began to appear. The TN content under the high removal rates with more soil erosion was significantly lower than the low removal treatment.

In this study, the crops planted were maize and canola, with low P content in their residues [23]. Studies showed that the returning of straw with low P content did not significantly contribute to the soil P content in either the short or long term [22]. However, our results showed that low straw removal rates (0%, 25%, and 50%) were beneficial to the TP content increase. The source of the increased P in the soil may be mainly the application of P fertilizer (1500 kg ha$^{-1}$ a$^{-1}$). Similar to TN, from the 3rd month to the 12th month,
the effect of straw removal on the TP content was not significant. With the advent of a period of high rainfall (12th to 18th month), the difference in soil erosion under different removal rates led to the difference in TP content.

4.3. Impact of Residue Removal on Yield

This study found that excessive straw removal resulted in reduced crop yields, which agreed with other research works \[8,26,42\]. Crop yield is affected by many factors, including the SOC content. A high SOC content could favor crop growth by enhancing the bond between soil particles, increasing soil porosity \[42\], and improving soil structure and water conditions \[43\]. Increasing or maintaining the SOC content is critical to maintaining soil fertility and crop productivity \[20\]. In our study, the decrease in SOC content caused by straw removal may be a reason for crop yield reduction. Percentage-wise, maize yield was more susceptible to straw removal than canola yield. The effect of straw removal on soil loss was more substantial during summer maize growth with high rainfall (see Figure 1). Therefore, the SOC content reduction caused by soil loss was more sensitive to straw removal in the summer and led to maize yield more susceptible to straw removal than canola yield.

A high N fertilizer usage efficiency is another reason for higher crop yields at low removal treatments. Without straw mulch, a high level of effective N would be produced in the soil at an early N fertilizer application stage, resulting in a high risk of leaching \[44\]. In the case of residue coverage, the residue first fixed the potential N leaching upon decomposition. In the later stage of straw decomposition, N was released and supplied to the crops for absorption, thereby establishing an effective link between N supply and crop demand \[12,24,43\] and enhancing the utilization efficiency of the N fertilizer. Therefore, higher yields were obtained at low removal treatments.

High nutrient availability is also a reason for high crop yields at low removal treatments. The residue releases a series of low molecular weight organic acids \[45\], which reduce the nutrient-adsorption capacity of the clay minerals and replace the adsorbed nutrients (such as P) during the decomposition process \[27,44\]. Therefore, the input of straw facilitates the release of nutrients combined with minerals, thereby increasing the availability of nutrients in the soil \[46\]. Consequently, more straw input makes the soil have higher nutrient availability, thereby obtaining high yields at low removal treatments.

4.4. How Much Crop Residue Can Be Safely Removed

Two years after the experiment was initiated, the TN and TP contents and yield under 25% straw removal rate did not decrease significantly compared to 0% removal treatment. Moreover, the content of TN and TP did not decrease over time under a 25% removal rate. Therefore, from the perspective of TN content, TP content, and yield, a 25% straw removal rate was acceptable in the purple soil area.

From the perspective of SOC and soil erosion, however, crop residue should not be removed, especially in the purple soil area. Compared to the 0% removal rate, the SOC content at other removal rates decreased after two years from the beginning of the experiment. In addition, the SOC content under treatments with more than 0% straw removal lost over time, indicating that straw removal was not conducive to the accumulation of SOC. As for soil erosion, only the soil loss under 100% removal rate exceeded the allowable amount of soil loss in purple soil at a slope of 0°. However, the ideal situation where the purple soil slope in Sichuan was 0° was minimal and not representative. Under other slopes in this study, only the soil loss wherein the slope of arable land was 2.5° at 0% removal rate met the minimum standards for maintaining purple soil productivity and fertility. Therefore, from the perspective of SOC content and soil erosion, crop residue should not be removed in the purple soil area of Sichuan.
5. Conclusions

After analyzing two-year data of residue removal experiments in the purple soil region, we drew the following conclusions:

(1) Residue removal significantly increased soil erosion of purple soil, and the amount of soil erosion increased with the increase of residue removal rate. High straw removal rate would significantly decrease the SOC content (relative to 0% removal treatment), and the decrease in the SOC content became more evident as the experiment time increases.

(2) The effect of residue removal on soil TN and TP was not consistent within one year. After two years, residue removal greater than 25% caused a decrease in TN by 1.6–3.7%, and straw removal greater than 50% caused a TP decrease by 8.5–9.3%.

(3) TN, TP, and yield decreased at plots with more than 25% straw removal. In contrast, SOC content reduction and soil erosion deterioration occurred at all residue removal treatments. In conclusion, crop residue removal was not recommended due to agricultural sustainability in Sichuan, China. We suggest a long-term study of the residue removal effect on purple soil to guide sustainable crop residue management strategies in this area.

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