Mung Bean Is Better Than Soybean in the Legume–Wheat Rotation System for Soil Carbon and Nitrogen Sequestration in Calcareous Soils of a Semi-ARid Region

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Abstract: Small changes in soil aggregates-associated organic carbon and soil nitrogen (N) can induce huge fluctuations in greenhouse gas emissions and soil fertility. However, there is a knowledge gap regarding the responses to long-term continuous rotation systems, especially in N-fixing and non-N-fixing crop wheat in terms of the distribution of soil aggregates and the storage of soil carbon (C) and N in aggregates in the semi-arid calcareous soil of Central China. This information is critical for advancing knowledge on C and N sequestration of soil aggregates in rainfed crop rotation systems. Our aim was to determine which legume (soybean (Glycine max)–or mung bean (Vigna radiata)–wheat (Triticum aestivum) rotation practice is more conducive to the formation of good soil structure and C and N fixation. A 10-year field experiment, including a soybean (Glycine max)–winter wheat (Triticum aestivum) rotation (SWR) with yield increments of 2020 compared to 2010 achieving 18.28% (soybean) and 26.73% (wheat), respectively, and a mung bean (Vigna radiata)–winter wheat rotation (MWR) achieving 32.66% (mung bean) and 27.38% (wheat), as well as farmland fallow, was conducted in Henan Province, China. The soil organic carbon (SOC), N content in the soil, and the soil aggregates were investigated. Legume–wheat rotation cropping enhanced the proportion of the >2 mm soil fractions and reduced the <0.053 mm silt + clay in the 0–40 cm soil profile. In the 0–30 cm soil layer, the SWR had a greater increment of the >2 mm aggregate fractions than the MWR. Two legume–winter wheat rotations enhanced the C and N sequestration that varied with soil depths and size fractions of the aggregate. In contrast, the MWR had greater SOC stocks in all fractions of all sizes in the 0–40 cm soil layers. In addition, the greater storage of N in the macro-, micro-, and silt + clay fractions was observed in the 0–30 cm layers; the MWR enhanced the C/N ratios in most of the size aggregates compared with the SWR. The MWR cropping system is more beneficial to the formation of good soil structure and the increasement of C and N reserves in soil. Thus, these findings show that mung bean, in contrast with soybean in the legume–wheat rotation system of a semi-arid temperate zone, may offer soil quality improvement.

Keywords: aggregates C; aggregates N; long-term; legume–wheat; rotation cropping

1. Introduction

Cropping rotation plays crucial roles in balancing inter-crop nutritional management, reducing biotic stressors, inhibiting soil degradation, and adapting to climate change [1,2]. Previous studies have already displayed the beneficial influences of crop rotation [3] at multiple levels, including crop yields as well as soil’s physical and chemical properties [4,5]. The rotation of nitrogen (N)-fixing and non-N-fixing crops is a recommended planting pattern to improve soil fertility in farmland [6,7]. Leguminous crops can increase the N utilization rate of subsequent crops [8]. Leguminous crops in rotation have been used as a
sustainable alternative to nitrogen fertilizer [9–11]. Soils, in which leguminous crops are planted, accumulate lower soil organic carbon (SOC) [12,13] due to easily decomposed residues with a lower C/N ratio [14,15]. However, leguminous plants prevent the mineralization of SOC by increasing the formation and stability of soil aggregates, thus promoting the soil carbon (C) storage [16–18]. Information about the effect of legume crop rotations on soil aggregates and C pools is important in order to understand the mechanism underlying SOC sequestration [19]. Previous investigations have been conducted to learn the effects of crop rotation with legumes on soil aggregation and carbon sequestration [19–24]. However, there is limited information about the effects of different legume species in rainfed legume–wheat rotation on the sequestration of soil C and N, which is very important to understand for maintaining cropland productivity and also for mitigating greenhouse gas emissions.

The cropping pattern and the integration of anthropogenic disturbances on farmland markedly influence the stability and distribution of soil aggregates [16,25]. Usually, intensive cropping cultivation leads to the disruption of soil aggregates and the losses of SOC [23,26]. Generally, SOC protected by the macro-aggregates is only stored for the short duration while the majority of the stable C is stored in the smallest silt + clay size fraction (<0.053 mm) [23]. Thus, soil aggregate fractionations have been widely applied to evaluate the stability of SOC and the influences of land use on the dynamics of SOC [15,27].

In recent years, in order to improve legume production, China advocates planting patterns of legume–wheat/maize rotation cropping in major grain-producing areas. Therefore, additional studies are needed on the rotation between legumes and non-nitrogen-fixing wheat crop in non-irrigation areas. However, the information is scanty about the effects of long-term rotation of which legume crop and wheat crop on the distribution of soil aggregates and the storage of C and N in aggregates for soil quality improvement. This information is critical for advancing knowledge on soil C and N sequestration in crop rotation systems in rainfed area. Based on a long-term rotation experiment using wheat and two different leguminous crops (soybean and mung bean) which began in 2010 in central and western China, we performed an investigation to compare the differences in SOC and the influences of land use on the dynamics of SOC [15,27].

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2. Materials and Methods

2.1. Experimental Site and Treatments

The experiment was started with the wheat season in October 2010 and located in Luoyang, Henan Province, China (N 34°32′, E 112°16′), a region where summer legume–winter wheat rotation has long been practiced. The climate is a semiarid temperate zone with a continental monsoon. The mean annual meteorological data were as follows: 12.1–14.6 °C temperature, 600 mm rainfall, 2113.7 mm evaporation, >2300 h sunshine hours, >215 days frost-free period, and 491.5 kJ m⁻² radiation. During the study period, average precipitation and temperature were 606 mm and 14.3 °C, respectively. At the study site, the soil was Calci-Ustic Luvisols with a sandy–loamy texture (USDA Soil Taxonomy). The soil properties in 2010 were as follows: soil density 1.31 g cm⁻³, alkalized nitrogen 33.86 mg kg⁻¹, available phosphorus 3.46 mg kg⁻¹, organic matter 10.72 g kg⁻¹, and pH 7.56. Beginning in 2010, a long-term experiment was initiated including three treatments: winter wheat–soybean rotation (SWR), winter wheat–mung bean rotation (MWR), and continuous farmland fallow (Fallow). The treatments were arranged in a completely randomized design. Four replicates were conducted with a 500 m² plot per replicate.

2.2. Crop Cultivation

Winter wheat was sown in late October every year and harvested in early June of the next year. Soybeans and mung bean were sown in mid-June and harvested in mid-October every year. Field management of fertilization, tillage, and residue management can be
seen in Table 1 below, and others followed the standard cultivation practices in this region. Information on yield or biomass could be found in Table 2. Specifically, the yield and biomass were 2718–3215 kg ha\(^{-1}\) (yield) and 6214–6554 kg ha\(^{-1}\) (biomass) of soybean and 5640–7148 kg ha\(^{-1}\) (yield) of wheat in SWR system during the period of 2010 to 2020, and corresponding amounts were 1730–2295 kg ha\(^{-1}\) (yield) and around 7791–8976 kg ha\(^{-1}\) (biomass) of mung bean and 5642–7187 kg ha\(^{-1}\) (yield) of winter wheat in the MWR system, respectively. The yield of soybean and mung bean increased by 18.28% and 32.66%, and the yield of wheat increased by 26.73% and 27.38% in SWR and MWR over the past 10 years, respectively.

Table 1. The description of fertilization, tillage, and residue management.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Tillage</th>
<th>Nutrient Management</th>
<th>Residue Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Rotary tillage twice, Deep plowing every two years</td>
<td>120:60:40 (N:P(_2)O(_5):K(_2)O kg ha(^{-1})), 65% N + full P + full K as basal fertilizer with plowing, 35% N applied at wheat jointing stage.</td>
<td>100% wheat residue incorporated</td>
</tr>
<tr>
<td>Soybean</td>
<td>Zero till</td>
<td>1 kg ha(^{-1}) of rare earth compound fertilizer applied with sowing</td>
<td>100% soybean residue incorporated</td>
</tr>
<tr>
<td>Mung bean</td>
<td>Zero till</td>
<td>1 kg ha(^{-1}) of rare earth compound fertilizer applied with sowing</td>
<td>100% mung bean residue incorporated</td>
</tr>
<tr>
<td>Fallow</td>
<td>Zero till</td>
<td>No fertilization</td>
<td>100% return of growth to the field</td>
</tr>
</tbody>
</table>

Table 2. Information on yield and biomass of crops during 2010–2020 years.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Planting Year</th>
<th>Cultivar</th>
<th>Average Yield (kg ha(^{-1}))</th>
<th>Crop Geometry</th>
<th>Seed Rate (kg ha(^{-1}))</th>
<th>Shoots (kg ha(^{-1}))</th>
<th>Roots (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>2010–2014</td>
<td>zhoumai 18</td>
<td>5640</td>
<td>20 (row to row), 3</td>
<td>110–130</td>
<td>8380</td>
<td>8412</td>
</tr>
<tr>
<td></td>
<td>2015–2017</td>
<td>zhoumai 23</td>
<td>6625</td>
<td>20 (row to row), 3</td>
<td>110–130</td>
<td>9100</td>
<td>9200</td>
</tr>
<tr>
<td></td>
<td>2018–2020</td>
<td>zhoumai 27</td>
<td>7148</td>
<td>20 (row to row), 3</td>
<td>110–130</td>
<td>9400</td>
<td>9468</td>
</tr>
<tr>
<td>Soybean</td>
<td>2010–2014</td>
<td>zhoudou 19</td>
<td>2718</td>
<td>40 (row to row), 0.17–0.19</td>
<td>75–80</td>
<td>6214</td>
<td>762</td>
</tr>
<tr>
<td></td>
<td>2014–2016</td>
<td>yudou 22</td>
<td>2965</td>
<td>40 (row to row), 0.18–0.23</td>
<td>75–80</td>
<td>6033</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>2017–2020</td>
<td>yudou29</td>
<td>3215</td>
<td>40 (row to row), 0.18–0.23</td>
<td>75–80</td>
<td>6554</td>
<td>804</td>
</tr>
<tr>
<td>Mung bean</td>
<td>2010–2014</td>
<td>zhonglv 10</td>
<td>1730</td>
<td>50 (row to row), 0.14–0.15</td>
<td>25.5–30</td>
<td>7791</td>
<td>289</td>
</tr>
<tr>
<td></td>
<td>2015–2017</td>
<td>zhenglv 8</td>
<td>1898</td>
<td>50 (row to row), 0.15–0.16</td>
<td>25.5–30</td>
<td>8644</td>
<td>321</td>
</tr>
<tr>
<td></td>
<td>2018–2020</td>
<td>kedalv 2</td>
<td>2295</td>
<td>50 (row to row), 0.19–0.23</td>
<td>25.5–30</td>
<td>8976</td>
<td>334</td>
</tr>
</tbody>
</table>

2.3. Soil Sampling and Analysis

Soil samples were collected when mung bean and soybean were harvested in October 2020. In each plot, 500 g soil samples well-distributed were collected from three depths (0–20, 20–30, and 30–40 cm) with a 3 cm diameter soil drill. Soil density was determined by weighing five randomly selected sampling points. For each depth class per plot, five sub-samples were mixed as a composite sample. Fresh soil samples were first screened through an 8 mm sieve. After being air-dried, the thoroughly mixed samples were used for the following analysis. Aggregate analysis followed the wet-sieving method from Six et al. [23] and Kou et al. [28]. Briefly, the sample was divided into four size fractions of soil aggregates (>2, 2–0.25, 0.25–0.053, <0.053 mm). Water-stable large (>2 mm), macro (2–0.25 mm), micro-aggregates (0.25–0.053 mm), and the silt + clay-sized fraction (<0.053 mm) were collected. Different size aggregates were weighed after oven drying until constant weight (at 50 °C), and the percentage of each size fraction was calculated. For further analysis of aggregate-associated C and N, groups of soils were used to determine SOC and total N by sieving the soil through a 0.149 and 0.841 mm sieve, respectively. The contents of C and N of all soil samples were measured with a CHNS/O analyzer (Vario MACRO CUBE).
2.4. Calculation

The C storage in each size aggregate for a specific soil layer of thickness \( d \) was calculated as follows:

\[
C_{\text{storage}} = C_{\text{concentration}} \times BD \times d \times 10 \times A,
\]

where \( C_{\text{storage}} \) refers to the total SOC with a given depth and soil size fraction within the soil profile (Mg ha\(^{-1}\)), \( C_{\text{concentration}} \) refers to C content in a certain soil size fraction (g kg\(^{-1}\)), \( BD \) is bulk density (Mg m\(^{-3}\)), and \( d \) is a given depth of the soil profile (cm). \( A \) is the aggregate content at a given depth (g kg\(^{-1}\)).

The N storage in each size aggregate for a specific soil layer of thickness \( d \) was calculated as follows:

\[
N_{\text{storage}} = N_{\text{concentration}} \times BD \times d \times 10 \times A,
\]

where \( N_{\text{storage}} \) refers to the total N for a given depth and soil size within the soil profile (Mg ha\(^{-1}\)), \( N_{\text{concentration}} \) refers to N content in a certain soil size aggregate (g kg\(^{-1}\)), \( BD \) is bulk density (Mg m\(^{-3}\)), and \( d \) is a given depth of the soil profile (cm). \( A \) is the aggregate content at a given depth (g kg\(^{-1}\)).

The C/N ratio in each size aggregate for a specific soil layer was calculated as follows:

\[
\frac{C}{N} = \frac{C_{\text{storage}}}{N_{\text{storage}}},
\]

where \( C_{\text{storage}} \) and \( N_{\text{storage}} \) refers to nutrient reserves of the same soil particle size in the same soil layer within the soil profile (Mg ha\(^{-1}\)).

The contribution rate of the aggregate (%) = [nutrient content of the aggregate size (g kg\(^{-1}\)) × the aggregate size content (%)/soil nutrient content] × 100.

2.5. Statistical Analysis

The analysis of data was performed with the analysis of variance (ANOVA) conducted in SPSS 11.5 software (SPSS Inc., Chicago, IL, USA) and least significant difference (LSD) test was used to evaluate the significance of the differences among the treatments at \( p < 0.05 \). Origin 2019 was used to plot the data.

3. Results

3.1. Effects of Long-Term Rotations on Aggregate Stability and Size Distribution

Long-term land use systems have changed the distribution of the aggregates in the soil, and the effect on the 0–20 cm soil layers is greater than 20–30 cm and 30–40 cm soil layers (Figure 1).

Overall, the soil fraction size classes were in the following order: macro-aggregates > silt + clay fraction > micro-aggregates > large aggregates. Different land use types had different effects on the distribution of different size fractions with soil depth in the 0–40 cm profile. The >2 mm fractions in the fields employing the continuous crop rotations with leguminous crops were significantly increased by 93–116.6% in the topsoil (0–40 cm), compared to the Fallow treatment, while the <2 mm fractions were decreased by 4.34–2.8% in the 0–20 cm layer. The SWR observably enhanced the proportions of large aggregates (>2 mm) by 28.2–42.0% in the 0–30 cm soil layer but dramatically decreased the proportions of large aggregates by 34.0% in the 30–40 cm soil layer, compared to the corresponding layers in the MWR. The SWR increased the macro-aggregates (2–0.25 mm) by 7.69% in the 20–30 cm layer while markedly decreased that in the 30–40 cm layers, compared to the MWR. The micro-sized fractions (0.25–0.053 mm) in the SWR treatment were significantly, 7.08–11.0%, lower in the 20–40 cm layer than the MWR. Moreover, the silt + clay fractions were observably lowered by 7.97–31.5% in the 0–30 cm soil layer of the SWR compared to the MWR. In the MWR, the silt + clay fractions were markedly increased by 30.4% in the 30–40 cm soil layer compared to the SWR. From the MWD values (Table 3), both the
SWR and MWR treatments were higher than those in the Fallow treatment in the 0–40 cm soil layer. The MWD values of the MWR treatment in the 0–30 cm soil layer were lower than those in the SWR treatment, and the MWD values in the 30–40 cm soil layer were significantly lower than those in the MWR treatment. This may be due to the role of mung bean roots in promoting the formation of water temperature aggregates in the soil.

![Figure 1](image-url)

**Figure 1.** Distribution of soil aggregates in the 0–40 cm soil profile of plots with three different treatments (N 34°32′, E 112°16′). Note: Different small letters above the bars indicate significant differences among treatments at the level. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively. Values are means ± 1 SE (n = 4).

**Table 3.** Mean weight diameter (MWD) of soil aggregate in different treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>MWD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–20 cm</td>
</tr>
<tr>
<td>SWR</td>
<td>1.01 ± 0.017 a</td>
</tr>
<tr>
<td>MWR</td>
<td>0.97 ± 0.015 b</td>
</tr>
<tr>
<td>Fallow</td>
<td>0.93 ± 0.015 c</td>
</tr>
</tbody>
</table>

Note: Values followed by different lowercase letters in a column indicate a significant difference at 0.05 level among treatments of 0–40 cm soil layers. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively.

3.2. Effects of Long-Term Different Rotations on the Content of SOC in Aggregates

Long-term different crop rotation systems significantly affected the SOC content of aggregates in each soil layer (Table 4), and the content of SOC in the aggregates was different from the SOC content in the soil (Table 5); the SOC content of each treated soil was roughly similar to that of 0.25–0.053 mm aggregates. The SOC content tends to decrease with the soil depth. For different size aggregates, the SOC content of the same treatment decreases with the reduction of the particle level, that is, the highest >2 mm, the lowest <0.25 mm.
Table 4. Organic carbon contents of each size of water-stable aggregates in 0–20, 20–30, and 30–40 cm soil layers under different rotation system.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Treatment</th>
<th>&gt;2 mm</th>
<th>2–0.25 mm</th>
<th>0.25–0.053 mm</th>
<th>&lt;0.053 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>Fallow</td>
<td>21.5 ± 0.70 aA</td>
<td>14.2 ± 0.86 cA</td>
<td>13.4 ± 0.93 cB</td>
<td>13.1 ± 0.05 cB</td>
</tr>
<tr>
<td></td>
<td>SWR</td>
<td>18.5 ± 0.22 bA</td>
<td>15.9 ± 0.57 bA</td>
<td>15.3 ± 0.3 aB</td>
<td>15.4 ± 0.31 bA</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>21.2 ± 0.75 aA</td>
<td>18.7 ± 0.72 aA</td>
<td>17.3 ± 0.26 aA</td>
<td>17.1 ± 0.69 aA</td>
</tr>
<tr>
<td></td>
<td>Fallow</td>
<td>14.2 ± 0.17 bC</td>
<td>12.2 ± 0.17 bC</td>
<td>11.9 ± 0.31 bC</td>
<td>12.5 ± 0.53 bC</td>
</tr>
<tr>
<td></td>
<td>SWR</td>
<td>13.3 ± 0.30 cB</td>
<td>11.6 ± 0.26 cB</td>
<td>11.4 ± 0.24 cB</td>
<td>11.4 ± 0.51 cB</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>16.3 ± 0.29 aB</td>
<td>14.6 ± 0.19 aB</td>
<td>14.3 ± 0.05 aB</td>
<td>14.2 ± 0.10 aB</td>
</tr>
<tr>
<td></td>
<td>Fallow</td>
<td>18.5 ± 0.21 aB</td>
<td>14.1 ± 0.17 aB</td>
<td>13.7 ± 0.4 aA</td>
<td>14.4 ± 0.38 aA</td>
</tr>
<tr>
<td>20–30</td>
<td>SWR</td>
<td>10.6 ± 0.51 cC</td>
<td>9.4 ± 0.28 cC</td>
<td>9.4 ± 0.35 cC</td>
<td>9.8 ± 0.37 cC</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>13.5 ± 0.05 bC</td>
<td>11.8 ± 0.24 bC</td>
<td>11.6 ± 0.13 bC</td>
<td>11.8 ± 0.63 bC</td>
</tr>
</tbody>
</table>

Note: Values followed by different lowercase letters in a column indicate a significant difference at 0.05 level among treatments of 0–40 cm soil layers, and values followed by different uppercase letters in a row indicate a significant difference at 0.05 level among particle sizes. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively.

Table 5. Soil organic carbon and total nitrogen contents in soil layers under various long-term rotation systems.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Treatment</th>
<th>SOC (g kg⁻¹)</th>
<th>TN (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>Fallow</td>
<td>13.92 ± 0.63 c</td>
<td>1.15 ± 0.03 b</td>
</tr>
<tr>
<td></td>
<td>SWR</td>
<td>15.49 ± 0.38 b</td>
<td>1.43 ± 0.25 a</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>17.05 ± 0.12 a</td>
<td>1.32 ± 0.06 ab</td>
</tr>
<tr>
<td></td>
<td>Fallow</td>
<td>12.02 ± 0.15 a</td>
<td>0.81 ± 0.05 c</td>
</tr>
<tr>
<td>20–30</td>
<td>SWR</td>
<td>11.43 ± 0.21 c</td>
<td>0.92 ± 0.05 b</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>14.34 ± 0.14 a</td>
<td>1.09 ± 0.04 a</td>
</tr>
<tr>
<td></td>
<td>Fallow</td>
<td>13.88 ± 0.11 a</td>
<td>0.86 ± 0.01 a</td>
</tr>
<tr>
<td>30–40</td>
<td>SWR</td>
<td>9.29 ± 0.23 c</td>
<td>0.79 ± 0.01 c</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>11.79 ± 0.21 b</td>
<td>0.81 ± 0.02 b</td>
</tr>
</tbody>
</table>

Note: Values followed by different lowercase letters in a column indicate a significant difference at 0.05 level among treatments of 0–40 cm soil layers. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively. SOC and TN are the abbreviations of soil organic carbon and total nitrogen, respectively.

In the 0–20 cm soil layer, the SOC content of the Fallow treatment aggregates decreased with the particle level, which was 21.5 g kg⁻¹, 14.2 g kg⁻¹, 13.4 g kg⁻¹, 13.1 g kg⁻¹, respectively, and the SOC content of the aggregates (>2 mm aggregates) decreased significantly in the SWR treatment compared with the Fallow treatment. The decrease was 20.6%, and the other aggregates increased significantly, with an increase of 12.0–17.6%. In contrast to the >2 mm aggregates of MWR treatment not increasing significantly, the other aggregates increased significantly, an increase of 29.1–31.7%. MWR treatment was significantly higher than SWR, and the increase of SOC at each level was 14.6%, 17.6%, 13.1%, and 11.0%, respectively.

In the 20–30 cm soil layer, the SWR treatment decreased to varying degrees compared with Fallow treatment, with a decrease of 4.2–8.8%, and the MWR treatment increased by different degrees, with an increase of 13.6–20.2%. Compared with SWR treatment, the SOC content of soil in aggregates of MWR treatment increased by 22.6–25.9%. In the 30–40 cm soil layer, the SOC content of each treatment aggregates was similar to that of the 0–20 cm soil layer, and the content of SWR and MWR treated aggregates decreased significantly compared with Fallow treatment, with the drops of 31.4–42.7% and 15.3–27.0%, respectively.

3.3. Effects of Different Long-Term Rotations on the Content of Total Nitrogen in Aggregates

Different crop rotation systems significantly affected the N content of the aggregates in each soil layer (Table 6), and the content of soil TN in each treatment was roughly similar to that of the two aggregates of 0.25–0.053 mm (Table 5). Similar to SOC, the total nitrogen content of the soil has a tendency to decrease gradually with the increase of soil depth. The
content of TN in the same treatment decreased with the reduction of the particle level, that is, the highest in >2 mm aggregates, the lowest in <0.053 mm aggregates.

**Table 6.** Soil total nitrogen contents of each size of water-stable aggregates in 0–20, 20–30, and 30–40 cm soil layers under different rotation system.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Treatment</th>
<th>&gt;2 mm</th>
<th>2–0.25 mm</th>
<th>0.25–0.053 mm</th>
<th>&lt;0.053 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>Fallow</td>
<td>1.80 ± 0.00 aA</td>
<td>1.18 ± 0.05 bA</td>
<td>1.03 ± 0.05 bA</td>
<td>1.10 ± 0.08 bA</td>
</tr>
<tr>
<td></td>
<td>SWR</td>
<td>1.60 ± 0.08 bA</td>
<td>1.50 ± 0.34 abA</td>
<td>1.30 ± 0.00 aA</td>
<td>1.38 ± 0.10 aA</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>1.78 ± 0.10 aA</td>
<td>1.58 ± 0.1 aA</td>
<td>1.35 ± 0.06 aA</td>
<td>1.23 ± 0.22 abA</td>
</tr>
<tr>
<td>20–30</td>
<td>Fallow</td>
<td>0.93 ± 0.05 cC</td>
<td>0.83 ± 0.05 cC</td>
<td>0.83 ± 0.05 bB</td>
<td>0.78 ± 0.10 bB</td>
</tr>
<tr>
<td></td>
<td>SWR</td>
<td>1.05 ± 0.06 bB</td>
<td>0.93 ± 0.05 bB</td>
<td>0.95 ± 0.06 aB</td>
<td>0.98 ± 0.10 aB</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>1.25 ± 0.10 aA</td>
<td>1.13 ± 0.05 ab</td>
<td>1.00 ± 0 aB</td>
<td>1.10 ± 0.08 aA</td>
</tr>
<tr>
<td>30–40</td>
<td>Fallow</td>
<td>1.08 ± 0.10 abB</td>
<td>0.90 ± 0.00 aB</td>
<td>0.88 ± 0.10 aB</td>
<td>0.78 ± 0.05 abB</td>
</tr>
<tr>
<td></td>
<td>SWR</td>
<td>0.85 ± 0.06 bc</td>
<td>0.80 ± 0.00 bB</td>
<td>0.78 ± 0.05 aB</td>
<td>0.80 ± 0.00 ac</td>
</tr>
<tr>
<td></td>
<td>MWR</td>
<td>1.54 ± 0.53 aA</td>
<td>0.80 ± 0.00 bc</td>
<td>0.78 ± 0.05 aB</td>
<td>0.73 ± 0.05 bB</td>
</tr>
</tbody>
</table>

Note: Values followed by different lowercase letters in a column indicate a significant difference at 0.05 level among treatments of 0–40 cm soil layers. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively.

In the 0–20 cm soil layer, compared with the Fallow treatment, the SWR treatment had different degrees of increase except for the decrease of TN content of >2 mm, with an increase of 11.8–27.1%; the TN content of each grain level (in addition to >2 mm) of MWR treatment was significantly increased, and the TN content was increased by 0.13–0.40 g kg\(^{-1}\). Compared with the SWR treatment, the TN content of the soil at all grain levels (except < 0.053 mm) was increased 0.18 g kg\(^{-1}\), 0.08 g kg\(^{-1}\), and 0.05 g kg\(^{-1}\), respectively.

In the 20–30 cm soil layers, the SWR and MWR treatments significantly increased the soil TN content in all aggregates. Compared with the Fallow treatment, the TN content of SWR and MWR treatments increased significantly, and the increments were 12.0–25.6% and 20.5–41.1%, respectively. Compared with the SWR treatment, the TN content of the soil in all aggregates was significantly increased by 0.2 g kg\(^{-1}\), 0.2 g kg\(^{-1}\), 0.05 g kg\(^{-1}\), and 0.12 g kg\(^{-1}\), respectively. For 30–40 cm layers, the SWR treatment significantly increased the TN content of the >2 mm aggregates. It can be seen that crop rotation mainly increases the SOC and TN content of >2 mm and 2–0.25 mm aggregates.

3.4. Effect of Long-Term Rotations on Aggregate-Associated Carbon and Nitrogen

The SOC stock in different aggregate size classes was related to land-use type and soil depth (Figure 2). The SOC stocks in the 2–0.25 mm fractions of the 0–20 cm soil layer in the MWR and SWR were observably larger than that of Fallow. In turn, the order of SOC stocks were SWR > MWR > Fallow in the >2 mm fractions and MWR > SWR and Fallow in the ≤2 mm fractions in the 0–20 cm soil layer; MWR > SWR > Fallow in all size fractions (except >2 mm fractions) in the 20–30 cm soil layer; and Fallow > MWR > SWR in all fractions in the 30–40 cm soil layer. The C stored in the ≤2 mm fractions was markedly enhanced in the MWR by 8.5–104% in the 0–30 cm soil layers compared to the Fallow treatment. In addition, the C stored in the >2 mm fractions observably increased in the MWR by 49.2% in the 20–30 cm layer, compared with the corresponding fraction in the Fallow treatment. The SWR only significantly enhanced the C stored in the >2 mm fractions by 120.3% and by 85.5% in the 0–20 cm and 20–30 cm soil layers. The SOC stocks observably increased in the MWR in ≤2 mm fractions by 16.5–38.3% and 8.6–101% in the 0–20 cm and 20–30 cm soil layers, respectively, compared with the SWR. In the >2 mm fractions of 0–20 and 20–30 cm soil layers, the SWR was significantly higher than the MWR.
Two cropping treatments observably enhanced N sequestration in the >2 mm MWR. In the 0–20 cm and 20–30 cm soil layers, respectively, compared with the SWR. In the >2 mm stocks observably increased in the MWR in the aggregates in the 20–40 cm soil layer. The C/N was observably lower (by 13.9%) in the SWR in the 0–20 cm soil layer by 5.3–54.3%, compared to the Fallow treatment. In addition, the C stored in the >2 mm fractions observably increased in the MWR by 9.7–27.2% and by 2.2–81% (p < 0.05) in the 20–30 cm layers compared with the Fallow treatment. The N stored in the >2 mm fractions was observably higher than the Fallow in the < 0.053 mm fractions in the 30–40 cm soil layer (Figure 3). Two cropping treatments observably enhanced N sequestration in the >2 mm fractions in the 30–40 cm layer. The C/N was observably lower (by 13.9%) in the SWR in the 0–20 cm soil layer. Note: Different small letters above the bars indicate significant differences among treatments at the level. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively. Values are means ± 1 SE (n = 4).

Similar dynamics of total N stock as well as SOC stock in different aggregate size classes were generally related to land-use types and soil depth. However, this was not true with SWR ≥ MWR ≥ Fallow in the < 0.053 mm fractions in the 30–40 cm soil layer (Figure 3). Two cropping treatments observably enhanced N sequestration in the >2 mm size fractions of the 20–30 cm soil layer by 75.1–125.2% and those in the <2 mm size fractions of the 0–30 cm soil layer by 5.3–54.3%, compared to the Fallow treatment. The N stored in the silt + clay (≤2 mm) fractions was observably increased in the MWR by 9.7–27.2% and by 2.2–81% (p < 0.05) in the 20–30 cm layers compared with the SWR.

Figure 2. Soil aggregate associated organic carbon in the 0–40 cm soil profile under different land use types. Note: Different small letters above the bars indicate significant differences among treatments at the level. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively. Values are means ± 1 SE (n = 4).

Figure 3. Soil aggregate associated nitrogen in the 0–40 cm soil profile of different land use types. Note: Different small letters above the bars indicate significant differences among treatments at the level. SWR and MWR are the abbreviations of soybean–winter wheat rotation and mung bean–winter wheat rotation, respectively. Values are means ± 1 SE (n = 4).
3.5. Effect of Long-Term Rotations on C/N in Aggregates

The effects of the rotation of leguminous crops with winter wheat on the C/N ratio in aggregates in the 0–20 cm soil layer were less than those in the 20–40 cm layer (Figure 4).

SWR remarkably decreased the C/N ratio in the 0.25–0.053 mm fraction by 7.7–8.2% in the 0–20 cm soil layer, compared with that in the MWR and Fallow treatments. No significant differences were found in the C/N ratio in aggregates between the MWR and Fallow treatments in the 0–20 cm layer. The C/N ratio was lower in SWR in the 20–30 cm and 30–40 cm layers, except for that in the >2 mm fractions of the 30–40 cm soil layer, compared with the MWR and Fallow treatments. MWR had a decreasing tendency in C/N in the aggregates in the 20–40 cm soil layer. Significant decreases were observed in the >2 mm fractions in the 30–40 cm layer. The C/N was observably lower (by 13.9%) in the SWR in the 0.25–0.053 mm fraction of the 20–30 cm soil layer and lower by 21.9–36.1% in the < 2 mm fractions of the 30–40 cm layer. In addition, the C/N was markedly enhanced (by 29.7%) in the >2 mm fractions of the 30–40 cm layer than MWR.

3.6. Effects of Different Long-Term Crop Rotations on the Distribution Ratios of SOC and TN in Aggregates

Long-term crop rotation systems changed the allocation ratio of the SOC in the aggregate (Figure 5) and had a great influence on the 0–20 cm soil layer; mainly distributed in 2–0.053 mm aggregates, >2 mm aggregates had the lowest SOC distribution ratio.

In the 0–20 cm soil layer, compared to the Fallow treatment, the MWR treatment significantly increased the specific SOC allocation ratio of >2 mm aggregates, from 3.9% to 6.43%, and significantly reduced the proportion of SOC allocation in 2–0.25 mm aggregate. However, the SWR treatment significantly increased the SOC content of more than 2 mm, by 3.9% to 7.96%, and significantly reduced the SOC allocation ratio of 0.25–0.053 mm aggregates, and there was no significant difference between aggregate size and the Fallow treatments.
In the 20–30 cm soil layer, the MWR treatment significantly increased the SOC allocation ratios of >2 mm and <0.053 mm aggregates, from 1.99% and 16.9% to 2.64% and 18.7%, respectively, compared to the Fallow treatment, significantly reducing the SOC allocation ratio of 2–0.25 mm aggregates. In the 30–40 cm soil layer, the MWR treatment was significantly higher for the SOC distribution ratios of >2 mm and 2–0.25 mm aggregates.

The effect of long-term crop rotation systems on the allocation ratio of TN in aggregates is similar to that of SOC, as shown in the Figure 5, the TN in different soil layers is still mainly distributed in 2–0.25 mm aggregates.

In the 0–20 cm soil layer, compared with the Fallow treatment, the MWR treatment significantly increased the TN allocation ratio of >2 mm aggregates, from 3.0% to 6.95%, and significantly reduced the TN allocation ratio of 2–0.25 mm aggregates, a decrease of 1.8%, while the SWR treatment significantly increased the TN content of >2 mm aggregates and significantly reduced the TN allocation ratio of 0.25–0.053 mm aggregates. There was no significant difference between other aggregate sizes and the Fallow treatments.

In the 20–30 cm soil layer, the MWR treatment significantly increased the TN allocation ratio of >2 mm and <0.053 mm and significantly reduced the TN allocation ratio of 2–0.25 mm aggregates. In the 30–40 cm soil layer, the TN distribution ratio of the two granular aggregates of 0.25–0.053 mm was significantly higher than that of the other two treatments for the TN distribution ratios of the >2 mm and 2–0.25 mm aggregates, but the TN allocation ratios of the two granular aggregates of 0.25–0.053 mm and <0.053 mm were significantly reduced.

4. Discussion

4.1. Soil Aggregate Fractions

Soil aggregates play a central role in soil structure and C and N pools [29,30]. In this study, the >2 mm aggregates in the 0–40 cm soil layer were observably greater in the SWR and MWR than that in the Fallow treatments after 10-year crop rotations, indicating that the cropping system of legumes (i.e., soybeans and mung beans in this experiment)–winter wheat rotation promoted the formation of large aggregates. Our results were consistent with those of the previous studies, which planted legumes as a cover crop with a grain–sorghum rotation [31] and whose intercropping with alfalfa [32] enhanced the formation of large aggregates of soil. Rillig et al. [33] found that the legume root system contains a high mycelium density, maybe promoting the formation and stability of large aggregates. Large (>2 mm) and macro (<0.25 mm) aggregates in the SWR were greater in the topsoil.
and lower in the 30–40 cm soil layer than those in the MWR. This may be due to the roots of soybean primarily being concentrated in the 0–30 cm layer. In contrast, that the roots of mung bean were more slender and able to reach 30–40 cm deep [34,35]. The micro-sized fractions (0.25–0.053 mm) in the 20–40 cm layer and the silt+ clay fractions in the 0–30 cm soil layer in the SWR were less than those in the MWR, further indicating that the use of soybean in the crop rotation contributes to the formation of better soil structure in the 0–30 cm soil layer than mung bean. In addition, good soil structure generally has higher soil microbe activity, which promotes the mineralization of soil organic matter [28,36] and lower soil C and N sequestration.

4.2. Aggregate-Associated Carbon and Nitrogen

In this study, SOC was mainly stocked in 2–0.25 mm aggregates (Figure 5), and the distribution ratio accounted for more than 70%, which greatly correlated with the high percentage content of aggregate size. However, the experimental results showed that, compared with Fallow treatment, SWR and MWR treatment significantly increased the specific distribution ratio of >2 mm groups. It shows that, with the progress of crop rotation, the proportion of carbon storage in soil aggregates gradually converges to large aggregates. In addition, the correlation between aggregate carbon and nitrogen showed that there was a significant positive correlation between the two, indicating that the change trend of soil aggregate TN was similar to that of SOC. In all treatments, the greater SOC stock was associated with the large aggregates, which was consistent with the results of monocropped soybean [22] and rice–winter wheat rotation [29]. Plant roots are the main source of SOC. A significant increase in C in the ≤2 mm (0–30 cm) and the >2 mm soil fractions (20–30 cm) in MWR and that in the ≤2 mm soil fractions (0–20 cm) in SWR showed that cropping would lead to C enrichment in aggregates [17]. The SOC stocks in all aggregate sizes in the 30–40 cm soil layer from two crop rotation systems were lower than those of the Fallow treatment, further indicating that crop roots primarily were grown in 0–30 cm soil layer [37,38]. The larger SOC stock of MWR was observed in all soil layers and aggregates compared with those of SWR. This may be the integrated effects of the greater shoots and roots biomass of mung bean (mung bean 8785 kg ha\(^{-1}\) while soybean 7035 kg ha\(^{-1}\), Table 2), which enhanced the accumulation of SOC and offered the relatively better soil structure in the SWR (Figure 1) promoting the mineralization of SOC [28,39]. Legume rhizobia and root hairs promote the polymerization of soil aggregation and C in crop and legume rotation systems. Other studies have also found that mung bean turnover [40] and returning soybean straw to the field increased SOC [41,42]. MWR promoted more C sequestration in all size fractions of the 0–40 cm soil layer compared with SWR, suggesting that MWR is better at sequestering SOC.

In our study, total N and SOC stocks in different size aggregates were influenced by land-use type and soil depth. Our results were also supported in a maize and soybean cropping system [22]. Both MWR and SWR enhanced N sequestration in the >2 mm (20–30 cm) and ≤2 mm size fractions (0–30 cm), indicating that legume–winter wheat rotation cropping can increase the soil N content. Numerous studies have shown that mung bean [40] and soybean cropping add soil N via nitrogen fixation [34,41]. The MWR increased the N storage in the ≤2 mm size fractions of the 0–30 cm soil layer compared with SWR. This indicates that mung bean–winter wheat cropping has more N sequestration than soybean–winter wheat cropping. This may be because (1) mung bean fixes more biological N than soybean [39] and/or (2) MWR has less soil N loss from crop uptake (plant N uptake of mung bean was 240 kg ha\(^{-1}\) and that of soybean was 360 kg ha\(^{-1}\) in 2020) and less environmental loss than SWR [34]. Mutualistic relationships between legumes and N-fixing bacteria contribute to the maintenance of aggregate mineral-organic components that prevent sequestration of C and N, which contribute to the improvement of topsoil aggregate C and N pools from the rotation of legumes (mung bean and soybean) and winter wheat [40,43]. However, further research should be conducted on the difference among
rhizobia of mung bean and soybean and how this influences belowground nutrient and soil composition.

4.3. Long-Term Rotation Effect on C/N in Aggregates

The soil C/N ratio is an indirect indicator of organic matter decomposition [44,45]. A lower C/N ratio in aggregates in the 0–20 cm soil layer compared to the 20–40 cm soil layer indicates that SOC in the topsoil (0–20 cm) decomposes more easily than that in the subsoil (20–40 cm). A lower C/N ratio will promote the decomposition of SOC [46,47]. Compared with the MWR, the SWR showed a lower C/N ratio in most of the aggregate fractions in each of the soil profiles, possibly supporting a greater C and N content in MWR.

5. Conclusions

The rotation practices utilizing different leguminous crops and winter wheat affect the storage and stability of SOC and N. Continuous leguminous crops and winter wheat rotation improved the soil structure and added SOC and N storage compared with the fallow farmland control. Continuous mung bean–winter wheat cropping is more conducive to the formation of good topsoil structure and the enrichment of SOC and N in aggregates than continuous soybean–winter wheat cropping. Understanding these differential responses to cropping practices in long-term leguminous crops–winter wheat rotation systems is critical for evaluating the cycling of soil C and N for maintaining cropland productivity and mitigating greenhouse gas emissions. Overall, it can be inferred that the rotation of mung bean and wheat will be conducive to achieving the new national goal of increasing grain production by one hundred billion catties and also will make a certain contribution to the dual carbon goal.

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Data Availability Statement: The data that support the findings of this study are available from the links to the submitted datasets.

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Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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