Effects of Shelter Forests on Soil Organic Carbon of Irrigated Soils in the Taklimakan Desert

Xuexi Ma 1, Zhengzhong Jin 1,2,3,*, Yingju Wang 1 and Jiaqiang Lei 1,3

Abstract: An experiment was carried out to test the effects of artificial vegetation on soil organic carbon in sandy soil. The soils were collected from the Taklimakan desert highway shelter forests with different stand age (the stand ages are 5, 7, 10, 13, 16, respectively, and three shrubs named Calligonum mongolicunl, Tamarix chinensis and Haloxylon ammodendron were planted along the highway) in Xinjiang, northwest of China. The soil organic carbon stock in soil vertical layers were calculated. We measured four passive organic carbons (i.e., micro-aggregates organic carbon, humic organic carbon, acid-resistant organic carbon and antioxidant organic carbon). Furthermore, we analyzed the correlations and ratios among the different passive organic carbons. Finally, the chemical composition of humus was detected and the relative contents of C=O and CH groups were determined. The main results showed that, (1) the soil organic carbon and organic carbon stock were decreased with the increase of depth, mainly in 0–50 cm. (2) With the increase of stand age, only in Tamarix chinensis forest, the total soil organic carbon stock increased a little. (3) Total soil organic carbon had more closely correlation with contents of micro-aggregate organic carbon and humic organic carbon. (4) C=O/C-O-C increased a little after 10 years; CH/C-O-C had no obvious change with stand age; CH2/CH3 did not change obviously after 13 years. The Tamarix chinensis forest is the most helpful for carbon sequestration in sandy soil and stabilization in surface layer than Calligonum mongolicunl and Haloxylon ammodendron.

Keywords: artificial vegetation; stand age; organic carbon stock; passive organic carbon; chemical composition of humus

1. Introduction

Buildup of an artificial shelter forest can bring extensive changes to the local soil properties [1]. SOM is closely associated with soil development [2,3]. SOM accumulation in surface soil indicates early soil development [4]. In a desert environment, after an artificial shelter forest was planted, the litter began to enter into surface soil and can provide nutrition for soil microorganisms, promoting the decomposition of litter [5,6]. SOC is a major component of SOM [7].

Therefore, research on changes of SOC, along with the increase of plantation time of artificial vegetation, can preliminarily clarify the OC dynamics of sandy soil under the influence of artificial vegetation.

SOC is contained in plant, animal and microbial residues in all stages of decomposition; SOC can be divided into active, intermediate and passive pools based on the turnover rate of different compounds [8–11]. Turnover rate of carbon is most often determined by two methods: (a) decomposition studies, (b) natural labeling of SOM using stable 13C
tracers [8]. Generally, the turnover rate of passive carbon is very long, with an average time of more than 100 years [12–14]. Thus, passive carbon pool is more stable to stay in soil for a long time, and research on passive carbon pool along with the change of stand age of artificial vegetation, can reflect the SOC dynamic, which helps to understand the development process of sandy soil. Passive carbon pool can be divided into physical and chemical fractions according to the methods used for the fractionation [8].

Humus is stabilized by humification processes and is considered to be refractory to decomposition, thus humus belongs to the passive SOM pool [15]. Extraction of humus by NaOH and Na$_4$P$_2$O$_7$ generally extracts large quantities of humic material in most soils [16]. Migration of mineral—organic chelate characteristics of the humus [17]. Therefore, humus can be considered as an indicator for SOC dynamics during soil development.

The ability of resistance to the decomposition of organic molecules can increase their own stability and extend turnover time [18], being helpful for carbon accumulation. For example, organic molecules with resistance to hydrolysis, are resistant to soil enzymes and are therefore also more biologically stable [19]. In an extensive review of HCl hydrolysis, we concluded that non-hydrolyzable carbon represented 30 to 80% of total SOC and had an average mean residence time of 1200 years [20]. Acid hydrolysis (treated with 6 M HCl) effectively removes carbohydrate and protein materials by the disruption of hydrolytic bonding, leaving more biological recalcitrant alkyl and aryl materials [21,22], belonging to pool of the chemical passive SOM.

Chemical oxidation imitates natural oxidative processes in soils [23], and the residue after NaOCl treatment is dominated by alkyl carbon compounds, and its aliphatic structures is refractory to decomposition [8,24]. NaOCl attack (pH 8) was reported to be one of the 94 most efficient and reliable to isolate a stable organic carbon, without dissolving pedogenic oxides [24,25]. NaOCl attack is more explicit to state the change of SOC during soil development. NaOCl attack belongs to the pool of chemical passive SOM.

Humus is an important fraction of soil passive carbon, and most of the benefits and properties of SOC relate specifically to humus. However, underlying stabilization mechanisms of humus are still not clear [14]. Conventional explanations assumed that stabilization of humus relies on the highly aromatic structure [26,27]. As known, humus is a kind of high polymers formed by partial decomposition of polymers from plant residues, followed by condensation and polymerization [17]. Alkyl carbon is considered as a particularly recalcitrant form of soil carbon [28]. For example, the content of alkyl carbon in humus increased during vegetation restores in the Tengger sand [29]. Therefore, the chemical structure of humus needs to be further studied, especially for carbon groups, and the humus stabilization needs to be proven for sandy soil.

SOM interacts with soil minerals mainly via functional C=O groups [14,30]. Humus significantly contributes to moisture and nutrient retention, mainly via functional C=O group, and the C=O band reflects the CEC of SOM [31]. The ratio C=O/C–O–C represents the relative content of C=O group in SOM fractions [32,33]. Meanwhile, the amount of C-H groups is related to soil wettability [34]. The methylene groups (CH2) and methyl groups (CH3) are important alkyl carbons, which are specifically representatives of carbon in branched carbon chain. The ratios of CH2/C-O-C and CH3/C-O-C may provide information for the degree of alkylation in SOM fractions, and CH2/CH3 indicates the ratio of branched (carbon) chain [35]. It reveals the molecular spatial complexity and demonstrates molecular stability.

Previous studies showed that the contents of SOM and OC$_{HS}$ in the soil surface (0–10 cm) layer increased with the stand age of the shelter forest [29,36], but the content of OC$_{MLA}$ had no obvious change [37]. OC resistant to hydrolysis and oxidation, and carbon stock after vegetation planted did not see public reporting. At the same time, the previous studies of humic structure characteristics show that, with the increase of stand age of the artificial vegetation, contents of C=O, CH in the soil humic molecules increased [29]. However, the finding is based on a qualitative study rather than a quantitative investigation. The aim of our study is to illustrate the influence of shelter forest on SOC dynamics
during the development of sandy soil. Thus, we selected several shelter forests along the Taklimakan desert highway with different stand age. By measuring soil passive carbon fractions, we would reveal the functional characteristics of soil humus and calculate soil carbon stock. At last, we would provide information for estimating the carbon balance for arid areas.

2. Materials and Methods

2.1. Area Description

The study area is located in the Tarim Oil Field of the Taklimakan Desert in Xinjiang, northwest of China. The annual average air temperature has been 12.4 °C for the last 20 years. The temperature on the surface of sand can reach 75.3 °C in summer. The average annual rainfall is 24.6 mm and the average annual potential evaporation is 3638.6 mm. Severe wind and sand hazards occur more than 130 days for one year. The soil chemical and physical properties before vegetation planted were shown in Table 1.

Table 1. The soil chemical and physical properties before vegetation planted.

| Chemical       | pH     | Conductivity (ms·cm⁻¹) | SOM (g kg⁻¹) | Total Salt Content (g kg⁻¹) | Ion Concentration (g kg⁻¹) |
|----------------|--------|------------------------|--------------|-----------------------------|-----------------------------|
|                |        |                        |              |                             | CO₂⁻  | HCO₃⁻ | Cl⁻ | SO₄²⁻ | Ca²⁺  | Mg²⁺  | Na⁺  | K⁺   |
|                | 8.26   | 0.437                  | 0.742        | 1.309                       | 0.1046 | 0.703 | 0.014 | 0.096 | 0.01  | 0.32  | 0.061 |
| Physical (%)   |        |                        |              |                             |     |       |      |       |       |       |      |
| Clay           | 0.27   |                        |              |                             |     |       |      |       |       |       |      |
| Silt           |        |                        |              |                             |     |       |      |       |       |       |      |
| Very Fine Sand |        |                        |              |                             |     |       |      |       |       |       |      |
| Fine Sand      |        |                        |              |                             |     |       |      |       |       |       |      |
| Medium Sand    |        |                        |              |                             |     |       |      |       |       |       |      |
| Coarse Sand    |        |                        |              |                             |     |       |      |       |       |       |      |

2.2. Soil Sampling

Soil samples were collected from the Taklimakan shelter forests with different stand ages in May 2011. The species of tree planted in the shelter forest are three shrubs named C.m., T.c. and H.a. which are resistance to drought, salt and alkali. The plant spacing is 1 m × 1 m. The width of the shelter forest is 72–78 m. The type of the soil is sandy soil (Arenosols) [38]. The shelter forest was drip-irrigated with saline water. The shelter forest was irrigated once every 15 days from March to May and September to October, once every 10 days from June to August and no irrigation from November to February. Overall, 30 mm per time was irrigated.

The five plots were comprised of shrubs with different stand ages (5, 7, 10, 13, and 16 with the plantation time of 2006, 2004, 2001, 1998, and 1995, respectively). The geographic coordinate and altitude are showed in Table 2. At each plot, as for each plant species, we selected three plants randomly which looked like eachother, and can mirror the characteristics of the samples in all the plants. The sampling location was 50 cm far from the roots of plant. Furthermore, 1 kg of sub-samples were collected from the soil layers of 0–10, 10–20, 20–35, 35–50, 50–70, 70–100 cm, respectively. The auger was used to soil sample Finally, one sample was mixed from six soil layers. Three sampling locations were collected in one plot. The number of total soil samples was 120. At the same time, soil BD was measured with a drying method in the layers of 0–10, 10–20, 20–35, 35–50, 50–70, 70–100 cm, respectively. The soil samples were air-dried for laboratory analysis.
### Table 2. Description of each soil sample plot.

| Sample Plots                                      | Plantation Time | Stand Age (a) | Geographic Co-Ordinates     | Altitude (m) |
|---------------------------------------------------|-----------------|---------------|------------------------------|--------------|
| The second phase of *Herba cistanches* base project| 2006            | 5             | 38°56'37.4" N 83°45'02.6" E | 1108         |
| The first phase of *Herba cistanches* base project| 2004            | 7             | 38°56'10.4" N 83°45'09.4" E | 1098         |
| Three-way intersection                            | 2001            | 10            | 38°58'29.0" N 83°39'57.8" E | 1095         |
| Botanical garden around                           | 1998            | 13            | 38°56'25.0" N 83°39'45.0" E | 1078         |
| Triangle places in Shayun Department              | 1995            | 16            | 39°01'04.8" N 83°36'52.2" E | 1094         |

### 2.3. Soil Analysis

#### 2.3.1. Soil TOC

The method for soil aggregate separation was the dry sieving method. The sieving was done manually to achieve aggregate separation by moving the sieve up and down, 50 times in 2 min. First, each soil sample of air-dried was sieved to pass the 2 mm. Then, each soil was divided into two parts. One was for determining the soil TOC, (no fractionates with particle size bigger than 2 mm), HCl hydrolysis, and NaClO oxidation; the other was for next aggregation separation. Next, the soil was sieved to pass 0.25 mm. Soil particle size less than 0.25 mm was micro-aggregate ($d < 0.25$ mm). OC$_{MIA}$ was determined by the dichromate oxidation method [39].

#### 2.3.2. Soil OC$_{HS}$, OC$_{NaClO}$ and OC$_{HCl}$

OC$_{HS}$ was determined by a NaOH-Na$_4$P$_2$O$_7$ extraction-separation technique according to Zhang et al. [29]. Moreover, 10 g soil ($d < 0.25$ mm) was extracted by NaOH (0.1 M)-Na$_4$P$_2$O$_7$ (0.1 M) alkali mixture solution (10 g soil/200 mL extraction) for 20 h, and filtered. The filtrate was then divided into two parts. One part was freeze-dried for 72 h and then mixed with KBr (1:120). The characteristics of the chemical structure of humus was determined by Fourier Transform infrared spectroscopy (Bruker Tensor 27, Leipzig Germany). The other part was dried at a constant temperature of 60 °C for three weeks and then determined by the dichromate oxidation method [39].

The OC$_{NaClO}$ was determined according to Siregar et al. [25], with minor modifications. In short, 20 g soil samples ($d < 2$ mm) were mixed with 50 mL 6% NaOCl solution (pH = 8). After extraction for 24 h at 25 °C, the soil residue was washed by 50 mL 1M NaCl followed by deionized water, then centrifuged (10,000 × g rpm for 5 min). The procedure was repeated twice and the residue was then dried at 60 °C for 72 h for the determination of antioxidant organic carbon. The OC$_{HCl}$ was extracted according to Pual et al. [40], with minor modification, by changing the extraction time from 18 h to 3 h. The procedure was similar to that for extraction of OC$_{NaClO}$, except the extractant was 6 M HCl.

The hierarchical structure of SOC fractions is shown in Figure 1.
2.4. SOC and OC Stock

The air-dried soils collected from layers of 0–10, 10–20, 20–35, 35–50, 50–70 and 70–100 cm, were sieved through a 0.25 mm sieve, and the content of SOC was measured by potassium dichromate oxidation by external heating method [30].

We used the following formula (Equation (1)) for the calculation of OC stock in the i layer:

\[
\text{OC}_{i,\text{Stock}} = \text{OC}_i \times \text{BD}_i \times \text{Thickness}_i \times 10
\]

\( \text{OC}_i \) was the concentration of organic carbon (g kg\(^{-1}\)) passed through 0.25 mm sieves in the bulk soil of the i layer, \( \text{BD}_i \) was the BD of the i layer (g cm\(^{-3}\)), and \( \text{Thickness}_i \) was the soil layer thickness (cm) of the i layer. \( \text{OC}_{\text{Stock}} \) (g m\(^{-2}\)) is the sum of all the SOC in each layer (Equation (2)).

\[
\text{OC}_{\text{Stock}} = \sum_{i=1}^{6} \text{OC}_{i,\text{Stock}}
\]

2.5. Statistical Analysis

Effects of stand age on soil organic stock and passive fractions were verified statistically using one-way ANOVA analysis, by the statistical softness of SPSS 16.0. Means were compared using new multiple range test (Duncan), and the relationships between different organic carbon fractions were analyzed with Pearson correlation coefficient. Difference was declared significantly at \( \alpha < 0.05 \). All the figures were conducted by the softness of Origin 8.0.

3. Results

3.1. SOC and OC\(_{\text{stock}}\) at Different Stand Ages and Soil Depth

The changes of SOC with soil depth and stand age can be seen from Table 3. Mainly in 0–100 cm, the contents of H.a. (in 5 years), T.c. (in 10 years) and C.m. (in 10 and 16 years) decreased with soil depths, and did not change obviously in those layers. The content of SOC in surface layer was the highest. As for three kinds of plants, C.m have more influence on the content of the soil carbon in a vertical space than those of H.a. and T.c.
Table 3. The changes of SOC (g kg\(^{-1}\)) with soil depth in the shelter forest under different stand ages. Data were mean ± standard error (n = 3). Different lowercase letters indicate significant differences among soil depth under the same shelter forest and the same year at p < 0.01 level, and different capital letters indicate significant differences among stand age under the same shelter forest and the same soil depth at p < 0.05 level.

| Plant Species | Soil Depth (cm) | 5     | 7     | 10    | 13    | 16    |
|---------------|----------------|-------|-------|-------|-------|-------|
| H.a.          | 0–10           | 1.68 ± 0.18 bA | 1.38 ± 0.36 aA | 2.13 ± 0.18 cA | 1.59 ± 0.19 bA | 1.68 ± 0.35 bA |
|               | 10–20          | 1.25 ± 0.19 abB | 0.82 ± 0.02 aA | 2.09 ± 0.12 cC | 1.54 ± 0.14 bB | 1.55 ± 0.03 bB |
|               | 20–35          | 1.09 ± 0.14 bA | 1.38 ± 0.37 aA | 1.51 ± 0.17 bA | 0.93 ± 0.17 bA | 1.24 ± 0.09 aB |
|               | 35–50          | 1.13 ± 0.12 bB C | 0.91 ± 0.15 aAB | 1.53 ± 0.18 bC | 0.59 ± 0.16 aA | 0.95 ± 0.05 aB |
|               | 50–70          | 0.96 ± 0.06 aB C | 0.84 ± 0.07 aAB | 1.23 ± 0.14 abC | 0.55 ± 0.10 aA | 0.85 ± 0.11 aAB |
|               | 70–100         | 1.28 ± 0.11 abB | 1.35 ± 0.32 aB | 0.92 ± 0.09 aAB | 0.55 ± 0.06 aA | 0.83 ± 0.05 aAB |
|               | 0–10           | 1.44 ± 0.25 aA | 1.59 ± 0.18 aA | 1.49 ± 0.07 cA | 2.15 ± 0.40 bA | 2.34 ± 0.38 aA |
|               | 10–20          | 1.40 ± 0.08 abB | 1.06 ± 0.18 aB | 1.25 ± 0.08 abB | 1.29 ± 0.22 abB | 2.10 ± 0.05 aB |
|               | 20–35          | 1.42 ± 0.10 aAB | 1.13 ± 0.21 aB | 1.48 ± 0.18 cAB | 1.18 ± 0.25 aA | 2.21 ± 0.44 aB |
|               | 35–50          | 1.51 ± 0.16 aA | 1.15 ± 0.05 aA | 1.11 ± 0.06 abA | 1.21 ± 0.07 aA | 1.35 ± 0.19 aA |
|               | 50–70          | 1.41 ± 0.13 aA | 1.01 ± 0.13 aA | 0.91 ± 0.13 aA | 1.53 ± 0.24 abA | 1.51 ± 0.37 aA |
|               | 70–100         | 1.20 ± 0.09 aA | 1.29 ± 0.40 aA | 0.78 ± 0.09 aA | 1.31 ± 0.37 abA | 1.38 ± 0.31 aA |
|               | 0–10           | 1.35 ± 0.36 aAB | 1.06 ± 0.12 aA | 2.05 ± 0.17 bBC | 2.39 ± 0.28 bC | 1.95 ± 0.17 bC |
|               | 10–20          | 1.19 ± 0.21 abB | 0.77 ± 0.08 aA | 1.52 ± 0.20 abBC | 1.86 ± 0.13 abC | 1.79 ± 0.18 bC |
|               | 20–35          | 1.36 ± 0.10 aAB | 0.73 ± 0.11 aA | 1.35 ± 0.30 aAB | 1.92 ± 0.41 abB | 1.43 ± 0.27 abAB |
|               | 35–50          | 1.60 ± 0.13 aA | 1.03 ± 0.22 aA | 0.93 ± 0.02 aA | 1.56 ± 0.27 abA | 1.07 ± 0.22 aA |
|               | 50–70          | 1.41 ± 0.16 aA | 1.02 ± 0.24 aA | 0.93 ± 0.14 aA | 1.53 ± 0.27 abA | 0.81 ± 0.12 aA |
|               | 70–100         | 1.21 ± 0.07 aA | 1.10 ± 0.25 aA | 0.94 ± 0.15 aA | 1.30 ± 0.19 aA | 0.83 ± 0.14 aA |

The value of OC\(_{\text{stock}}\) in 0–100 cm was calculated in Table 4. The results showed that the content of OC\(_{\text{stock}}\) was higher under T.c. than those under H.a. (except 10 years), and C.m. (except for 10 years and 13 years). This indicates that in early times during the development of the sandy soil, T.c. has more effects on accumulation of OC\(_{\text{stock}}\) in BD than those of H.a. and C.m.

Table 4. Changes of soil OC\(_{\text{stock}}\) (g m\(^{-2}\)) in different stand ages in the soil layer of 0–100 cm. Data were mean ± standard error. Different lowercase letters indicate significant differences among plant species at p < 0.01 level, and different capital letters indicate significant differences among stand age at p < 0.05 level.

| Plant Species | 5     | 7     | 10    | 13    | 16    |
|---------------|-------|-------|-------|-------|-------|
| H.a.          | 994 ± 40.4 aBC | 695 ± 17.8 aA | 1422 ± 27.9 cD | 1078 ± 58.1 aC | 953 ± 18.9 aB |
| T.c.          | 1279 ± 41.5 bB | 944 ± 19.0 cA | 850 ± 30.6 aA | 1294 ± 29.6 bB | 1542 ± 33.7 cC |
| C.m.          | 1245 ± 32.1 bC | 839 ± 29.4 bA | 1128 ± 21.9 bB | 1613 ± 30.7 cD | 1096 ± 28.9 bB |

3.2. Dynamic Changes of Different Carbon Fractions under Different Stand Age

Dynamic changes of different carbon fractions under different stand age can be seen from Figure 2. Only the total SOC stock in T.c. forest increased with the stand age. This indicates that the stand ages in T.c. forest have great influence on the sequestration of soil carbon.

With the increase of stand age, all the contents of TOC, OC\(_{\text{MIA}}\), OC\(_{\text{HS}}\), OC\(_{\text{HCl}}\) and OC\(_{\text{NaClO}}\) increased (Figure 2). The contents of TOC, OC\(_{\text{MIA}}\), OC\(_{\text{HS}}\) increased year by year. The contents of OC\(_{\text{HCl}}\) and OC\(_{\text{NaClO}}\) increased mainly in the first few years (except OC\(_{\text{NaClO}}\) in T.c. forest and OC\(_{\text{HCl}}\) in C.m. forest). The contents of OC\(_{\text{HCl}}\) and OC\(_{\text{NaClO}}\) in H.a. forest increased faster in 5–7 years, the content of OC\(_{\text{NaClO}}\) in C.m. forest increased faster in 5–10 years. The content of OC\(_{\text{HCl}}\) in T.c. forest increased faster in 5–10 years. The order of five carbon content for three kinds of forest was: TOC > OC\(_{\text{MIA}}\) (except 5 years in T.c. forest), OC\(_{\text{NaClO}}\) > OC\(_{\text{HS}}\) > OC\(_{\text{HCl}}\) (Table 5). This indicates that the T.c. is more helpful for passive carbon accumulation in surface soil than those of H.a. and C.m.
Figure 2. Changes of TOC and different organic carbon fractions in the soil layer of 0–10 cm in the shelter forests with different stand ages. Bars show the standard errors of means.

Table 5. The average values of TOC and different organic carbon fractions (g kg\(^{-1}\)).

| Plant Species | TOC   | OC\(_{\text{MIA}}\) | OC\(_{\text{HS}}\) | OC\(_{\text{HCl}}\) | OC\(_{\text{NaClO}}\) |
|---------------|-------|----------------------|-------------------|-------------------|----------------------|
| H.a.          | 1.95  | 1.49                 | 0.67              | 0.42              | 1.20                 |
| T.C.          | 2.10  | 1.77                 | 0.76              | 0.45              | 1.00                 |
| C.m.          | 1.74  | 1.55                 | 0.67              | 0.31              | 0.92                 |

3.3. The Relationships among Carbon Fractions

The correlation coefficients between OC\(_{\text{MIA}}\), OC\(_{\text{HS}}\) and TOC were higher than those of OC\(_{\text{HCl}}\), OC\(_{\text{NaClO}}\) and TOC. This indicates that the humic and aggregate organic carbon changed in line with TOC during the early development stage of sandy soil, and had a closer relationship with TOC.

Correlation coefficients between the various passive carbon fractions showed that OC\(_{\text{HS}}\) and OC\(_{\text{MIA}}\) were the highest (0.954, 0.981, 0.954), followed by OC\(_{\text{NaClO}}\) and OC\(_{\text{MIA}}\) (0.909, 0.834, 0.656) (Table 6). This indicates that the relationship between OC\(_{\text{HS}}\) and OC\(_{\text{MIA}}\) was closer than those between other passive carbon fractions.

The values of OC\(_{\text{MIA}}\)/TOC, OC\(_{\text{HS}}\)/TOC, OC\(_{\text{HCl}}\)/TOC and OC\(_{\text{NaClO}}\)/TOC reflected the relative percentage of passive carbon accounting for soil TOC (Table 6). OC\(_{\text{HCl}}\)/TOC and OC\(_{\text{NaClO}}\)/TOC in the different forests almost decreased with the increase of stand age. In H.a. forest, OC\(_{\text{HS}}\)/TOC was enhanced with the increase of stand age. In T.c. and C.m. forests, the value of OC\(_{\text{HS}}\)/TOC was less than the values of OC\(_{\text{HCl}}\)/TOC and OC\(_{\text{NaClO}}\)/TOC. This indicates that, with the increase of stand age, the role of humification may become a more important factor in carbon sequestration in a chemical way.
Table 6. The correlations among TOC and carbon fractions.

| Plant Species | TOC   | OC\textsubscript{MIA} | OC\textsubscript{HS} | OC\textsubscript{HCl} | OC\textsubscript{NaClO} |
|---------------|-------|------------------------|----------------------|------------------------|------------------------|
| H.a.          |       |                        |                      |                        |                        |
| TOC           | 1     |                        |                      |                        |                        |
| OC\textsubscript{MIA} | 0.949 ** | 1                     |                      |                        |                        |
| OC\textsubscript{HS}    | 0.966 ** | 0.954 **               | 1                    |                        |                        |
| OC\textsubscript{HCl}  | 0.744 ** | 0.795 **               | 0.769 **             | 1                     |
| OC\textsubscript{NaClO} | 0.794 ** | 0.909 **               | 0.773 **             | 0.708 **             | 1                     |
| T.c.          |       |                        |                      |                        |                        |
| TOC           | 1     |                        |                      |                        |                        |
| OC\textsubscript{MIA} | 0.950 ** | 1                     |                      |                        |                        |
| OC\textsubscript{HS}    | 0.968 ** | 0.981 **               | 1                    |                        |                        |
| OC\textsubscript{HCl}  | 0.203  | 0.251                  | 0.186                | 1                     |
| OC\textsubscript{NaClO} | 0.867 ** | 0.834 **               | 0.840 **             | 0.354                 | 1                     |
| C.m.          |       |                        |                      |                        |                        |
| TOC           | 1     |                        |                      |                        |                        |
| OC\textsubscript{MIA} | 0.900 ** | 1                     |                      |                        |                        |
| OC\textsubscript{HS}    | 0.786 ** | 0.912 **               | 1                    |                        |                        |
| OC\textsubscript{HCl}  | 0.264  | 0.224                  | 0.253                | 1                     |
| OC\textsubscript{NaClO} | 0.674 ** | 0.656 **               | 0.499                | 0.267                 | 1                     |

** Correlation is significant at the 0.01 level.

The percentage size of four fractions in TOC was OC\textsubscript{MIA}/TOC > OC\textsubscript{NaClO}/TOC > OC\textsubscript{HS}/TOC > OC\textsubscript{HCl}/TOC. The relative proportion of OC\textsubscript{MIA} and OC\textsubscript{NaClO} in TOC is higher than those of OC\textsubscript{HCl} and OC\textsubscript{HS} (Table 7). This indicates that aggregation and resistance to oxidation may play more important role than humification and resistance to hydrolysis in soil carbon sequestration during early times in the soil forming process; aggregation played the most important role in the sequestration of soil carbon. The role of resistance to hydrolysis was the weakest.

Table 7. The relative contents of all passive organic carbon fractions in TOC.

| Plant Species | Stand Age (a) | OC\textsubscript{MIA}/TOC | OC\textsubscript{HS}/TOC | OC\textsubscript{HCl}/TOC | OC\textsubscript{NaClO}/TOC |
|---------------|---------------|---------------------------|--------------------------|----------------------------|-----------------------------|
| H.a.          | 5             | 76.4                      | 18.5                     | 36.3                       | 96.1                        |
|               | 7             | 90.7                      | 31                       | 27.3                       | 84.4                        |
|               | 10            | 71.5                      | 33.3                     | 18.5                       | 56.3                        |
|               | 13            | 71.1                      | 34.8                     | 19.1                       | 51.2                        |
|               | 16            | 75.5                      | 40.9                     | 18.1                       | 51                          |
| T.c.          | 5             | 110.4                     | 45.7                     | 41                         | 71.7                        |
|               | 7             | 86.3                      | 35.9                     | 24.7                       | 58.5                        |
|               | 10            | 88.2                      | 37.3                     | 34.1                       | 63.6                        |
|               | 13            | 88.2                      | 36.6                     | 18.6                       | 39.9                        |
|               | 16            | 72.5                      | 33.3                     | 11.8                       | 35.8                        |
| C.m.          | 5             | 72.2                      | 36.9                     | 22.6                       | 53.9                        |
|               | 7             | 99.5                      | 45.9                     | 21.7                       | 59.6                        |
|               | 10            | 85.7                      | 32.4                     | 19.1                       | 59.2                        |
|               | 13            | 94.3                      | 39.7                     | 16.5                       | 51.8                        |
|               | 16            | 89.1                      | 38.5                     | 14.5                       | 42.6                        |

The relative content of passive organic carbon fractions of T.c. forest was the highest. This indicates that the role of T.c. in carbon stabilization was higher than those of C.m. and H.a.

3.4. The Chemical Structure of the Humic Molecular

The baseline correction of original infrared spectra on shapes of humus was conducted first. The infrared spectra were obtained by taking the absorbance as peak height, and wave number as peak position (Figure 3) [29,33,35,41].
The relative content of passive organic carbon fractions of T.c. forest was the highest. The value of \( b/a \) increased within 10-16 years (Table 8). The values of \( c/a \) and \( d/a \) represented \( CH_3/CH_2/CH_3 \) and \( CH_2/CH_3 \) to \( C-O-C \) and provide information about the relative content of \( CH_3 \) and \( CH_2 \) groups in 5 years.

The FTIR spectra were half quantitatively analyzed at two absorption bands. In this study, we take the original peak height of \( C=O-C \) group (at 1134 cm\(^{-1}\)) as \( a \), and the original peak height of \( C=O \) group (at 1670 cm\(^{-1}\)) as \( b \), and the value of \( b/a \) represents the amount of \( C=O \) groups relative to the \( C-O-C \) groups, providing information about the relative content of the \( C=O \) group in SOM fractions [32,33]. The calculation results showed that the value of \( b/a \) increased within 10-16 years (Table 8). The values of \( c/a \) and \( d/a \) represented \( CH_3/CH_2/CH_3 \) and \( CH_2/CH_3 \) to \( C-O-C \) and provide information about the relative content of \( CH \) group (\( CH_3 \) and \( CH_2 \) respectively) in the organic matter molecule [32,33]. Furthermore, the value of \( d/c \) (\( CH_2/CH_3 \)) indicates the ratio of branched chain to carbon chain [35]. With the increase of stand age, the values of \( c/a \) and \( d/a \) did not change noticeably. The value of \( d/c \) had no obvious change with stand age. The ratios of \( C=O, CH_2 \) and \( CH_3 \) to \( C-O-C \) were: \( C=O > CH_2 > CH_3 \).

**Table 8. Effects of stand age on the ratios of \( C=O, CH_2 \) and \( CH_3 \) to \( C-O-C \).**

| Stand Age | C-O-C (a) | C=O (a) | CH\(_3\) (b) | CH\(_2\) (c) | C=C (d) | \( C=O/\text{C-O-C} \) (e) | \( \text{CH}_2/\text{C-O-C} \) (b/a) (%) | \( \text{CH}_3/\text{C-O-C} \) (c/a) (%) | \( \text{CH}_2/\text{CH}_3 \) (d/a) (%) | \( \text{CH}_2/\text{CH}_3 \) (d/c) (%) |
|-----------|-----------|---------|------------|------------|--------|------------------------|-----------------|-----------------|-----------------|-----------------|
| 5         | 0.39      | 0.084   | 0.018      | 0.027      | 0.065  | 21.4                   | 1.02            | 1.55            | 1.74            | 1.15            |
| 7         | 1.33      | 0.073   | 0.028      | 0.031      | 0.040  | 3.98                   | 2.3             | 2.52            | 1.1             |
| 10        | 1.24      | 0.043   | 0.018      | 0.022      | 0.030  | 3.45                   | 1.31            | 1.74            | 1.33            |
| 13        | 1.24      | 0.049   | 0.028      | 0.031      | 0.040  | 3.98                   | 2.3             | 2.52            | 1.1             |
| 16        | 0.94      | 0.037   | 0.011      | 0.014      | 0.032  | 3.95                   | 1.14            | 1.5             | 1.31            |
4. Discussion

4.1. The Changes of SOC and Soil Carbon Stock

The accumulation rate of SOC is associated with the amount of decomposable exogenous organic matter. Litter and dead plant roots are important exogenous organic matter. In our study, the increases of organic carbon and organic carbon stock with depth mainly appeared in the 0–50 cm soil layer. This is because litter is above this layer, and plant root is below this layer. The amount of litter may be greater than the amount of dead root. Litter decomposition rate is affected by their own characteristics, including contents of N, C/N and contents of lignin and cellulose in litter [42]. The litter characteristics of T.c. may be more conducive to the processes of litter decomposition and nutrient release, so the soil carbon content in T.c. forest is higher.

4.2. The Effects of Artificial Vegetation on Chemical Passive Organic Carbon

The content of TOC was 0.73–3.55 g kg\(^{-1}\) in the surface layer of sandy soil, which was the smallest compared with other soils developed from different parents, such as podzol 35.33 g kg\(^{-1}\) [16], Molisols 5.5–8.5 g kg\(^{-1}\) [43], loess 5.5–8 g kg\(^{-1}\) [44], and fen 200.4 g kg\(^{-1}\) [45]. This indicates that the pedogenic process of arenosols may be the slowest. In our study, the contents of TOC were 2.53, 2.80 and 3.61 g kg\(^{-1}\) and those of the OC\(_{\text{MIA}}\) were 1.79, 2.47, 3.40 g kg\(^{-1}\) in 13 years, for different artificial vegetation (Figure 2). This result is smaller than the findings of Tan et al. [37] who reported that the contents of TOC and OC\(_{\text{MIA}}\) were 27.6 and 42.79 g kg\(^{-1}\), respectively in 12 years. This could be because the dominant species and litter quantity in two sites are different. Thus, the quantity and chemical composition of plant tissues entering the soil should be different, which is related to the content of SOM [46]. The main species in this study is Calligonum mongolicum, Tamarix chinensis and Haloxylon ammodendron, and the one in Tan’s is Pinus sylvestris var. mongolica. Different litter quality and quantity may lead to different contents of TOC and OC\(_{\text{MIA}}\) in two sites.

In our study, the content of TOC was higher than that of OC\(_{\text{MIA}}\), which is consistent with Yu et al. [47]. However, it is not consistent with Tan et al. [37]. This may be due to one of the stabilization mechanisms of soil OC: physicochemical leads to occlusion of organic matter into micro- and macro-aggregates by binding SOM and mineral particles [48]. This process may mainly occur in macro-aggregates but not micro-aggregates during the early period (about 10 years) of sandy soil development, and a similar phenomenon occurred in previous studies [49,50]. After that, the process of occlusion of organic matter into micro-aggregates may play a more important role in soil OC stabilization, so the difference between TOC and OC\(_{\text{MIA}}\) may be shortened and even TOC may smaller than OC\(_{\text{MIA}}\). The first stage may continue for a longer time in sandy loam soil and crop ecological environment.

The TOC and OC\(_{\text{MIA}}\) were increasing with stand age (Figure 2). This is consistent with Jin [36]. However, it is not consistent with Tan [37]. This may because the amount of TOC and OC\(_{\text{MIA}}\) may stop accumulating in sandy soil after a specific development time scale.

Humus is more resistant to decomposition than the non-humic material [51], and is generally fixed in the process of humification [15]. In our study, the content of OC\(_{\text{HS}}\) increased with stand age, being consistent with the findings of Zhang [29,52]. The reason for this phenomenon could be attributed to the amount of litter that can be decomposed and changed into humus in the soil surface increasing with the increase of stand age.

The contents of OC\(_{\text{HCl}}\) and OC\(_{\text{NaClO}}\) increased slowly after 10 years. The OC\(_{\text{HCl}}\) and OC\(_{\text{NaClO}}\) simulate the oxidation and hydrolysis decomposition process of organic matter in nature [22,23]. They are two complex chemical reaction processes. Chemical reaction rate is affected by local climate, such as the air temperature rainfall and the characteristics of the plant species. The air temperature influences soil temperature. The rainfall influences soil humidity. The plant species, such as the content of litter from lignin and cellulose, affect the possibility of the reaction substrates. Therefore, the specific reason for these two kinds of passive fractions contents stop increasing the need for intensive research.
4.3. The Relation among Carbon Fractions

The correlations between OC$_{\text{MIA}}$ and TOC in our study are 0.949, 0.950, 0.900 (Table 7); it is close to the results of Tan [37] and Yu [47], who reported that the correlation between OC$_{\text{MIA}}$ and TOC is 0.979 and 0.964, respectively. This indicates that the correlation between OC$_{\text{MIA}}$ and TOC is relatively stable, although the soil development time and vegetation species are not the same.

The average value of OC$_{\text{MIA}}$/TOC (84.8%) is similar to Tan et al. (80.13%) [37], but lower than Yu et al. (97.29%) [47]. The development time of Tan’s study is 39 years and Yu’s is more than 100 years. Therefore, a longer development time may influence the value of OC$_{\text{MIA}}$/TOC.

The humification plays a more important role in carbon stabilization by chemical way. The reason for this may be that NaClO attack and HCl hydrolysis are chemical activities carried out by enzymes and biodegradation. However, SOM’s major part is bound to the mineral soil component, and mineral particles act as a surface for HS self-assembly [53], so humus exists in the soil with an inorganic–organic compound. Therefore, with the increase of stand age, humification may become more active.

The content of OC$_{\text{HCl}}$, OC$_{\text{NaClO}}$, OC$_{\text{HCl}}$/TOC and OC$_{\text{NaClO}}$/TOC decreased. This indicated that resistance to hydrolysis and oxidation were restrained. The reason for this phenomenon may be related to two SOM stabilization mechanisms: (1) the innate stability (recalcitrance) of the organic matter; and (2) the absence of the required suite of microbial decomposers [18].

The absence of the required suite of microbial decomposers can make the turnover time of OM longer [18]. In initial years, after the shelter forest had been planted, the amount of litter in the surface soil was very low, so the microbial available carbon and nitrogen source was limited, leading to the low microbial population [54]. Therefore, the exogenous organic matter was difficult to mineralize, but the possibility changed into passive organic carbon, such as OC$_{\text{HCl}}$ and OC$_{\text{NaClO}}$ increasing, so OC$_{\text{HCl}}$/TOC and OC$_{\text{NaClO}}$/TOC was very high. With the increase of stand age, exogenous organic matter accumulated in the surface soil. The situation appeared opposite, causing the decomposition rate of soil carbon pool to intensify. The possibility of active carbon pool transforming to passive carbon would decrease, while the TOC continued increasing, so the OC$_{\text{HCl}}$/TOC and OC$_{\text{NaClO}}$/TOC decreased.

4.4. The Influence of Artificial Vegetation on Chemical Composition of Humus

The main functional groups appeared in the humus molecular of sandy soil during humification process in Tarim desert is C=O, CH and C=C (Figure 3). This is in line with Zhang [29]. The number of aliphatic groups decreased except for C-O-C in 5 years and C=O, CH in 13 years. This is in line with Zhang [29]. The stand age of Zhang is 0, 20, 32, 43, 51, and the major plant species were Caragana korshinskii, Artemisia or dosica, Hedysarium. This indicates that the stand age and species of artificial vegetation would have little effect on the aliphatic changes in the humic chemical structure during the development of sandy soil.

The year when CH group appeared is different to that of Zhang [29]. Our study took place in 7 years, but CH appeared until 51 years in Zhang. The reason for this inconsistency may also be explained as composition of the plant species is different in the two studies and could have impact on the development of humic substance in soils. Thus, the different properties of litters in the two studies could lead to a difference in CH groups of humic substance. This indicated that the evolution rate of CH groups may be different under different artificial vegetation. Similar results can be seen in different ecological systems [33,55].

Zhang [29] showed in Tengger Desert that, the changes of the chemical structure of an aromatic compound of a humic substance developed constantly over the years. The reason may be because the time scale in two studies is different. The first age of the former study is 5 years, but the latter is 20 years. The former increased in 13 years, and may continue...
to increase, so the number changes of aromatic groups in humus molecular may increase with stand age.

The content of C=O (C=O/C-O-C) in soil organic matter increased from 10 years to 16 years (Table 8). This means that the ability of soil to form a mineral–organic compound to stabilize carbon is increased. This may be related to the soil clay particles contents which are affected by stand age. SOM interacts with soil minerals mainly via functional C=O groups [8,31]. With the stand age increased, the quality of soil increased, and the soil clay particles contents increased, which made soil humification intensity strengthen and form more clay particles in soil [56]. However, the process is very slow at the beginning of the development of sandy soil, so the C=O/C-O-C increased a little.

The contents of C=O, CH$_2$ and CH$_3$ after 7 years followed the order: C=O > CH$_2$ > CH$_3$. SOM interacted with soil minerals mainly via functional C=O groups [8,34]. This means that the mineral-organic compound may play more important roles in humification process than alkyl carbon in early times of soil development. SOM was stabilized by interaction with mineral components [18,55], so the C=O > CH. Additionally, humus is a kind of high polymer formed by the partial decomposition of polymers from plant residues, followed by condensation and polymerization reactions [17]. CH$_2$ can be a structure monomer of polymethylene [28], but CH$_3$ cannot. Therefore, the humic molecular tends to form more CH$_2$ than CH$_3$ to strengthen its own stabilization.

5. Conclusions

The content of SOC reduced with the increase of soil depth, mainly in 0–100 cm. The T.c. forest played the most important role in soil carbon accumulation in unit mass and C.m. play the most in unit area. The space variation caused by C.m. is the biggest.

In terms of the contents, the passive organic carbon increased with stand age, and the OC$_{MIA}$ and OC$_{HS}$ increased years by years, while the OC$_{NaClO}$ and OC$_{HCl}$ increased remarkably in the first few years, then had no obvious change. Aggregation and resistance to oxidation played a more important role than humification and resistance to hydrolysis in carbon sequestration during the early soil development stage. With the increase of stand age, the humification may play a more important role.

The T.c. forest is the most helpful for carbon and sequestration carbon stabilization in sandy soil. The artificial vegetation influenced the molecular stability of the humic substance. Mineral–organic compounds may play more important roles in the humification process than alkyl carbon in the early times of soil development.

Some conclusions need further study to prove their accuracy. First, the vegetation species may influence: (1) the changes of TOC and OC$_{MIA}$; (2) the speed of CH group appeared in humic molecular. Second, the macro-aggregates may appear before micro-aggregates in sandy soil.

The stabilization mechanism of carbon in sandy soil needs more investigation to enclose the chemical structure of humus, and the chemical bonds of CH$_2$ and CH$_3$. The time scale that the studies chose may influence the results in studying aromatic groups.

Author Contributions: Conceptualization, formal analysis, writing—original draft preparation, X.M.; data curation, investigation, Y.W.; formal analysis, funding acquisition, methodology, writing—review and editing, Z.J.; writing—review and editing, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by National Natural Science Foundation of China (Grant No. 41571498; 31300449). The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.
Acknowledgments: The authors thank all staff at the Taklimakan Desert Research Station and Z and M who gave a lot of support and help in the central laboratory of Xinjiang Institute of Ecology and Geography. Authors also thank Y. Li, and X.P.G. for and comments on an early version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

C.m. Calligonum mongolicunl
H.a. Haloxylon ammodendron
T.c. Tamarix chinensis
BD Bulk density
OC Organic carbon
OC$_{HCl}$ Acid-resistant organic carbon
OC$_{HS}$ Humic organic carbon
OC$_{MIA}$ Microagglomerates organic carbon
OC$_{NaClO}$ Antioxidant organic carbon
OC$_{stock}$ Soil organic carbon stock
SOC Soil organic carbon
SOM Soil organic matter
TOC Total organic carbon

References

1. Lei, J.Q.; Li, S.Y.; Jin, Z.Z.; Fan, J.L.; Wang, H.F.; Fan, D.D.; Zhou, H.W.; Gu, F.; Qiu, Y.Z.; Xu, B. Comprehensive eco-environmental effects of the shelter-forest ecological engineering along the Tarim Desert Highway. Chin. Sci. Bull. 2008, 53, 190–202. [CrossRef]

2. Chen, C.R.; Xu, Z.H.; Mathers, N.J. Soil carbon pools in adjacent natural and plantation forests of subtropical Australia. Soil Sci. Soc. Am. J. 2004, 68, 282–291. [CrossRef]

3. Yang, H.; Mo, B.; Zhou, M.; Zhu, T.; Cao, J. Effects of plum plantation ages on soil organic carbon mineralization in the karst rocky desertification ecosystem of Southwest China. Forests 2019, 10, 1107. [CrossRef]

4. Huggett, R.J. Soil chronosequences, soil development, and soil evolution: A critical review. Catena 1998, 32, 155–172. [CrossRef]

5. Paul, S. Humus: Still a mystery. In Northeast Organic Farming Association (NOFA). About Calendar Chapters TNF Conference Publications Exchange Search; The National Farmer (TNF): Manchester, UK, 2002; pp. 1–8.

6. Varadachari, C.; Ghosh, K. The Formation of humic substances. Plant Soil 1984, 77, 305–313. [CrossRef]

7. Schwendenmann, L.; Pendall, E. Response of soil organic matter dynamics to conversion from tropical forest to grassland as determined by long-term incubation. Biol. Fertil. Soils 2008, 44, 1053–1062. [CrossRef]

8. Lützow, M.V.; Kgel-Knabner, I.; Ekschmitt, K.; Flessa, H.; Marschner, B. SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. Soil Biol. Biochem. 2007, 39, 2183–2207. [CrossRef]

9. McGill, W.B. Review and classification of ten soil organic matter (SOM) models. In Evaluation of Soil Organic Matter Models; Smith, U.J., Ed.; Springer: Berlin/Heidelberg, Germany, 1996; pp. 111–132.

10. Smith, P.; Smith, J.U.; Powlson, D.S.; McGill, W.B.; Arah, J.R.M.; Chertov, O.G.; Colman, K.; Franko, U.; Froliking, S.; Jenkinson, D.S.; et al. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 1997, 81, 153–225. [CrossRef]

11. Wang, S.; Zhuang, Q.; Yang, Z.; Yu, N.; Jin, X. Temporal and spatial changes of soil organic carbon stocks in the forest area of Northeastern China. Forests 2019, 10, 1023. [CrossRef]

12. Trumbore, S.E. Potential responses of soil organic carbon to global environmental change. Proc. Natl. Acad. Sci. USA 1997, 94, 8284–8291. [CrossRef]

13. Paul, E.A.; Morris, S.J.; Bohm, S. The determination of soil C pool sizes and turnover rates: Biophysical fractionation and tracers. In Assessment Methods for Soil Carbon; Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A., Eds.; Lewis: Boca Raton, FL, USA, 2001; pp. 193–206.

14. Lützow, M.V.; Kögel-Knabner, I.; Ekschmitt, K.; Matzner, E.; Flessa, H. Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions—A review. Eur. J. Soil Sci. 2010, 57, 426–445. [CrossRef]

15. Hayes, M.H.B.; Clapp, C.E. Humic substances: Considerations of compositions, aspects of structure, and environmental influences. Soil Sci. 2001, 166, 723–737. [CrossRef]

16. Stevenson, F.J. Humus Chemistry. Genesis, Composition, Reactions, 2nd ed.; Wiley: New York, NY, USA, 1994.

17. Abakumov, E.; Trubetskoj, O.; Demin, D.; Celi, L.; Cerli, C.; Trubetskaya, O. Humic acid characteristics in podzol soil chronosequence. Chem. Ecol. 2010, 26, 59–66. [CrossRef]

18. Smernik, R.; Skjemstad, J. Mechanisms of organic matter stabilization and destabilization in soils and sediments: Conference introduction. Biogeochemistry 2009, 92, 3–8. [CrossRef]
19. Krull, E.S.; Swanston, C.W.; Skjemstad, J.O.; McGowan, J.A. Importance of charcoal in determining the age and chemistry of organic carbon in surface soils. *J. Geophys. Res.* 2015, 111, 277–305. [CrossRef]
20. Paul, E.A.; Morris, S.J.; Conant, R.T.; Plante, A.F. Does the acid hydrolysis-incubation method measure meaningful soil organic carbon pools? *Soil Sci. Soc. Am. J.* 2006, 70, 1023–1035. [CrossRef]
21. Bruun, S.; Thomsen, I.K.; Christensen, B.T.; Jensen, L.S. In search of stable soil organic carbon fractions: A comparison of methods applied to soils labeled with 14 C for 40 days or 49 years. *Eur. J. Soil Sci.* 2007, 59, 247–256. [CrossRef]
22. Helrich, M.; Flessa, H.; Mikutta, R.; Drees, A.; Ludwig, B. Comparison of chemical fractionation methods for isolating stable soil organic carbon pools. *Eur. J. Soil Sci.* 2007, 58, 1316–1329. [CrossRef]
23. Paul, S.; Veldkamp, E.; Flessa, H. Differential response of mineral-associated organic matter in tropical soils formed in volcanic ashes and marine Tertiary sediment to treatment with HCl, NaClO, and Na₂P₂O₇. *Soil Biol. Biochem.* 2008, 40, 1846–1855. [CrossRef]
24. Mikutta, R.; Kleber, M.; Kaiser, K.; Jahn, R. Review: Organic matter removal from soils using hydrogen peroxide, sodium hypochlorite, and disodium peroxodisulfate. *Soil Sci. Soc. Am. J.* 2005, 69, 120–135. [CrossRef]
25. Siregar, A.; Kleber, M.; Mikutta, R.; Jahn, R. Sodium hypochlorite oxidation reduces soil organic matter concentrations without affecting inorganic soil constituents. *Eur. J. Soil Sci.* 2004, 56, 481–490. [CrossRef]
26. Oades, J.M.; Waters, A.G. Aggregate hierarchy in soils. *Austral. J. Soil Res.* 1991, 29, 815–828. [CrossRef]
27. Hedges, J.L.; Eglington, G.; Hatcher, P.G.; Kirchman, D.L.; Rullkötter, J. The molecularly-uncharacterized component of nonliving organic matter in natural environments. *Org. Geochem.* 2000, 31, 945–958. [CrossRef]
28. Baldock, J.A.; Masiello, C.A.; Gassner, B. Chemical composition and stocks of soil organic matter in a southern California oak woodland. *Soil Sci. Soc. Am. J.* 1997, 61, 1288–1300. [CrossRef]
29. Yuan, G.; Theng, B.K.G.; Parfit, R.L.; Percival, H.J. Interactions of allophane with humic acid and cations. *Eur. J. Soil Sci.* 2001, 52, 35–41. [CrossRef]
30. Celi, L.; Schnitzer, M.; Négre, M. Analysis of carboxyl groups in soil humic acids by a wet chemical method, Fourier-transform infrared spectroscopy and solution-state carbon-13 nuclear magnetic resonance. A comparative study. *Soil Sci. 1997, 162, 189–197. [CrossRef]
31. Ellerbrock, R.H.; Gerke, H.H. Characterizing organic matter of soil aggregate coatings and biopores by Fourier transform infrared spectroscopy. *Eur. J. Soil Sci.* 2004, 55, 219–228. [CrossRef]
32. Kaiser, M.; Ellerbrock, R.H.; Gerke, H.H. Long-term effects of crop rotation and fertilization on soil organic matter composition. *European Journal of Soil Science* 2007, 58, 1460–1470. [CrossRef]
33. Capriel, P.; Beck, T.; Borchert, H.; Gronholz, J.; Zachmann, G. Hydrophobicity of the organic matter in arable soils. *Soil Biol. Biochem.* 1995, 27, 1453–1458. [CrossRef]
34. Dou, S. Soil Organic Matter; Science Press: Beijing, China, 2010; pp. 154–155. (In Chinese)
35. Jin, Z.Z.; Lei, J.Q.; Xu, X.W.; Li, S.Y.; Zhao, S.F.; Qiu, Y.Z.; Xu, B. Evaluation of soil fertility of the shelter-forest land along the Tarim Desert Highway. *Chin. Sci. Bull.* 2008, 53, 125–136. [CrossRef]
36. Tan, W.B.; Zhou, L.P.; Liu, K.X. Soil aggregate fraction-based C-14 analysis and its application in the study of soil organic carbon turnover under forests of different ages. *Chin. Sci. Bull.* 2013, 58, 1936–1947. [CrossRef]
37. Food and Agriculture Organization. *World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; Food and Agriculture Organization: Rome, Italy, 2015.
38. Walkley, A.; Black, A. Methods of Soil Analysis, 1st ed.; American Society of Agronomy: Madison, WI, USA, 1965; pp. 1372–1375.
39. Paul, E.A.; Follett, R.F.; Leavitt, S.W.; Halvorson, A.; Peterson, G.A.; Lyon, D.J. Radiocarbon dating for determination of soil organic matter pool sizes and dynamics. *Soil Sci. Soc. Am. J.* 1997, 61, 1058–1067. [CrossRef]
40. Santana, G.S.; Dick, D.P.; Tomazi, M.; Bayer, C.; Jacques, A.V.A. Chemical composition and stocks of soil organic matter in a south Brazilian oxisol under pasture. *J. Braz. Chem. Soc.* 2013, 24, 821–829. [CrossRef]
41. Swift, M.J.; Anderson, J.M. Decomposition. In *Tropical Rainforest Ecosystems Biogeographica Land Ecological Studies*, 1st ed.; American Society of Agronomy: Madison, WI, USA, 1965; pp. 1372–1375.
42. Jin, Z.Z.; Lei, J.Q.; Xu, X.W.; Li, S.Y.; Zhao, S.F.; Qiu, Y.Z.; Xu, B. Evaluation of soil fertility of the shelter-forest land along the Tarim Desert Highway. *Chin. Sci. Bull.* 2008, 53, 125–136. [CrossRef]
43. Capriel, P.; Beck, T.; Borchert, H.; Gronholz, J.; Zachmann, G. Hydrophobicity of the organic matter in arable soils. *Soil Biol. Biochem.* 1995, 27, 1453–1458. [CrossRef]
44. Food and Agriculture Organization. *World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; Food and Agriculture Organization: Rome, Italy, 2015.
45. Walkley, A.; Black, A. Methods of Soil Analysis, 1st ed.; American Society of Agronomy: Madison, WI, USA, 1965; pp. 1372–1375.
46. Paul, E.A.; Follett, R.F.; Leavitt, S.W.; Halvorson, A.; Peterson, G.A.; Lyon, D.J. Radiocarbon dating for determination of soil organic matter pool sizes and dynamics. *Soil Sci. Soc. Am. J.* 1997, 61, 1058–1067. [CrossRef]
47. Santana, G.S.; Dick, D.P.; Tomazi, M.; Bayer, C.; Jacques, A.V.A. Chemical composition and stocks of soil organic matter in a south Brazilian oxisol under pasture. *J. Braz. Chem. Soc.* 2013, 24, 821–829. [CrossRef]
48. Swift, M.J.; Anderson, J.M. Decomposition. In *Tropical Rainforest Ecosystems Biogeographica Land Ecological Studies*, 1st ed.; American Society of Agronomy: Madison, WI, USA, 1965; pp. 1372–1375.
49. Food and Agriculture Organization. *World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; Food and Agriculture Organization: Rome, Italy, 2015.
48. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]

49. Xu, H.; Qu, Q.; Li, P.; Guo, Z.; Wulan, E.; Xue, S. Stocks and stoichiometry of soil organic carbon, total nitrogen, and total phosphorus after vegetation restoration in the loess hilly region, China. *Forests* **2019**, *10*, 27. [CrossRef]

50. McLauchlan, K.K.; Hobbie, S.E. Comparison of labile soil organic matter fractionation techniques. *Soil Sci. Soc. Am. J.* **2004**, *68*, 1616–1625. [CrossRef]

51. Ceccanti, B.; Alcaniz, J.M.; Gispert, M.; Gassiot, M. Characterization of organic matter from two different soils by pyrolysis–gachromatography and isoelectro focusing. *Soil Sci.* **1986**, *142*, 83–90. [CrossRef]

52. Shan, Z.; Yin, Z.; Yang, H.; Zuo, C.; Zhu, T. Long-term cultivation of fruit plantations decreases mineralization and nitrification rates in calcareous soil in the Karst region in Southwestern China. *Forests* **2020**, *11*, 1282. [CrossRef]

53. Semenov, V.M.; Tulina, A.S.; Semenova, N.A.; Ivannikova, L.A. Humification and nonhumification pathways of the organic matter stabilization in soil: A Review. *Eurasian Soil Sci.* **2013**, *46*, 355–368. [CrossRef]

54. Jin, Z.; Lei, J.; Li, S.; Xu, X. Variation characteristics of soil microbial activities in the Tarim Desert Highway shelter forests, Xinjiang of Northwest China. *Chin. J. Appl. Ecol.* **2013**, *24*, 2464–2470. (In Chinese)

55. Wang, D.; Yu, X.; Jia, G.; Qin, W.; Shan, Z. Variations in soil respiration at different soil depths and its influencing factors in forest ecosystems in the mountainous area of North China. *Forests* **2019**, *10*, 1081. [CrossRef]

56. Sparks, D.L. *Environmental Soil Chemistry*; Academic Press: San Diego, CA, USA, 1995; pp. 23–51, 99–104.