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Soil Aggregate Stability and Carbon Density in Three Plantations in the Loess Plateau, China

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Abstract: Afforestation plays an important role in mitigating soil erosion and improving soil quality in the Loess Plateau. However, there is no consistent conclusion about the effect of tree species on soil properties. *Robinia pseudoacacia*, *Pinus tabulaeformis*, and *Malus pumila* plantations were selected as the research objects. Soil indices such as the content of soil organic carbon (SOC) and inorganic carbon (SIC), carbon density, soil aggregate stability, and bulk density were selected to study the effects of different plantations on soil properties. The mean weight diameter (MWD) was calculated to evaluate soil aggregate stability. The results showed that: (1) MWD of *R. pseudoacacia* was 22%–67% lower than that of *P. tabuliformis* across the 0–80 cm soil layers. MWD of *M. pumila* was 27%–45% and 57%–78% lower than that of *R. pseudoacacia* and *P. tabuliformis* across 0–50 cm layers. (2) SOC of *P. tabuliformis* was 61%–127% and 67%–148% higher than that of *R. pseudoacacia* and *M. pumila*, respectively, while SIC was 55%–82% and 12%–14% lower than that of *R. pseudoacacia* and *M. pumila*. (3) Soil carbon density, including soil organic carbon density and inorganic carbon density, of *P. tabuliformis* was 36%–49% and 3%–31% lower than that of *R. pseudoacacia* and *M. pumila*, respectively. (4) Aggregate organic carbon increased with increasing aggregate size, while inorganic carbon decreased. Water-stable aggregates with larger sizes had higher soil organic carbon and lower carbonate calcium. (5) The inorganic carbon in soil was both a binder and a dispersant of soil aggregates, which depends on its content. *P. tabuliformis* should be planted in the semi-arid area of the Loess Plateau in China, because this species was able to increase soil organic matter and improve soil structure compared with the other two species.

Keywords: soil water-stable aggregate; mean weight diameter; soil carbon sequestration; calcareous soils

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1. Introduction

In 2018, the eighth national forest resources inventory data showed that the preserved area of China's artificial forests reached 69.33 million hectares through vigorously carrying out afforestation, ranking first in the world. To adapt to poor soils and an arid and cold climate, the exotic species *Robinia pseudoacacia*, which is fast growing and aids nitrogen fixation, was introduced a long time ago. The native species *Pinus tabulaeformis* has also been chosen as a major tree species for afforestation. *Malus pumila* was also planted widely by local farmers to seek higher economic profits than others (such as *Triticum aestivum* and *Zea mays*). Each plant species provides different qualities and quantities of organic materials into soils, resulting in changes in soil properties [1]. Chen et al. [2,3] found that fine root biomass and carbon: nitrogen: phosphorus stoichiometry were significantly different between *P. tabulaeformis* and *R. pseudoacacia* in the Loess Plateau. Bhattacharya et al. [4] showed that the varieties of trees significantly changed the soil properties through roots and litter. Zhang et al. [5] concluded that *P. tabulaeformis* plantation greatly increased the number of plant residues and vegetation coverage, thereby improving the soil micro-environment and ultimately improving the physical-chemical properties and biological activity of soil. Mataix-Solera et al. [1] reported that *Pinus halepensis* should be planted in semi-arid areas, because this species was able to produce more hydrophobic substances into the soil compared with other species. However, Liu et al. [6] found that broadleaved forests can most obviously improve soil quality, followed by broadleaved coniferous mixture and coniferous plantations. In addition, Nie et al. [7] found varieties of trees have no significant influence on soil organic carbon concentration. Cao et al. [8] also reported that the differences in soil nutrients between black locusts and Chinese pine plantations are not obvious. It can be seen from the above analysis that the effect of tree species on soil properties has not been agreed upon.

Afforestation has played an important role in mitigating soil erosion and improving soil quality, mainly by increasing the content of soil organic carbon (SOC). It is believed that SOC plays an important role in the formation of water-stable aggregation [7]. Aggregate stability, indicating soil structural stability, is also considered to be an important index of soil quality [9]. In addition, aggregate stability is an important factor in soil erodibility. Ding et al. [10] regarded the K value of soil erodibility to be significantly correlated with the stability index of soil aggregates. Huang et al. [11] believed that the mean weight diameter (MWD) of water-stable aggregates decreased with increasing degree of erosion. Meanwhile, stable aggregates played an important role in the stabilization of SOC [12]. Micro-aggregates were bound together by young organic matter into larger macro-aggregates, and a breakdown of macro-aggregates resulted in a release of labile soil organic matter (SOM) [13]. It was generally accepted that the stability of SOC in soil aggregates was closely related to the protection of the aggregate structure from microbial decomposition [12]. In a word, soil water-stable aggregates and soil organic matter are two very important soil attributes, and they interact and influence each other.

The focus of afforestation has changed to carbon stocks in recent decades [14]. Among the numerous sources of greenhouse gases, emissions of CO_2 have been affected by changes in land use [4]. Land-use type has influenced SOC density in 0–100 cm, especially in the 0–30 cm soil layer [15]. Soil carbon consists of soil organic carbon (SOC) and soil inorganic carbon (SIC) [16]. Determining changes in soil organic carbon (SOC) and inorganic carbon (SIC) caused by afforestation is important for estimating the regional carbon budget and evaluating ecological effects [17]. The choice of tree species plays an important role in SOC accumulation. The quantitative contribution of different tree species to carbon stocks was much debated. For example, Cao et al. [18] found that the SOC densities of the nitrogen-fixing black locust plantations were significantly lower than those of the Chinese pine plantations and secondary oak forests. However, Wang et al. [19] found that, after 23 years of growth, nitrogen fixation trees performed better in restoring soil carbon.

The purpose of this study is to quantify the aggregate stability, SOC, and SIC in the soil profiles of *R. pseudoacacia*, *P. tabuliformis*, and *M. pumila* plantations. We hypothesize that: (1) plantation types and soil layers can affect soil properties, and (2) the content of organic carbon and inorganic carbon is different in water-stable aggregates of different sizes. This study will contribute to tree species selection in afforestation to attain more soil carbon sequestration and improve soil quality.

2. Methods

2.1. Sample Area and Soil Sampling

The sample area is located in the north of Liquan County, situated in the south region of the Loess Plateau, China (Figure 1). The mean annual temperature is 12.6 °C, with the highest monthly temperature being in July (34 °C), and the lowest in January (−4 °C), with a frost-free period of 214 days. The mean precipitation is less than 600 mm, and its temporal—spatial distribution is extremely uneven. About fifty years ago, three tree species—*R. pseudoacacia*, *P. tabuliformis*, and *M. pumila*—were planted following the same site preparation on one and the same hillslope. The *P. tabuliformis* plantation was above the *R. pseudoacacia* plantation, and the *M. pumila* plantation was at the level ground on the bottom of the hillslope. The mean diameter at breast height (DBH) of *M. pumila*, *R. pseudoacacia*, and *P. tabuliformis* was 12.98 cm, 12.73 cm, and 15.42 cm, respectively. The studied soil was Alfisols, as classified by the USDA Taxonomy [20], which was developed from the Loess parent material. Therefore, it can be considered that the parent material, topographic conditions, climatic factors, and age were similar, and the differences in soil attributes mainly reflect the differences in tree species. In September 2018, a plot was chosen in the central area of each plantation, in which three soil profiles were dug to a depth of 50 cm (in *M. pumila* plantation) or 80 cm (in *R. pseudoacacia* and *P. tabuliformis* plantations), at intervals of 10 cm, for sampling. Soil samples were air-dried for one week and stored at room temperature.

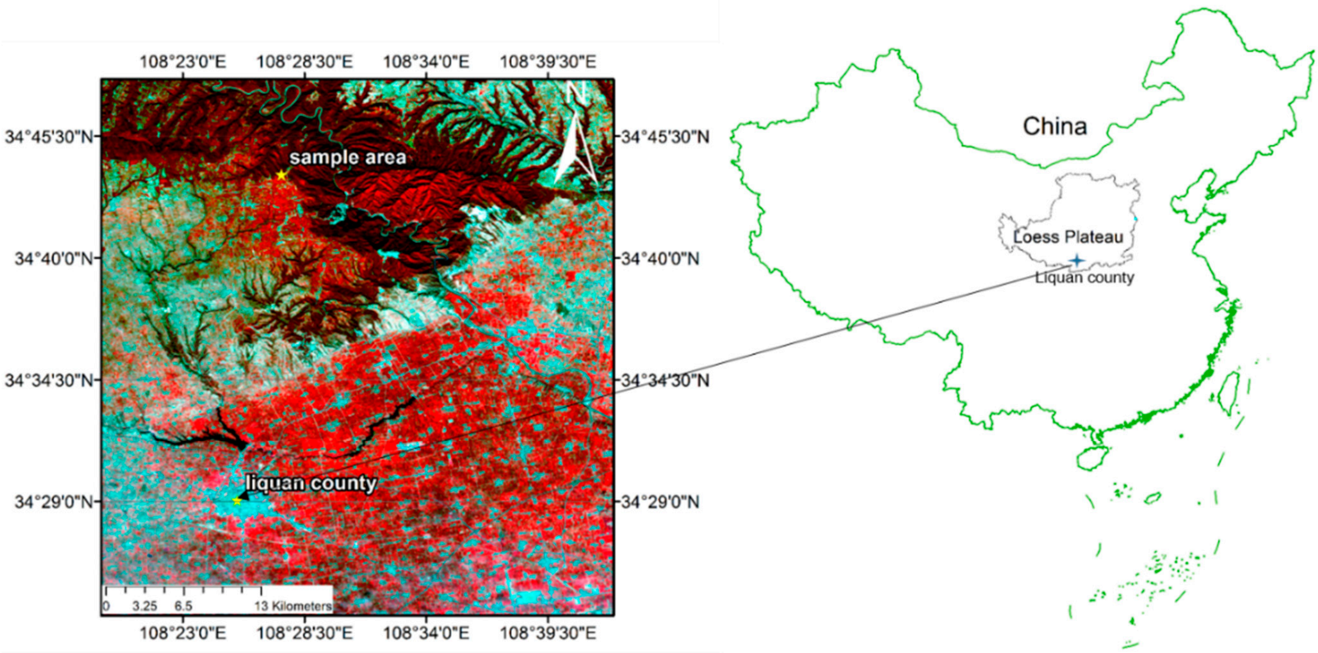

Figure 1. The location of the sample area in the north of Liquan County, China.

2.2. Experimental Design

Weigh 5–10 g dry aggregates with diameter of 2–5 mm and submerge them gently into distilled water for 30 min; then, wash them on a 0.05 mm sieve using ethyl alcohol. After shaking about 15 times at a speed of 25 times per minute, all soil particles on the sieve were washed into a 200 mL beaker using ethyl alcohol. After drying at 40 °C, all soil particles in the beaker were separated by moving a cascade of sieves with openings of 5, 2, 1, 0.5, 0.2, and 0.1 mm. The water-stable aggregates with diameters of <0.1 mm, 0.1–0.2 mm, 0.2–0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm and >2.0 mm were weighed, and mass percentages were calculated [21]. This treatment was replicated three times.

SOC concentrations of the aggregate fractions and the bulk samples were determined using the oil bath–$K_2Cr_2O_7$ titration method [22]. Soil bulk density was measured using a cutting ring driven vertically downward into the midrange of each horizon. The content of inorganic carbon was determined by the volume of carbon dioxide from the reaction with hydrochloric acid [23].

2.3. Data Analysis

Mean weight diameter (MWD) was calculated using the following formula.

$$\mathrm{MWD} = \frac{\sum_{i=1}^{6} \overline{x_i} w_i}{\sum_{i=1}^{6} w_i} \quad (1)$$

where $\overline{x_i}$ (in millimeter) is the mean diameter of two consecutive sieves, and w_i is the corresponding mass percent.

Soil organic carbon density (hereafter: SOCD) and soil inorganic carbon density (hereafter: SIOCD) were computed at different soil layers using the following equations:

$$\mathrm{SOCD(i)} = \frac{\mathrm{SOC(i)} \times \mathrm{BD(i)} \times \mathrm{H(i)}}{10} \quad (2)$$

$$\mathrm{SIOCD(i)} = \frac{\mathrm{SIOC(i)} \times \mathrm{BD(i)} \times \mathrm{H(i)}}{10} \quad (3)$$

where SOC(i) and SIOC(i) are the content of SOC (%) and 0.12 × $CaCO_3$ (%) in the soil layer, respectively, BD(i) is the soil bulk density (g/cm^3) in the soil layer i, and H(i) is the soil layer's thickness (10 cm).

The diagrams in the paper were drawn using the ggplot2 package in R [24] and Excel 2013. SPSS software (version 16.0) (SPSS Inc., Chicago, IL, USA) was used to perform the statistical and variance analyses. One-way ANOVA followed by the LSD (least significant difference) test was used to compare the significance of the difference of MWDs among the different soil layers under the same plantation and the different plantations at the same soil layer. An independent t-test was used to test the differences between *R. pseudoacacia* and *P. tabuliformis* plantations in the 50–80 cm soil layers.

3. Results

3.1. Aggregates Stability Characteristics

The three plantations had a great influence on the MWD of soil water-stable aggregates (Figure 2). The MWD was 0.18–0.27 mm, 0.35–0.57 mm, and 0.11–0.15 mm under *R. pseudoacacia*, *P. tabuliformis*, and *M. pumila* plantations, respectively. The MWD of *R. pseudoacacia* was 22%–67% lower than that of *P. tabuliformis* across the 0–80 cm soil layers. The MWD was 27%–45% and 57%–78% lower in *M. pumila* than in *R. pseudoacacia* and *P. tabuliformis* across 0–50 cm layers. Under the three types of plantations, the variation characteristics of MWD were different in the soil profiles. The MWD of 20–80 cm was higher than that of 0–20 cm under the *P. tabuliformis* plantation. The MWD of 0–10 cm was the highest, followed by 10–30 cm, and that of 30–80 cm was the lowest under the *R. pseudoacacia* plantation. The MWD did not differ significantly at any of the layers under the *M. pumila* plantation.

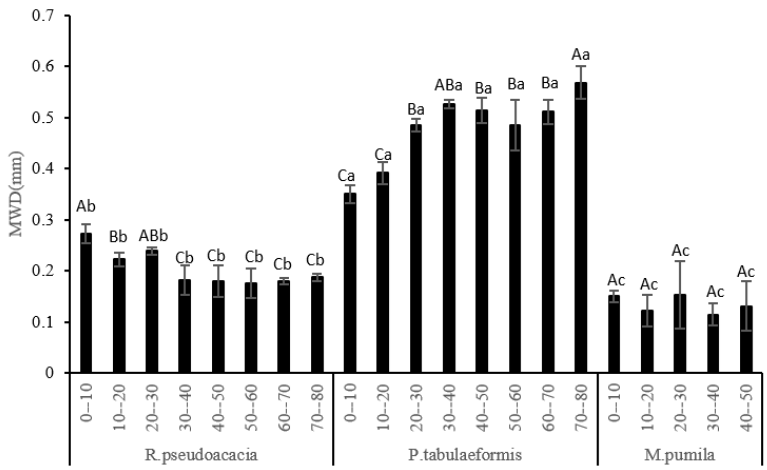

Figure 2. MWDs of water–stable aggregates under several soil layers in the plantations. Notes: The different capital letters mean differences are significant among the different soil layers under the same plantation ($p < 0.05$). The different lowercase letters mean differences are significant among the three plantations at the same soil layer ($p < 0.05$). Error bars represent standard error.

3.2. The Content of SOC and SIC

Our findings showed that 26%, 30%, and 31% of SOC content was distributed in the topsoil (0–10 cm) in *P. tabuliformis*, *R. pseudoacacia*, and *M. pumila* plantations, respectively.

In the subsurface layer (10–60 cm), there was little difference in soil organic carbon content between *R. pseudoacacia* and *M. pumila* plantations. In all soil layers, the SOC content was the higher in the *P. tabuliformis* plantation compared with *R. pseudoacacia* and *M. pumila* plantations (Figure 3A).

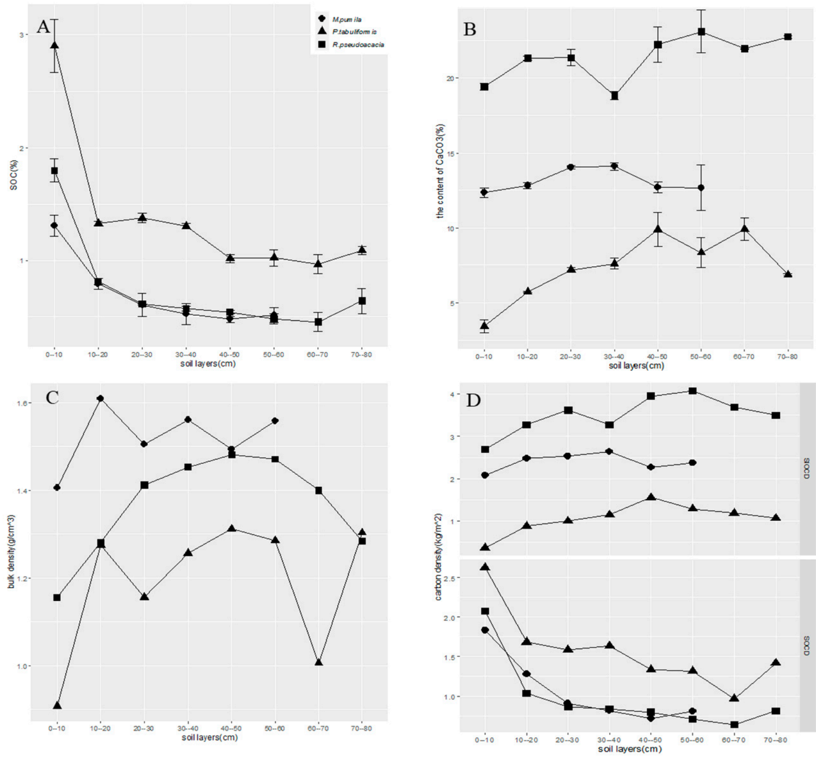

Figure 3. The content of soil organic carbon (**A**), $CaCO_3$ (**B**), bulk density (**C**), soil inorganic carbon density (above) and organic carbon density (below) (**D**) under several soil layers in the three plantations.

The percentages of SIC are shown in Figure 3B. In different soil layers, the content of SIC, represented by $CaCO_3$ content, varied from 19% to 23% in the *R. pseudoacacia* plantation, from 12% to 14% in the *M. pumila* plantation, and from 3% to 10% in the *P. tabuliformis* plantation, showing the order of *R. pseudoacacia* > *M. pumila* > *P. tabuliformis*. The SIC content in the *R. pseudoacacia* plantation was 2.22–5.67 times that of the *P. tabuliformis* plantation in different soil layers. Although the soils were developed over Loess parent material rich in carbonate materials, the SIC content varied among the tree plantations, which is mainly due to the types of plantation.

3.3. Bulk Density Characteristics

The bulk density of the *M. pumila* plantation was between 1.41 g/cm^3 and 1.56 g/cm^3, that of *P. tabuliformis* plantation was between 0.91 g/cm^3 and 1.31 g/cm^3, and that of *R. pseudoacacia* plantation was between 1.16 g/cm^3 and 1.48 g/cm^3 (Figure 3C). The bulk density of *M. pumila* plantation in the whole soil layers was always higher than that of the two other plantations.

Soil Organic and Inorganic Density

At the soil profiles, the soil organic carbon density (SOCD) was the highest at the surface soil, and its distribution pattern was similar to that of SOC. Soil inorganic carbon density (SIOCD) increased gradually to the maximum and then decreased (Figure 3D). On the soil profiles, the average value of SOCD and SIOCD was 0.97 kg/m^2 (SD = 0.46) and 3.57 kg/m^2 (SD = 0.44) in the *R. pseudoacacia* plantation, 1.58 kg/m^2 (SD = 0.49) and 1.06 kg/m^2 (SD = 0.34) in the *P. tabuliformis* plantation, 1.06 kg/m^2 (SD = 0.43) and 2.40 kg/m^2 (SD = 0.20) in the *M. pumila* plantation, respectively. Soil total carbon density

(STCD) was calculated by SOCD plus SIOCD (Figure 4). The ratios of SOCD to STCD were 15%–44%, 45%–88%, and 24%–47% in the *R. pseudoacacia*, *P. tabuliformis*, and *M. pumila* plantations, respectively. STCD was the highest in the *R. pseudoacacia* plantation, the middle in the *M. pumila* plantation, and the lowest in the *P. tabuliformis* plantation (Figure 4). The STCD fluctuated with the increase of the soil layer. In the 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70 and 70–80 cm soil layer, the STCD of the *P. tabuliformis* plantation was 37%, 41%, 42%, 39%, 39%, 46%, 50%, 42% lower than that of the *R. pseudoacacia* plantation. In the 0–10, 10–20, 20–30, 30–40, 40–50, 50–60 cm soil layer, the STCD of the *P. tabuliformis* plantation was 23%, 32%, 25%, 20%, 3%, and 18% lower than that of *M. pumila* plantation.

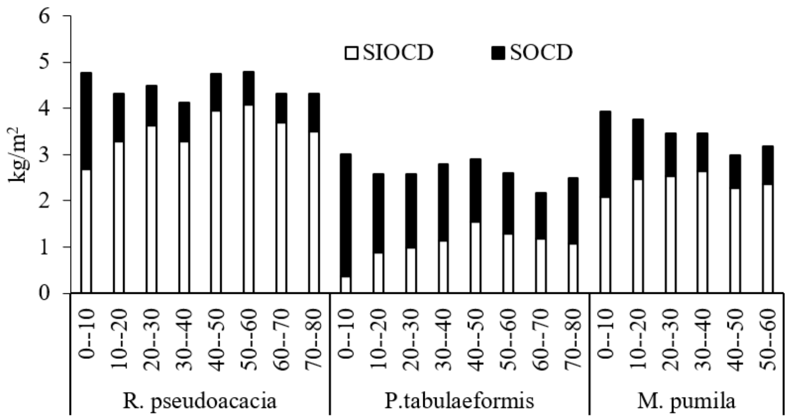

Figure 4. Soil total carbon density under several soil layers in three artificial forest types.

3.4. The Relationship between Stable Aggregate Size and Soil Carbon Content

$CaCO_3$ content decreased successively with the increase of aggregate sizes, which was the lowest in >2 mm fraction (Figure 5). Inversely, the SOM content increased linearly with the increase in aggregate size, and the highest was in >2 mm fraction (3.93%) (Figure 5). Obviously, there was a trade-off between SOM and $CaCO_3$ content.

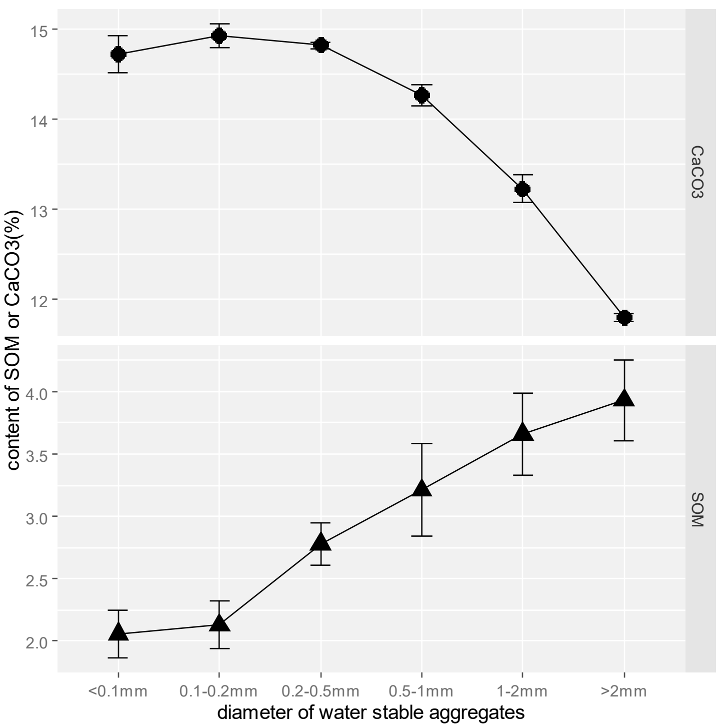

Figure 5. Content of calcium carbonate ($CaCO_3$) and soil organic matter (SOM) in water–stable aggregates with different sizes.

There was a linear positive correlation between $CaCO_3$ content and MWD of water-stable aggregates in the soil profile of *P. tabulaeformis* plantation, whereas there was a linear negative correlation in the soil profile of *R. pseudoacacia* plantation (Figure 6).

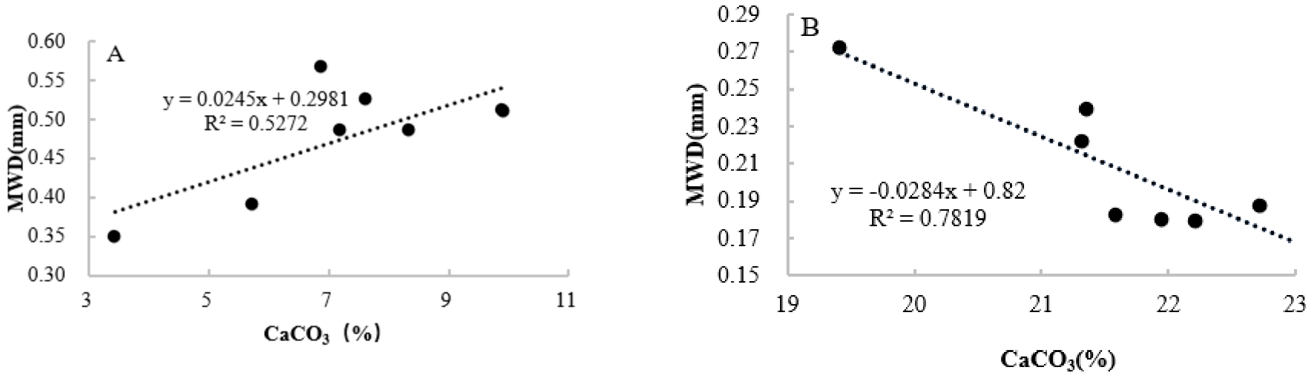

Figure 6. Relationship between MWD of water-stable aggregates and $CaCO_3$ content in *P. tabulaeformis* (**A**) and *R. pseudoacacia* (**B**) plantations.

4. Discussion

It is very important to evaluate the changes in soil properties caused by afforestation, especially in ecologically fragile areas [25]. Our results supported the hypothesis that bulk density, aggregate stability, and carbon content were affected by varieties of tree species, and these soil properties changed significantly between different soil layers. In addition, the soil organic matter content of water-stable aggregates with larger particle sizes was higher, but the content of calcium carbonate was lower. Compared with the *M. pumila* and *R. pseudoacacia* plantations, the *P. tabuliformis* plantation was more conducive to increasing soil organic carbon and decreasing soil inorganic carbon and bulk density. The *P. tabuliformis* plantation was also able to improve the water stability of soil aggregates, which was conducive to the improvement of soil quality.

4.1. Effects of Tree Species on Soil Properties

Soil aggregate stability was considered to be one of the soil properties providing information on soil quality [26]. The order of water stability of soil aggregates and organic carbon content was *P. tabuliformis* > *R. pseudoacacia* > *M. pumila*, indicating that there were great differences in soil structure, soil nutrients, and related soil functions among the plantations. Similarly, Chen et al. [2] reported that the content of soil organic carbon in the *P. tabulaeformis* plantation was higher than that in the *R. pseudoacacia* plantation, although both of them were planted in the same year. Our study showed that *P. tabuliformis* was more conducive to increasing SOC content and aggregate stability compared with *R. pseudoacacia* and *M. pumila*. This was in agreement with results found by previous studies, which observed that the *Pinus* spp. plantation could supply the soil with lots of organic material and improve water repellency of soil [27]. The increase in SOC was mostly associated with the increase in soil hydrophobicity, especially under the wax/aromatic oil-rich litter of the *Pinus halepensis* trees [1]. Moreover, the presence of water repellency played an important role in the formation and stabilization of aggregates and avoided high levels of soil degradation [26]. Therefore, in this study, the *P. tabulaeformis* plantation improved SOC and aggregate stability at the same time, which seemed logical. Additionally, the fine root biomass (FRB) and fine root production (FRP) of *P. tabulaeformis* were greater than those of *R. pseudoacacia* [2]. Small and fine roots produced optimal conditions to form and stabilize aggregates due to the polysaccharides produced by the microorganisms [28]. Meanwhile, bulk density was significantly related to most of the other soil parameters, which could be used as an indicator of soil structure [25]. The order of bulk density was *P. tabuliformis* < *R. pseudoacacia* < *M. pumila*, which indicated that there was a negative relationship between bulk density and MWD or SOC. Our study showed that the increase in SOC represented the improvement of aggregate stability and the decrease of BD, which was significant in the *P. tabulaeformis* plantation, followed by *R. pseudoacacia* plantation. At the *M. pumila* plantation, the MWD of water-stable aggregates was the smallest (Figure 2), and the SOC content was the lowest (Figure 3A). This could be explained by long-term cultivation management practices, such as pruning and weed control, which reduced the input and increased the decomposition of organic matter. Our results also showed that compared with other soil layers, the content of soil organic matter in the surface layer (0–10 cm) was the largest. This was in agreement with the previous study conducted in other forest ecosystems [29]. This was also a logical result, because the sources of organic matter including dry branches and fallen leaves were the most abundant in topsoil.

4.2. Effects of Tree Species on Soil Carbon Sequestration

It was also becoming increasingly clear that carbon accumulation in soil represented an important carbon stock [29]. The quantitative relationship between the changes of SOC and SIC stocks in deep soil layers following vegetation restoration should be further determined [17]. SIOCD to STCD ratios in *R. pseudoacacia* and *M. pumila* plantations are 56%–85% and 53%–76%. Zethof et al. [9] and Wang et al. [30] also reported that inorganic carbon content was often much higher than that of organic carbon in semi-arid regions. SIOCD to STCD ratio was lower (12%–55%) in the *P. tabulaeformis* plantation, which was due to coniferous trees having more acid exudate compared with broadleaf trees. In addition, therefore, more carbonate can be dissolved [30]. Furthermore, higher organic matter content in the *P. tabulaeformis* plantation increased saturated hydraulic conductivity [25], which also increased carbonate leaching. The $CaCO_3$ content and SIOCD fluctuated with deepening soil layers, showing there was more inorganic carbon content in subsoils. Han et al. [17] also found that the maximum soil inorganic carbon (SIC) values are at 60–100 cm soil layer. SIC content at subsoil increased significantly due to the dissolution and leaching of carbonates from topsoil and the subsequent precipitation in subsoil [16].

4.3. Effects of $CaCO_3$ Content on Aggregate Stability

In many semi-arid regions, where the presence of carbonates in the soil is frequent, it is necessary to study the correlation between carbonates and aggregate stability. For example, Fernández-Ugalde et al. [31] revealed that carbonates should be considered when modeling soil structure formation. Chrenková et al. [26] found carbonate had a positive influence on MWD for sandy soils. In semi-arid calcareous soils, Fernández-Ugalde et al. [31] reported that the interaction between corn straw and carbonate resulted in higher stability of macro-aggregates (>250 μm) in carbonated soil than in non-carbonated soil, and concluded that the formation of secondary carbonates in and/or around macro aggregates can explain this stability. In our study, the effect of carbonates in the stabilization of aggregates showed two sides. Firstly, aggregate-inorganic carbon decreased with increasing aggregate size (Figure 5). This occurred because $CaCO_3$ could cause the soil particles to consolidate in the dry state. However, when the soil is rapidly wetted by water, $CaCO_3$ will dissolve in the water to separate and disperse the soil particles. Therefore, the aggregates of calcareous soil can be easily broken under the condition of rapid wetting. Our study also found that *P. tabulaeformis* could effectively decrease the content of $CaCO_3$, so as to improve soil stability and slow down soil erosion. Secondly, when the content of soil calcium carbonate was low, i.e., 3%–10%, it was linearly positively correlated with the mean weight diameter of water-stable aggregates; when the content of soil calcium carbonate was high, i.e., 19%–23%, there was a negative linear relationship between them (Figure 6). Therefore, this study assumed that there was a threshold value of inorganic carbon content in the soil. When it is higher than the threshold value, the aggregate structure can be destroyed by the dissolution of calcium carbonate in the process of rapid wetting; when it is lower than the threshold value, calcium carbonate can be used as a cementing agent. Wuddivira et al. [32] reported that adding calcium ions with the concentration of 2.7 and 3.1 cmol/kg to the soil would increase the percentage content of water-stable aggregates, on the contrary, adding calcium ions with the concentration of 13.9 cmol/kg in the soil could disperse more aggregates. Virto et al. [33] also indicated that compared with the soil with 30% carbonate content, the carbonate in the soil with 15% carbonate content played a major cementation role in soil aggregates.

4.4. Effects of SOM Content on Aggregate Stability

Qiao et al. [12] suggested that micro-aggregates played key roles in protecting SOC because they stored SOC that was more difficult to degrade. However, in our results, the content of organic carbon in macro-aggregates was higher than that in micro-aggregates, which was similar to the results of a previous study [34]. Elliott [13] found more organic matter to be associated with macro-aggregates than with micro-aggregates in a temperate grassland soil. This conclusion was also in line with the theory of aggregate hierarchy, which suggests an increase in carbon concentration with increasing aggregate size class, because large aggregate size classes are composed of small aggregate size classes plus organic binding agents [13]. In addition, there was a trade-off between SOC and $CaCO_3$ (Figure 5), which is similar to the findings of Yang et al. [16] and Han et al. [17].

5. Conclusions

Our study demonstrated that tree species affect soil properties, which also changes with vertical soil profile. The economic forest *M. pumila* decreased the content of SOM and MWD of water-stable aggregates due to the effect of management. *M. pumila* and *R. pseudoacacia* are not as beneficial as *P. tabulaeformis* for the sequestration of SOC and the improvement of soil structures. However, *P. tabulaeformis* forest significantly reduced the content of soil calcium carbonate. The content of organic carbon and inorganic carbon is different in water-stable aggregates with different sizes. Organic materials are the major cementing agents influencing aggregation formation and stabilization. Calcium carbonate may be a dispersing agent when it is higher than a threshold value. Conversely, when it is lower than the threshold value, it may be an aggregate cement. During the construction of artificial vegetation, forestry departments may choose *Pinus tabulaeformis* as a tree species for afforestation in the semi-arid area of the Loess Plateau in China.

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