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Forest Conversion and Soil Depth Can Modify the Contributions of Organic and Inorganic Colloids to the Stability of Soil Aggregates

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Abstract: The stability of soil aggregates is critical for maintaining soil structures and is positively correlated with soil resident organic and inorganic colloids. Forest conversion and soil depth affects the formation of soil aggregates; however, the detailed mechanisms involved in their stabilization have not been well investigated. Therefore, to explore the main factors that influence the stability of soil aggregates for different forest types and soil depths, twelve soil samples were collected from four types of forests (native, mixed, Chinese fir, and bamboo forest) and three soil depths (0–10 cm, 10–20 cm, and 20–30 cm) in subtropical forests. The results revealed that the distributions and mean weight diameters (MWDs) of large macroaggregates in the bamboo forest were significantly lower than those in the other forest types at all soil depths ($p < 0.05$). Organic and inorganic colloids (organically-complexed Fe oxide and fulvic acid) in the soil directly impacted the stability of soil aggregates, while soil properties (e.g., pH and bulk density) indirectly promoted soil aggregate stability through the modification of colloids. In both native and bamboo forests, organic colloids contributed most to the stability of soil aggregates, reaching 80.31% and 61.37%, respectively. The contributions of organic colloids were found to decrease with soil depth, which was primarily due to changes in the organic matter caused by the decomposition of litter. Elucidating and promoting the specific contributions of organic and inorganic colloids on the stability of soil aggregates will be increasingly important for the optimal management of different forest types.

Keywords: forest conversion; soil depth; soil organic colloids; soil inorganic colloids; soil aggregate stability

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1. Introduction

The structural composition of soil is one of its fundamental properties, which determines its capacity to transport and retain water, air, and nutrients, while providing a suitable habitat for microbes and animals [1]. Soil structures are determined by the combination of individual soil particles [2], which are cemented together by organic and inorganic colloids and compounds to form stable microaggregates, which then form large aggregates under the action of transient cements such as root exudates [3]. Consequently, soil aggregates are intimately related to the structural composition of soils.

The stability of soil aggregates is vital for directly or indirectly maintaining a number of physical attributes related to it, such as root penetration [4]. Soil aggregate stability is also positively correlated with major colloids [5], such as soil organic matter (SOM) [6,7], and

Fe/Al oxide [1,8]. Humus is a component of soil organic matter [9] that is also considered to be a colloid related to the stabilization of soil aggregates [3]. In previous studies, researchers suggested that 84.3% of the changes in soil aggregates could be explained by soil organic matter and Fe/Al oxide [10]. Consequently, a focus on soil resident organic matter (e.g., soil organic carbon, SOC in mineral-associated organic matter, SOC in particulate organic matter, humus, humic acid, and fulvic acid) and Fe/Al oxides (e.g., free Fe/Al oxides, amorphous Fe/Al oxides, and organically complexed Fe/Al oxides) is critical for elucidating the stabilization of soil aggregates.

Subtropical evergreen broadleaved forests have significant environmental and economic importance worldwide [11]. In China's subtropical regions, the large-scale conversion of natural forests to secondary or plantation forests has proceeded over the last few decades to meet the rapid increases in timber demands [12,13]. Thus, ecosystems have been significantly negatively impacted. In previous studies, the conversion of evergreen broadleaved forests to Chinese fir forests decreased the SOC [14], altered the availability of carbon for soil microorganisms [13], reduced the soil's *p* availability [15], and decreased the soil respiration rate [12].

The conversion from evergreen broadleaf forests to bamboo forests altered the chemical structures of SOC and labile C pools, and decreased the content of SOC [16]. The conversion of evergreen broadleaved forests to Chinese fir/broadleaved mixed forests modified the nanoscale pores in the soil [17] but did not alter the diversity of soil bacteria [18]. However, the impacts of forest conversion on soil aggregates and the organic and inorganic colloids that facilitate their stability have not been investigated.

Plant roots have the capacity to effectively control soil erosion and stabilize soil structures, which play critical roles in the formation of soil aggregates [19]. Soil depth might effectively regulate the composition of humus [20], aggregate-associated SOC saturation behavior [21], and soil aggregate stability [22]. The stability of soil aggregates is also significantly influenced by land use or land cover types [23]. Therefore, forest conversion and soil depth might alter soil aggregate stabilization through changes in the SOM (affected by root exudates, decomposed roots, and litter) and Fe/Al oxides (affected by root growth and soil pores). Our primary objective was to explore the main factors that influenced the stability of soil aggregates for different forest types and soil depths.

According to previous studies, we proposed the following hypotheses: (1) forest conversion alters the distribution of water-stable aggregate sizes within the soil and increases the stability of soil aggregates; (2) the soil aggregate stability of different forest types or soil depths is determined by various organic or inorganic colloids; (3) the soil depth also affects the distribution of water-stable aggregate sizes; and (4) the soil stability of soil aggregates continues to increase with soil depth. These results will be useful in guiding the management of converted forests.

2. Materials and Methods

2.1. Study Site and Experimental Design

The field experiments were conducted at the Feng Yang Mountain Nature Reserve (119°06′ E~119°15′ E, 27°46′ N~27°58′ N) in Zhejiang, China. This region resides in a warm and humid subtropical climate zone, with a mean annual temperature and precipitation of 12.3 °C and 2438 mm, respectively.

Our study included four forest types—native forest, Chinese fir/broadleaved mixed forest, Chinese fir forest, and bamboo forest—that ranged from 1300 to 1400 m above sea level. For each of the four forest types, we randomly selected three replicate plots (the dimensions of every plot were 20 m × 20 m), for a total of 12 sample stand plots. The experimental plots (20 × 20 m) had the same geographical and environmental characteristics as the control plots, such as altitude (1340–1400 m), soil type (yellow brown soil), slope (10–15°), and aspect (south).

2.2. Soil Sampling

Soil samples were taken from five random locations at every site from three soil depth layers (0–10 cm, 10–20 cm, and 20–30 cm). These soil samples were combined in the laboratory to produce one composite soil sample, after which the following measurements were made.

2.3. Measurement of Soil Physicochemical Properties and Enzyme Activities

The soil pH was measured using a PB-10 pH meter (Sartorius GmbH, Göttingen, Germany), whereas the soil TN was quantified via an elemental analyzer (Vario EL III, ELementar, Hanau, Germany). The bulk density and total capillary porosity were determined using the ring knife method [24]. The activities of soil enzymes were calculated based on the method described in a previous study [25].

2.4. Soil Aggregate Distribution and Stability Analysis

A wet-sieving method was employed to determine the soil aggregate size fraction [26]. First, the samples were sifted through 2.0 mm, 0.25 mm, and 0.53 mm sieves, to obtain four size fractions, namely >2.0 mm (large macroaggregates), 0.25–2.0 mm (small macroaggregates), 0.053–0.25 mm (microaggregates), and <0.053 mm (small microaggregates). Second, according to the mass percentage of the aggregates obtained from dry sieving, a composite soil for wet sieving was prepared. The measurement of water-stable soil aggregates was conducted using an aggregate analyzer, where the set of sieves were kept consistent with those used for dry sieving (2.0 mm, 0.25 mm, and 0.53 mm). Third, the aggregate analyzer was shaken for 30 min, after which the soil was rinsed from every sieve, oven-dried, and weighed. The mean weight diameter (MWD) was expressed by the following relationships:

$$MWD = \sum_{n=1}^{n} x_i \times w_i \quad (1)$$

where x_i is the average soil aggregate diameter with i and w_i is the mass percentage of soil aggregates with i.

2.5. Measurement of Organic and Inorganic Soil Colloids

The total soil organic carbon (SOC) content was measured via a potassium dichromate method [27], where 20 g of an air-dried soil sample (through a 2 mm sieve) was placed in a 250 mL flask to which 100 mL $(NaPO_3)_6$ (5 g/L) was also introduced. The flask was then shaken for 18 h under a constant temperature (90 r/min). The resulting slurry was then transferred and spread on a reciprocal sieve shaker with a 53 µm sieve, and repeatedly washed with distilled water until the water was clear on the screen. All fractions were calculated by drying at 60 °C for 24 h. The SOC in the particulate organic matter (POC) and mineral-associated organic matter (MOC) were then obtained [28].

The humic substances in the bulk soil, or every aggregate fraction, were extracted from the soil using pyrophosphate-sodium hydroxide-sodium in a 50 °C water bath. The suspended materials were then separated by centrifugation at 3500 rpm for 5 min. The residues were then dialyzed with pyrophosphate-sodium hydroxide-sodium until the solution was colorless, and the supernatant was humus [26]. Furthermore, to extract the humic acid from humus, the supernatant was acidified with H_2SO_4 (pH $\leq$ 1.5) and heated at 80 °C for 30 min. The suspended materials were filtered in the laboratory overnight, and the residues on the filter paper were percolated with H_2SO_4 until the precipitate was colorless. Finally, the remaining residues were dissolved at 60 °C with NaOH to separate the humic acids. The fulvic acid was measured by subtracting the humic acid from the humus [26].

The free Fe/Al oxides were extracted with citrate-biocarbonate-dithionite, whereas the amorphous Fe/Al oxides were extracted by ammonium oxalate, and the organically-complexed Fe/Al oxides were extracted using sodium pyrophosphate [29].

2.6. Statistical Analysis

One-way analysis of variance (ANOVA) (SPSS, version 26.0, Chicago, IL, USA) was applied to evaluate the statistical significance of the soil physicochemical properties, soil enzyme activities, soil aggregates, and soil organic and inorganic colloids. Two-way analysis of variance (ANOVA) (SPSS 26) was applied to evaluate the effects of forest type and soil depth on the soil physicochemical properties, soil enzyme activities, soil aggregates, and soil organic and inorganic colloids. Pearson correlation (R, https://www.r-project.org/ (accessed on 29 April 2021) and Hemi 1.0, http://hemi.biocuckoo.org/ (accessed on 29 April 2021)) was used to evaluate the stability of the soil aggregates and soil physical–chemical properties, soil enzyme activities, and soil organic and inorganic colloids.

Structural equation model (SEM) analysis (Amos, version 26.0, Chicago, IL, USA) was employed to estimate the direct and indirect effects of soil organic or inorganic colloids and soil properties on the soil aggregate stability. Some indices (χ^2, p value, GFI, and RMSEM) were utilized to test the goodness of fit of the model: p value > 0.05, GFI > 0.9, RMSEM < 0.08. Boosted regression tree (BRT) analysis (R 4.1.0) was conducted to estimate the contributions of organic and inorganic soil colloids to the stability of soil aggregates. Other figures were completed in Origin (Origin, version 2015, Northampton, MA, USA).

3. Results

3.1. Soil Physicochemical Properties and Enzyme Activities

Within the 0–10 cm layer, the pH in the mixed forest was significantly lower than the pH in the bamboo forest ($p < 0.05$) (Figure S1A), and there were no significant differences between the native forest and other forest types (Figure S1A). Within the other soil layers, forest conversion did not significantly affect the soil pH. Further, forest conversion did not significantly affect the soil TN, total capillary porosity, and bulk density (Figure S1B–D). For the Chinese fir forest, the TN in the 0–10 cm layer was significantly higher than that in the 20–30 cm layer ($p < 0.05$) (Figure S2B). For the other forest types, soil depth did not significantly impact the soil properties (Figure S2A,C,D).

The soil urease activities in the mixed forest were significantly lower than those in the native forest across all soil layers ($p < 0.05$) (Figure S3A). The soil phosphatase activities in the mixed and bamboo forests were significantly lower than those in the native forest across all soil layers ($p < 0.05$) (Figure S3B). The soil urease activities in the mixed, Chinese fir, and bamboo forests were significantly lower than those in native forest across all soil layers ($p < 0.05$) (Figure S3C). The soil catalase activities in the mixed and Chinese fir forests were significantly lower than those in the native forest within the 10–20 cm layer. Forest conversion also significantly decreased the activities of soil catalase in the 20–30 cm layer ($p < 0.05$) (Figure S3D). Additionally, the activities of soil enzymes decreased significantly with the soil depth (Figure S4, Table S1).

3.2. Soil Aggregate Distribution and Stability

Within all soil layers, the distribution of large macroaggregates in the bamboo forest was significantly lower than that of in the other forest types. The distribution of small macroaggregates in the bamboo forest was significantly higher than that of in the other forest types ($p < 0.05$) (Figure 1). Furthermore, forest conversion did not significantly affect the distribution of microaggregates (Table S1). Within the 20–30 cm layer, the distribution of large macroaggregates in the native forest was significantly lower than that in the Chinese fir forest; however, the small macroaggregate distribution in the native forest was significantly higher than that in the Chinese fir forest ($p < 0.05$) (Figure 1C). Across all soil layers, the MWDs in the bamboo forest were significantly lower than those in the other forest types ($p < 0.05$) (Figure 2A). Furthermore, the soil depth had no significant effects on the distribution and stability of soil aggregates (Figure 2B, Table S1).

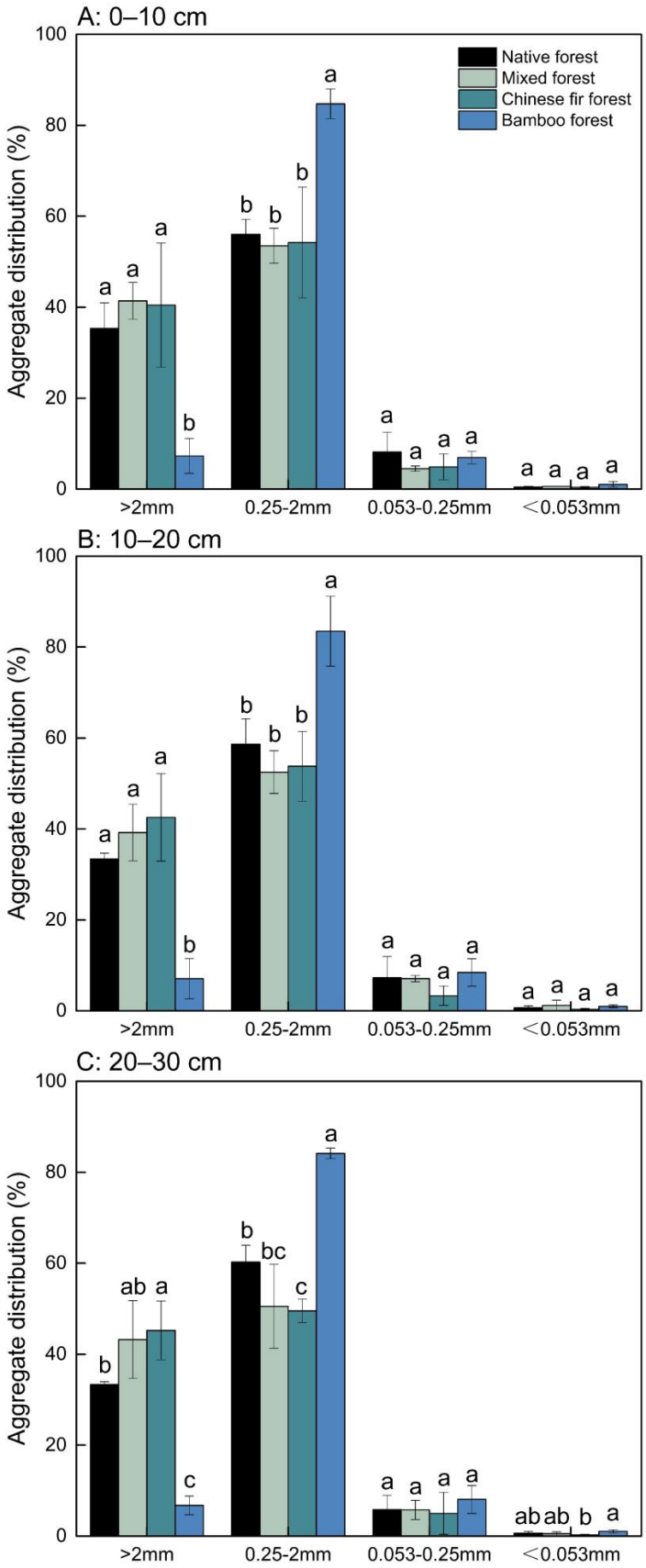


Figure 1. Distribution of water-stable aggregate sizes at depths of from 0 to 30 cm for different forest types. (**A**): 0–10 cm soil depth; (**B**): 10–20 cm soil depth; (**C**): 20–30 cm soil depth. Different letters indicate significant difference ($p < 0.05$) between different forest types.

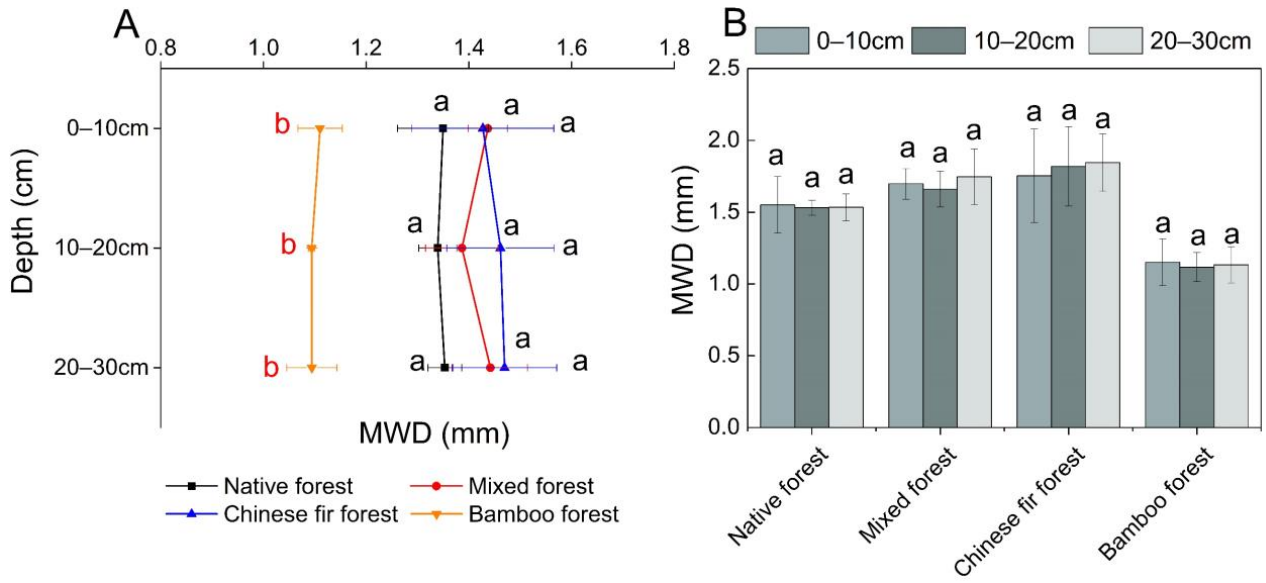


Figure 2. Soil aggregate stability characteristics at depths of from 0 to 30 cm for different forest types. (**A**): Different forest types; (**B**): different soil depths. Different letters indicate significant difference ($p < 0.05$) between different forest types.

3.3. Soil Organic Colloid

The conversion of the native forest to other forest types had no significant effects on the SOC and POC contents (Figure 3A,B, Table S1). However, the MOC content in the Chinese fir forest was significantly lower than that in the native forest across all soil layers ($p < 0.05$) (Figure 3). Within the 20–30 cm layer, the MOC content in the mixed forest was also significantly lower than that in the native forest ($p < 0.05$). Further, there was a significant decrease in the SOC and POC contents with soil depth ($p < 0.05$) (Figure S6, Table S1).

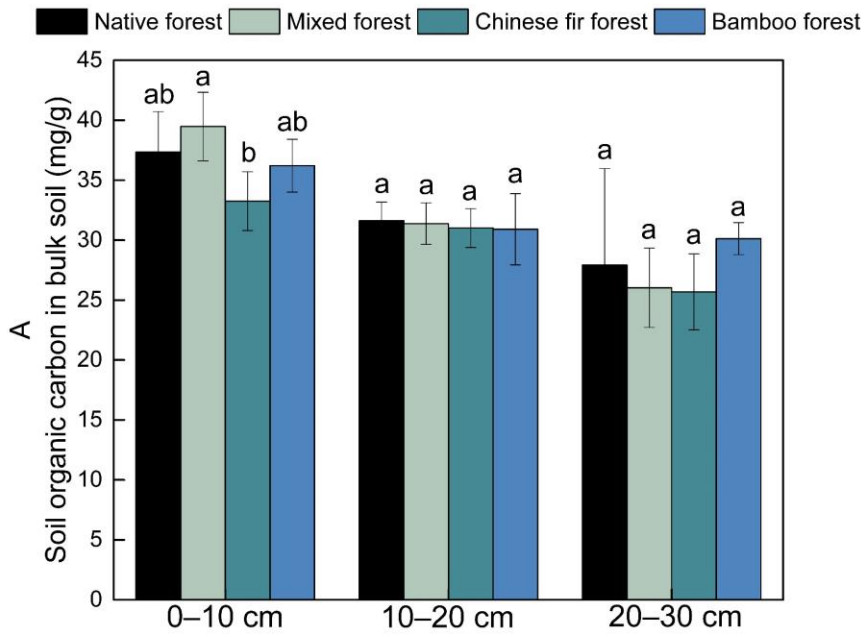


Figure 3. *Cont.*

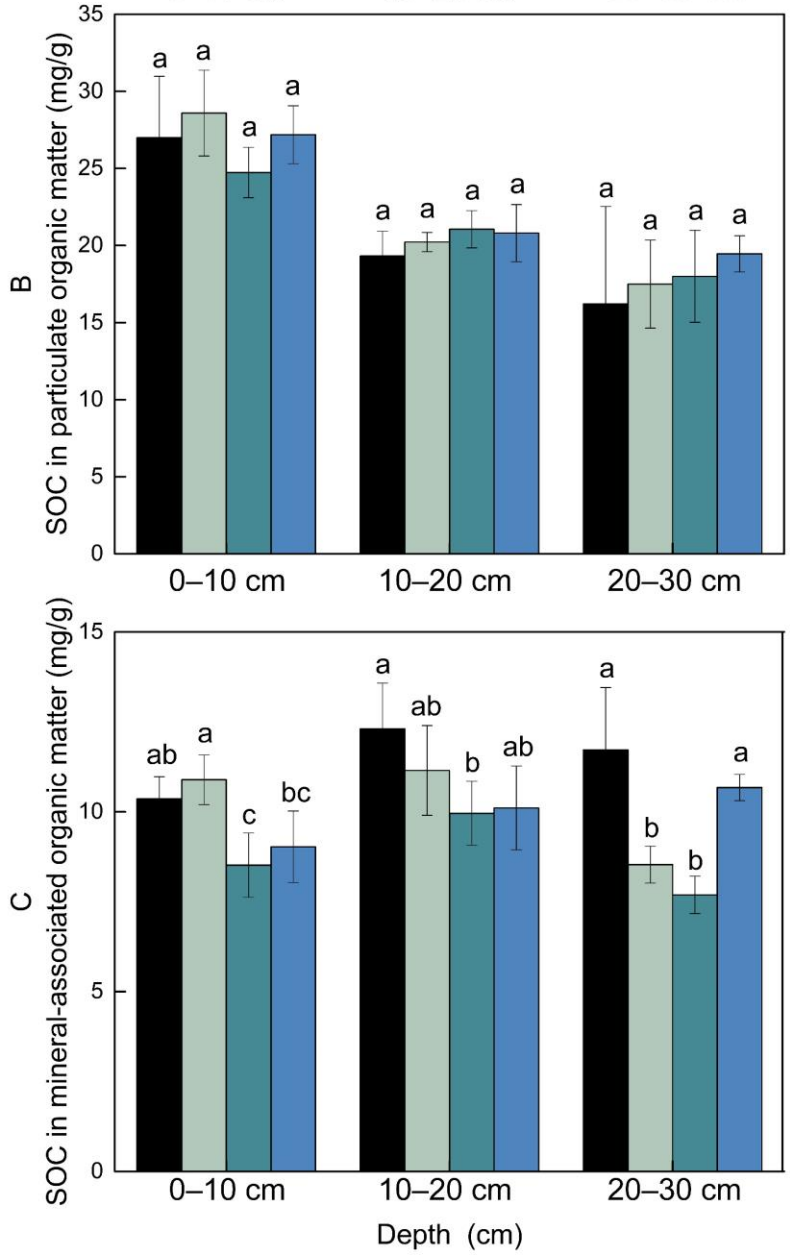


Figure 3. SOC, POC, and MOC contents at depths of from 0 to 30 cm for different forest types. (**A**): soil organic carbon (SOC); (**B**): SOC in particulate organic matter (POC); (**C**): SOC in mineral-associated organic matter (MOC). Different letters indicate significant difference ($p < 0.05$) between different forest types.

For the 20–30 cm layer, the humus content in the native forest was significantly lower than that in the mixed and bamboo forests ($p < 0.05$) (Figure 4A), whereas the fulvic acid content in the native forest was significantly lower than in the mixed forest ($p < 0.05$) (Figure 4B). Within the 10–20 cm layer, the humic acid content in the bamboo forest was significantly higher than the other forest types ($p < 0.05$) (Figure 4C). Further, the humus, humic acid, and fulvic acid contents were significantly decreased ($p < 0.01$) with soil depth (Figure S7, Table S1).

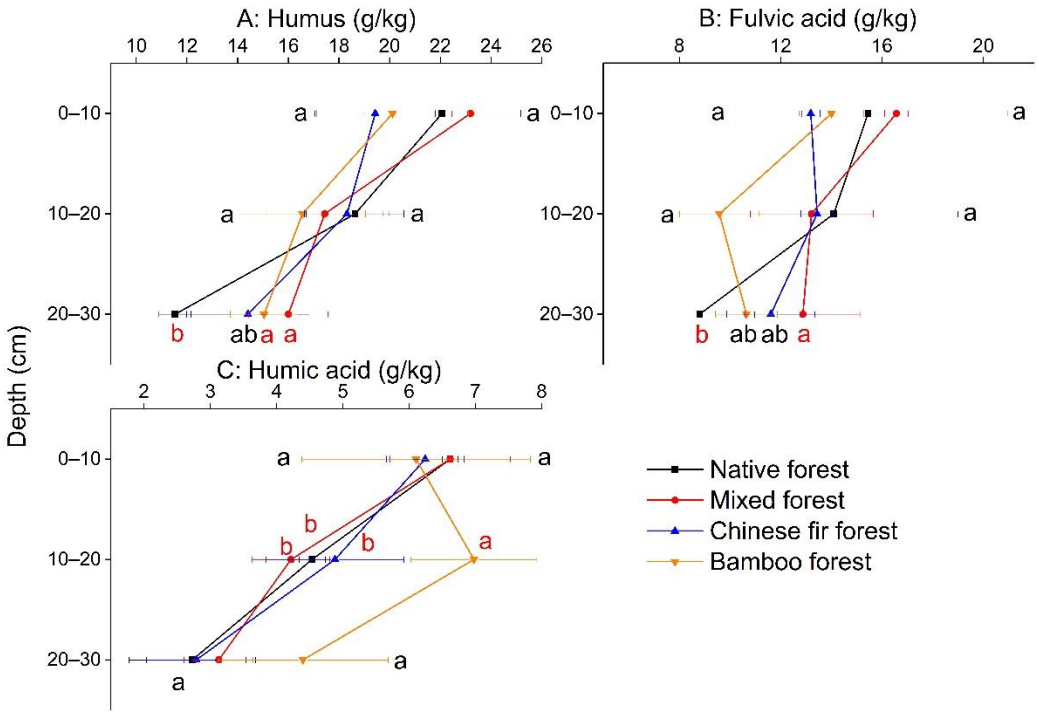


Figure 4. Humic substance contents of bulk soil at depths of from 0 to 30 cm for different forest types. (**A**): Humus; (**B**): humic acid; (**C**): fulvic acid. Different letters indicate significant difference ($p < 0.05$) between different forest types.

3.4. Soil Inorganic Colloid

Within the 0–10 cm layer, the free Fe oxide in the native forest was significantly lower than that in the Chinese fir forest ($p < 0.05$) (Figure 5A). Within the 10–20 cm and 20–30 cm layer, the conversion of the native forest to other forest types had no significant effects on the free Fe oxide and amorphous Fe oxide (Figure 5A,B). The organically complexed Fe oxides in the native forest were significantly higher than those in the bamboo forest within the 0–10 cm and 20–30 cm layers ($p < 0.05$) (Figure 5C). In addition, soil depth had no significant effects on the free Fe oxide or organically complexed Fe oxide (Figure S8A,C). For the bamboo forest, the amorphous Fe oxide decreased with the soil depth (Figure S8B).

For the free Al oxide, there were no significant differences between the various forest types across all soil layers (Figure 6A, Table S1). Within the 0–10 cm layer, the amorphous Al oxide in the native forest was significantly lower than that in the other forest types ($p < 0.05$) (Figure 6B). Within the 10–20 cm layer, the amorphous Al oxide in the native forest was significantly lower than that in the bamboo forest ($p < 0.05$). Within the 20–30 cm layer, the amorphous Al oxide in the native forest was significantly lower than that in the mixed forest ($p < 0.05$).

For the 0–10 cm and 20–30 cm layers in the various forest types, the organically-complexed Al oxides, in significantly decreasing order, were as follows: native, mixed, Chinese fir, and bamboo forest ($p < 0.05$) (Figure 6C). Within the 10–20 cm layer, the organically complexed Al oxide in the native forest was significantly higher than that in the Chinese fir and bamboo forests ($p < 0.05$). Furthermore, the soil depth had no significant effects on the free Al oxides for all forest types (Figure S9A) but had significant effects on the amorphous Al oxide and organically complexed Al oxide ($p < 0.01$) (Table S1).

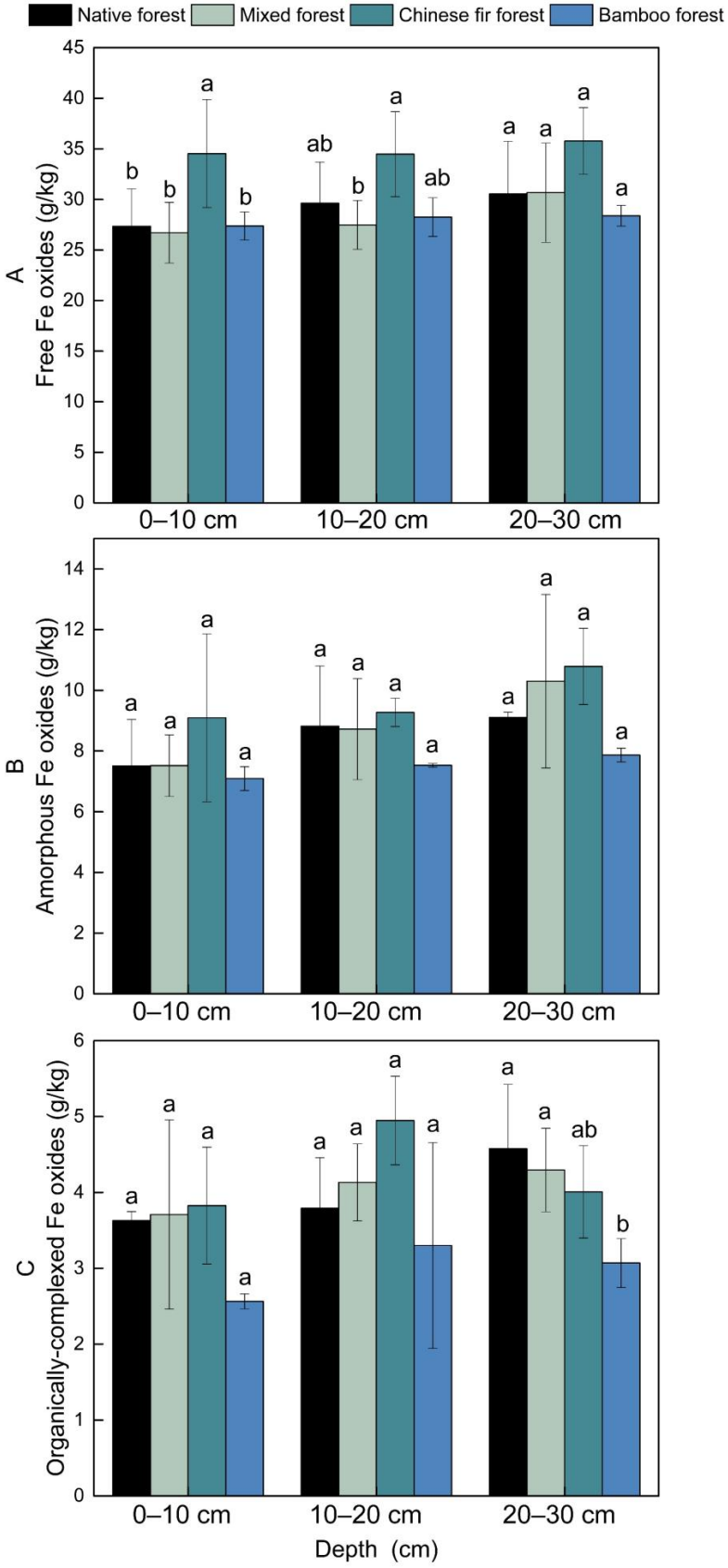


Figure 5. Contents of Fe oxides at depths of from 0 to 30 cm for different forest types. (**A**): Free Fe; (**B**): amorphous Fe oxides; (**C**): organically–complexed Fe oxides. Different letters indicate significant difference ($p < 0.05$) between different forest types.

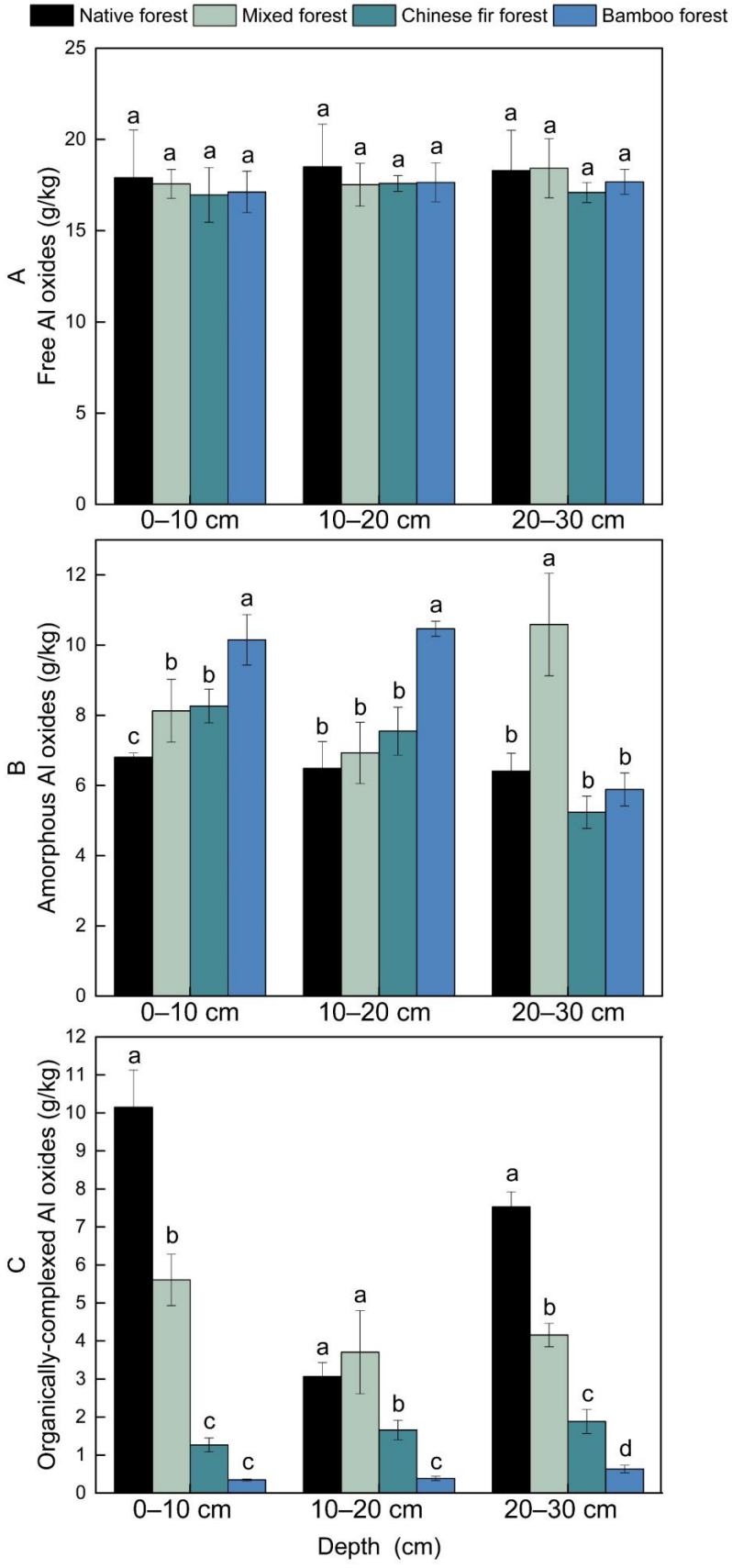


Figure 6. Contents of Al oxides at depths of from 0–30 cm for different forest types. (**A**): Free Al; (**B**): amorphous Al oxides; (**C**): organically-complexed Al oxides. Different letters indicate significant difference ($p < 0.05$) between different forest types.

3.5. Correlation and SEM Analysis

The results of the Pearson correlation analysis revealed that the MWD was positively correlated with the bulk density and organically complexed Fe oxide, but negatively correlated with the pH, urease activity (Figure 7a, Table S2), and humic acid. The SOC, POC, humus, humic acid, and fulvic acid were positively correlated with the TN, total capillary porosity, urease, invertase, and catalase activity, but negatively correlated with the bulk density. The humus, humic acid, and fulvic acid were positively correlated with the SOC and POC. The free Fe oxide and amorphous Fe oxide were positively correlated with free Al oxide, but negatively correlated with the urease activity. The organically complexed Al oxide was positively correlated with phosphatase, invertase, catalase activity, and MOC, but negatively correlated with pH.

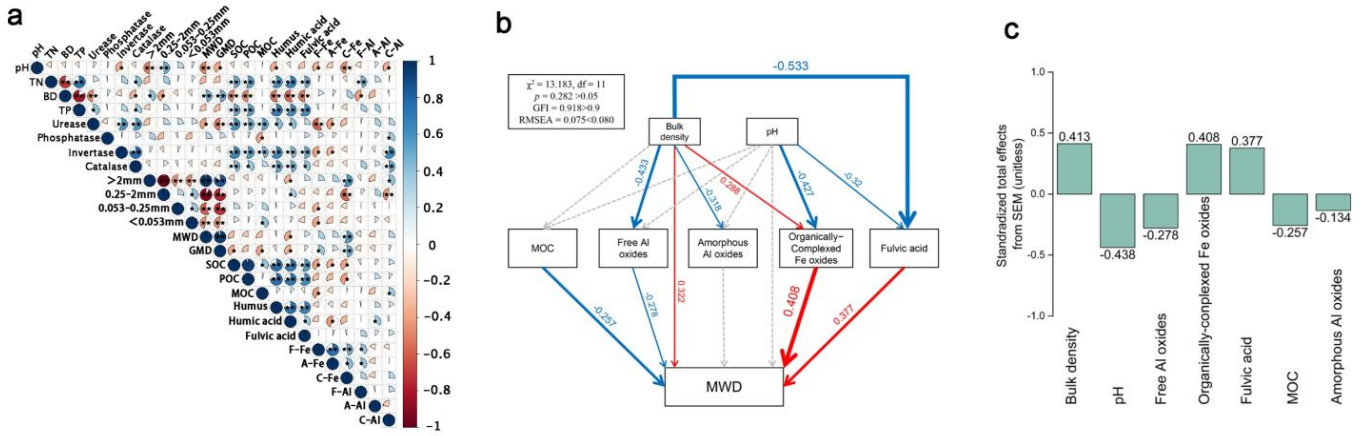


Figure 7. Pearson correlation and SEM analysis. (**a**): Pearson correlation between soil physical–chemical properties, soil enzyme activities, soil aggregates, and organic and inorganic soil colloids. Abbreviations are as follows: total nitrogen (TN), bulk density (BD), total capillary porosity (TCP), soil organic carbon (SOC), SOC in particulate organic matter (POC), SOC in mineral-associated organic matter (MOC), free Fe (F-Fe), amorphous Fe oxides (A-Fe), organically complexed Fe oxides (C-Fe), free Al (F-Al), amorphous Al oxides (A-Al), organically complexed Al oxides (C-Al). ** indicates significant correlation at $p < 0.01$, * indicates significant correlation at $p < 0.05$. (**b**): Structural equation model (SEM) analysis estimating the direct and indirect effects of organic or inorganic soil colloids and soil properties on soil aggregate stability. Boxes show variables included in the model. Test results of the goodness of model fit: Chi-square (χ^2) = 13.183, p value = 0.282 > 0.05, goodness-of-fit index (GFI) = 0.918 > 0.9, root square mean error of approximation (RMSEA) = 0.075 < 0.08. Numbers on arrows are standardized path coefficients. Widths of arrows represent the strength of the relationships. Blue arrows indicate negative relationships, and red arrows indicate positive relationships. Solid arrows indicate significance ($p < 0.05$) and dashed arrows represent non-significance ($p > 0.05$) (the p value is calculated in terms of the nonnormalized path). (**c**): Standardized total effects (direct plus indirect effects) derived from the structural equation models depicted above.

To estimate the direct and indirect effects of the organic or inorganic soil colloids and soil properties on the stability of soil aggregates, the aggregate stability was determined based on the mean weight diameter (MWD) [30]. The structural equation model (SEM) showed that the organically complexed Fe oxide (path coefficient = 0.408; $p < 0.001$) and fulvic acid (path coefficient = 0.377; $p < 0.01$) had direct positive effects on the soil aggregate stability, whereas the pH had an indirect effect through the regulation of organically complexed Fe oxide and fulvic acid. The bulk density (path coefficient = 0.322; $p < 0.05$) had direct positive impacts on the stability of the soil aggregates, and also had an indirect effect by regulating the organically complexed Fe oxide (Figure 7b).

The standardized total effects of the different parameters were analyzed to further assess the comprehensive regulatory effects of the driving factors on the soil aggregate stability (Figure 7c). The results revealed that the bulk density had the greatest positive

integrated effect on soil aggregate stability, followed by organically complexed Fe oxide and fulvic acid. In addition, the organically complexed Fe oxide and fulvic acid had completely standardized direct effects, whereas the bulk density had completely standardized indirect effects on soil aggregate stability. In contrast to the above parameters, the pH had a highly negative total effect on the stability of soil aggregates, which confirmed the contribution of soil acidification to the aggregation process.

3.6. Main Factors Affecting Soil Aggregate Stability for Different Forest Types and Soil Depths

The results of the Pearson correlation analysis are depicted in Figure 8. In the native forest, there was no significant correlation between the MWD and all other factors (Figure 8a). In the mixed forest, the MWD was significantly negatively correlated only with the total capillary porosity. In the Chinese fir forest, the MWD was significantly negatively correlated with TN and free Al oxide, and significantly positively correlated with bulk density. In the bamboo forest, the MWD was significantly negatively correlated with the pH, TN, total capillary porosity, and humic acid, and significantly positively correlated with the bulk density (Figure 8a).

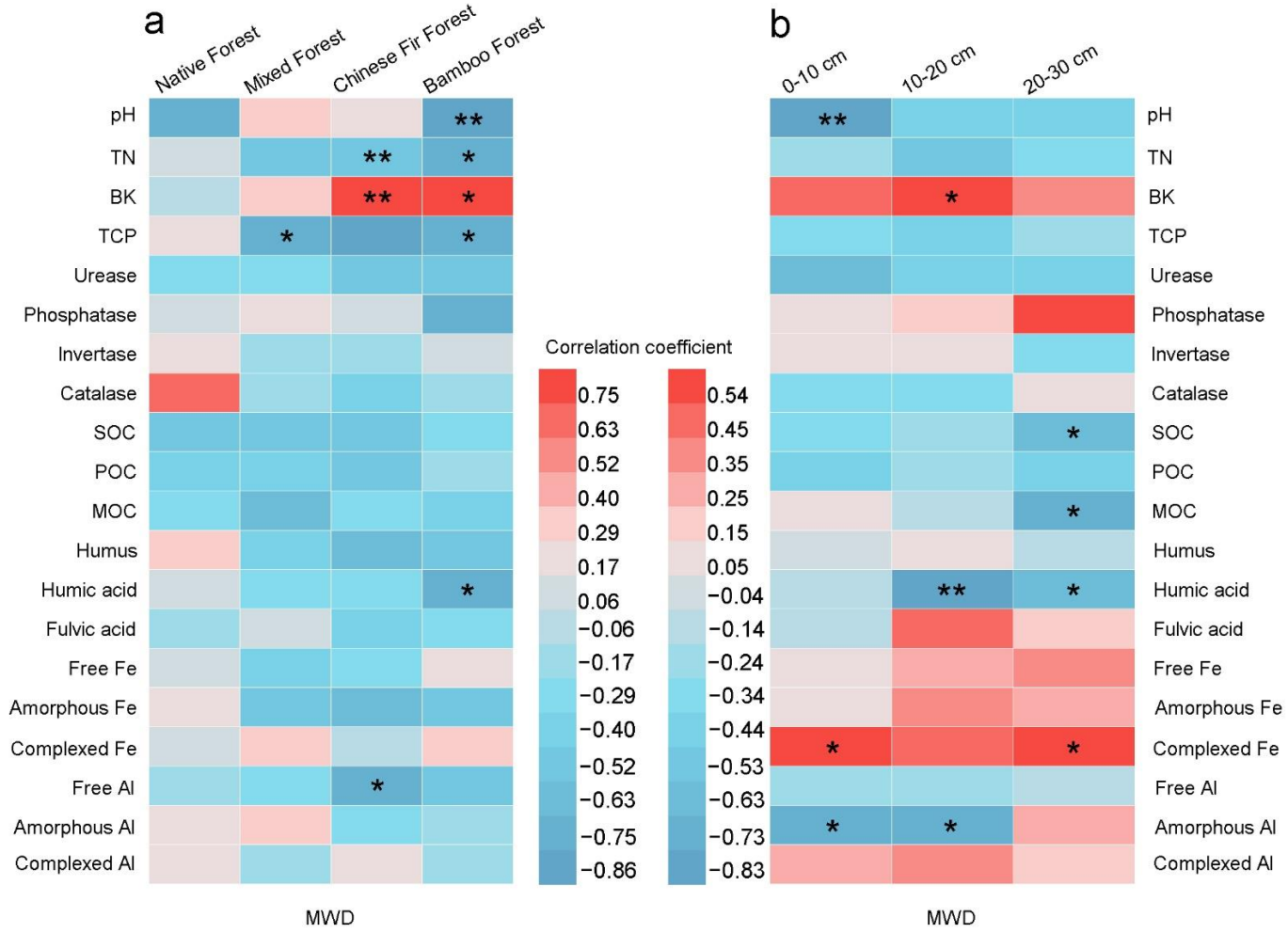


Figure 8. Correlation between MWD and other indexes for different forest types (**a**) and soil depths (**b**). Abbreviations are shown in Figure 7. ** indicates significant correlation at $p < 0.01$, * indicates significant correlation at $p < 0.05$.

For the 0–10 cm soil layer, the MWD was significantly negatively correlated with the humic acid and amorphous Al oxide, and significantly positively correlated with the bulk density. Within the 10–20 cm soil layer, the MWD was significantly negatively correlated with the SOC, MOC, and humic acid, and significantly positively correlated with the

organically complexed Fe oxide (Figure 8b). For the 20–30 cm soil layer, the MWD was significantly negatively correlated with the pH and amorphous Al oxide, and significantly positively correlated with the organically complexed Fe oxide (Figure 8b).

The boosted regression tree (BRT) model analyzed the contribution of the organic and inorganic soil colloids to MWD for different forest types and soil depths (Figures 9 and 10). The results signified that in the native forest (Figure 9A), the greatest contributors to the MWD were humus, SOC, fulvic acid, and organically complexed Al oxide. In the mixed forest (Figure 9B), the largest contributors to the MWD were the amorphous Fe oxide, POC, and organically complexed Fe oxide. In the Chinese fir forest (Figure 9C), the most significant contributors to the MWD were humus, amorphous Fe, free Al oxide, and organically complexed Fe oxide. In the bamboo forest (Figure 9D), the greatest contributors to the MWD were free Al oxide, humic acid, and MOC.

For the 0–10 cm soil layer (Figure 10A), the greatest contributors to the MWD were fulvic acid and humic acid. The contribution rate of the organic soil colloid to the MWD was 82.52% (Table S3); Within the 10–20 cm soil layer (Figure 10B), the biggest contributors to the MWD were MOC, organically complexed Fe oxide, and SOC. The contribution rate of the organic soil colloid to the MWD was 62.35% (Table S3). For the 20–30 cm soil layer (Figure 10C), the greatest contributors to the MWD were amorphous Al, amorphous Fe, and free Al oxide. The contribution rate of the inorganic soil colloid to the MWD was 77.43% (Table S3).

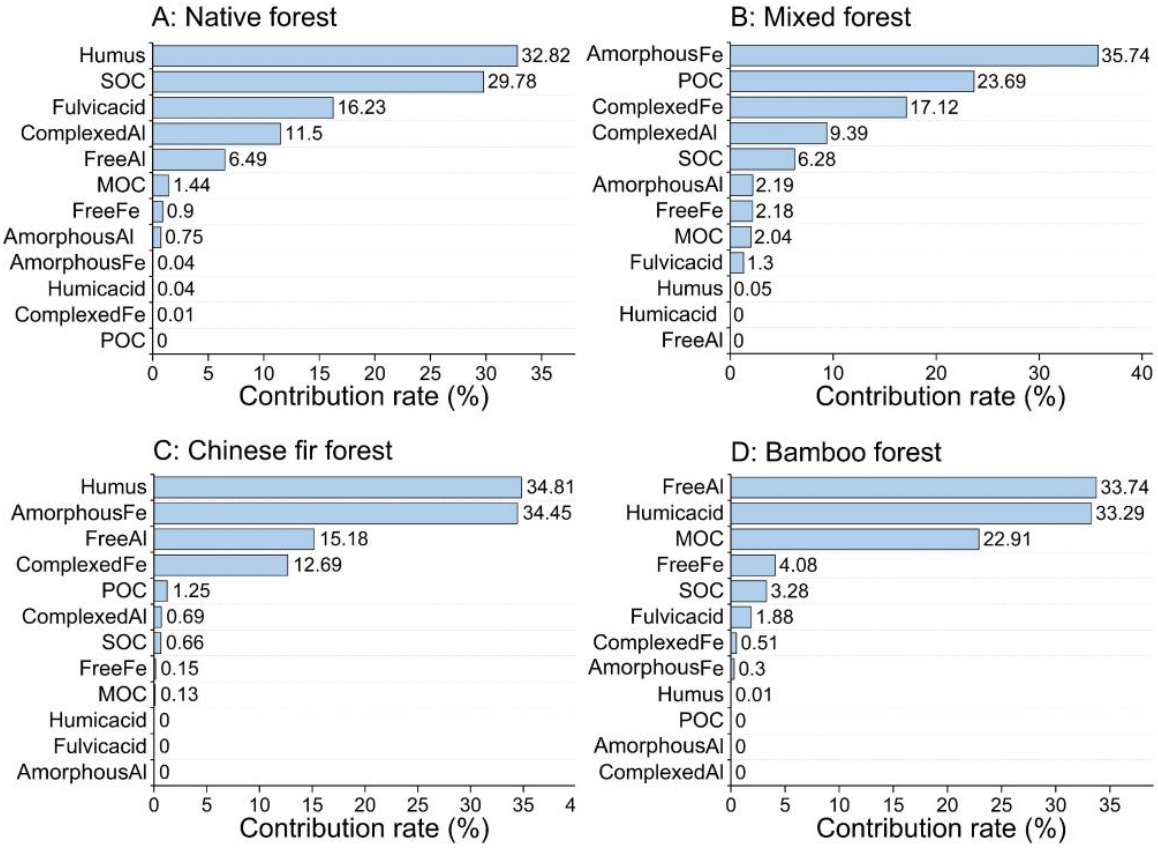


Figure 9. The contribution of organic and inorganic soil colloids to MWD under different forest types. Abbreviations are shown in Figure 7.

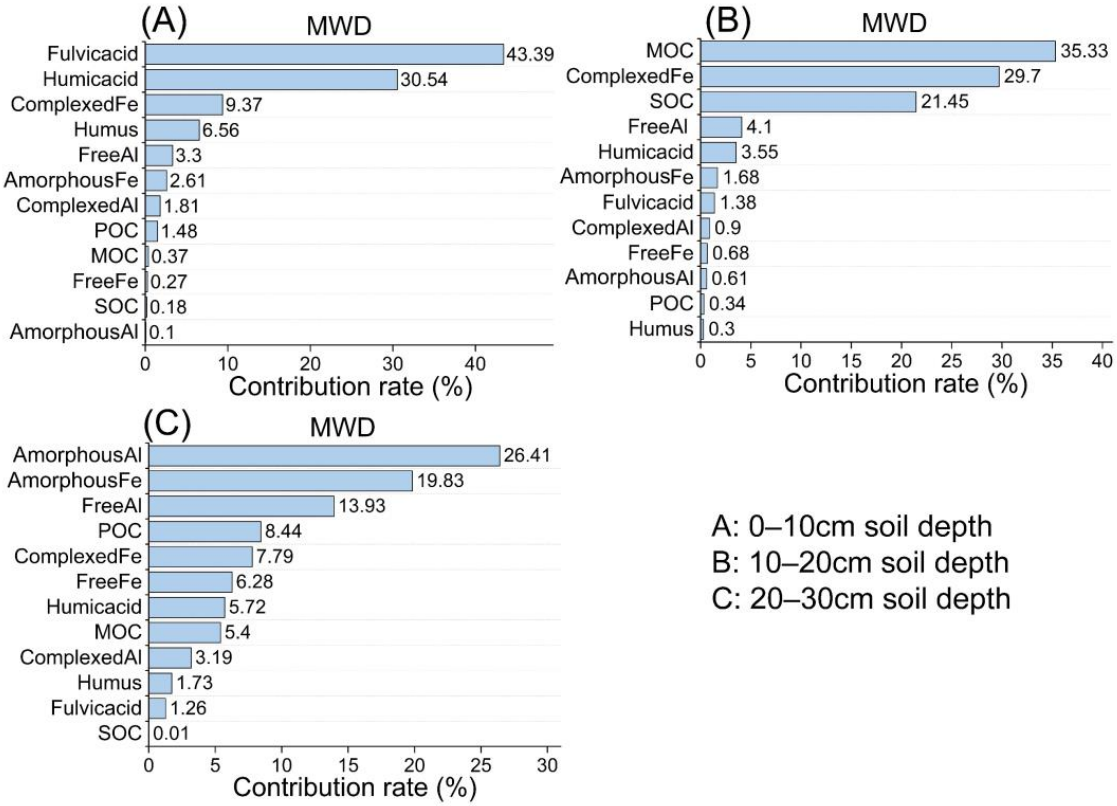


Figure 10. Contributions of soil organic and inorganic colloids to MWD at different soil depths. Abbreviations are shown in Figure 7.

4. Discussion

4.1. Effects of Forest Conversion and Soil Depth on Soil Properties and Enzyme Activities

The forest type had significant effects on the soil pH, bulk density, and enzyme activities (Table S1). This was consistent with previous studies, which observed that forest conversion could alter exchangeable cations to modify the soil pH [31]. Forest conversion could affect the activities of soil enzymes by altering the distribution of soil particle sizes, soil water contents, and soil pH values [32,33]. Changes in the soil bulk density were also correlated with soil enzyme activities [34].

The pH value and bulk density of the soil were increased, whereas the TN content and total capillary porosity were decreased with soil depth, which aligned with earlier studies. Rock weathering resulted in the release and leaching of large quantities of Ca_2^+ and Mg_2^+ in the soil profile, which might decrease the soil pH [35]. However, the lower rock weathering rate with soil depth resulted in higher pH values along the soil profiles [36]. Greater soil compaction in the deeper soil layers increased the soil bulk density [37], which decreased the total capillary porosity [38].

At greater soil depths, plant litter components and root exudates decrease with the lower distribution of plant roots, which likely results in a lower TN content than in the soil surface layers [39]. Furthermore, the activities of soil enzymes are typically decreased at greater soil depths. The reason for this might be that in contrast to subsoil layers, trees have higher litter inputs within the surface and topsoil, where soil aeration is better [40]. The higher density of plant roots and soil fauna in the topsoil might be another explanation for the greater activities of soil enzymes in topsoil [41].

4.2. Effects of Forest Conversion and Soil Depth on Organic Soil Colloids

The conversion from native forest to other forest types did not alter the SOC and POC contents (Figure 3), which was not consistent with previous studies [42,43]. The reason might have been that the conversion time was quite rapid. Cook et al. [44] observed that

thirty-four years following the conversion of a broadleaved to coniferous forest, the SOC pool did not change (i.e., it remained at similar levels); thus, the recovery of these disturbed soils may be a very long-term process. The SOC and POC contents decreased with soil depth (Figure S6), and because they had a strong correlation with root C inputs, other organic residues tended to accumulate on the soil surface [45]. Additionally, soil organisms (e.g., earthworms) also absorbed topsoil organic matter and translocated SOC and POC into deeper soil levels via bioturbation [46].

It has been often believed that MOC represents the recalcitrant C pool; thus, the conversion of native forest to Chinese fir forest could significantly decrease the MOC content (Figure 3). In the native forest, the quantity of aboveground and belowground litter, high population of fine roots, and greater number of root exudates influenced the accumulation of the non-protected C fraction, thus maintaining the MOC content and soil C stability [47]. However, the MOC content of the native forest could increase, and that of the Chinese fir forest could decrease with soil depth (Figure S6), which was consistent with previous studies. In the native forest, the higher recalcitrance indices of the deep soil in contrast to the topsoil indicated that the deep soil C was more stable than that of the topsoil. However, for the Chinese fir forest, the stability of the SOC in the deep soil layers was increased [47,48].

The forest type had no significant effects on the soil humus and fulvic acid, but did on the soil humic acid (Table S1). The humic acid in the bamboo forest was significantly higher than that in other forest types at the 10–20 soil depth (Figure 4C). The reason might be that the bamboo forest had higher annual growth and turnover rates [49]. Furthermore, the soil humus, humic acid, and fulvic acid were decreased with soil depth (Figure S7). The reason might be consistent with the decreases in SOC and POC [45,46].

4.3. Effects of Forest Conversion and Soil Depth on Inorganic Soil Colloids

The forest type had significant effects on the free Fe oxide, amorphous Fe oxide, and organically complexed Fe oxide (Table S1). The reason might have been that the Fe oxides were bound with organic polymers to form organo-mineral complexes [1], and the Fe oxides were correlated with the SOC (Figure 7); thus, the Fe oxides might have been affected by the SOC. The soil depth had no significant impacts on the free Fe oxide and organically complexed Fe oxide; however, the deepening of soil depth increased the amount of amorphous Fe oxide (Table S1). The amorphous Fe oxide possessed reactive sites that were exposed to multivalent oxyanions [50], where the pH value increased and hydrogen ions decreased with soil depth. Consequently, changes in the amorphous Fe oxide were correlated with those of the pH value.

The amorphous Al oxide in the bamboo forest was significantly higher than that of the native forest within the topsoil (Figure 6). The reason might have been that bamboo is a typical Si accumulator [51], where the high Si uptake by bamboo roots might lead to an increase in amorphous Al oxide [49,52]. The organically complexed Al oxides in the Chinese fir and bamboo forests were significantly lower than those of the native forest. The reason might have been that the root distribution and growth in the native forest were more robust than for the other forests. Root exudates and metabolism were major sources of dissolved organic matter [53,54], which strongly influenced the content of organically complexed Al oxide. Further, the soil depth had significant effects on both the amorphous Al oxide and organically complexed Al oxide (Table S1). The reason may have been that they were affected by the soil organic matter [55], which could be modified with soil depth.

4.4. Effects of Forest Conversion and Soil Depth on Distribution and Stability of Soil Aggregates

The distributions of soil aggregate sizes and aggregate stability were significantly affected by the conversion of the native forest to bamboo forest (Figures 1 and 2). In this study, significant decreases in the mass proportions of large-macroaggregates (>2 mm) and the values of MWD were found in the bamboo forest, in contrast to the other forest types. This suggested that the conversion of the native to bamboo forest exerted negative effects

on the soil aggregate structures. The reason behind this phenomenon was that the canopy densities of the native, mixed, and Chinese fir forests were higher than those of the bamboo forest, which generated a greater quantity of litter [56].

Increased litter input aided in the production of macroaggregates and improved soil aggregate stability [57]. Additionally, a significant increase in the mass proportions of small-macroaggregates (0.25–2 mm) was found in the bamboo forest compared to the other forest types. This might have been due to the high rooting density of bamboo that initiated the formation of small-macroaggregates [49]. Compared to forest conversion, the soil depth had no significant effects on the distribution and stability of soil aggregates. There were two possible explanations for this. One was that the study sites were managed (e.g., logging) in 1970, and there was no significant disturbance (such as tillage) subsequently [58]. Another was that the plant root length of the four forest types can reach 30 cm, which might influence the stabilization of aggregates through the physical or chemical bonding of the soil [59]. Therefore, soil disturbances could be a major factor that drives the distribution and stability of soil aggregates with soil depth.

4.5. Relationships between Soil Properties, Enzyme Activities, Organic and Inorganic Soil Colloids, Soil Aggregate Distribution, and Stability in Subtropical Forests

The stability of soil aggregates was affected by soil properties [60], enzyme activities [32], organic colloids, and inorganic colloids [61]. In this study, the soil aggregate stability was significantly correlated with the pH, bulk density, and organically-complexed Fe oxide (Figure 7a, Table S2). In previous studies, the pH value could affect the soil stability through the modification of plant-derived inputs, thereby accelerating the activities of microbes. The microbial activities also affected the stability of soil aggregates via soil colloids [62,63].

The bulk density of the soil were significantly negatively correlated with the SOC and POC (Figure 7a, Table S2), and positive correlations between the soil organic matter and aggregate stability was also proven in other studies [64,65]. Consequently, we hypothesized that soil properties may indirectly alter soil aggregate stability through organic and inorganic soil colloids [66]. The SEM results verified our hypothesis (Figure 7b,c) that the organically complexed Fe oxide and fulvic acid could serve directly as organic and inorganic colloids that affected the stability of soil aggregates. The pH and bulk density indirectly but positively altered the soil aggregate stability by directly influencing the organically complexed Fe oxide and fulvic acid in subtropical forests. The effects of pH on the change of plant-derived inputs, internal decay rates, and macroaggregate turnover could explain the effect [62,67].

4.6. Main Factors Affecting Soil Aggregate Stability for Different Forest Types and Soil Depths

Through the analysis of soil properties, enzyme activities, soil organic colloids, inorganic colloids, and soil aggregate stability, we observed that the effects of different forest types or different soil depths were not consistent. Therefore, we needed to investigate the factors that affected the stability of soil aggregates for each forest type at each soil depth.

In the native and bamboo forests, organic soil colloids contributed most to the stability of soil aggregates, reaching 80.31% and 61.37%, respectively. In the mixed and Chinese fir forest, inorganic soil colloids contributed most to the soil aggregate stability, attaining 66.62% and 63.15%, respectively. This might have been because, compared to the mixed and Chinese fir forests, the vegetative ground cover and quantity of organic matter inputs in the native and bamboo forest were higher [32]. Large amounts of organic matter penetrated into the soil and affected the soil aggregate stability. Further, the contributions of organic colloids were decreased with soil depth (Figure 10, Table S3).

A large amount of litter was present on the soil surface, where the decomposition of litter formed more soil organic matter [68,69], thus increasing the distribution of organic colloids in the topsoil. At deeper soil levels, the soil density was increased and the organic matter was reduced [70], thus decreasing the distribution of organic colloids. Therefore,

the contribution of colloids to the stability of soil aggregates might be due to changes in the soil organic matter caused by the decomposition of litter.

5. Conclusions

The results of this study indicated that forest conversion and soil depth affected soil properties, enzyme activities, organic and inorganic soil colloids, and the distribution and stability of soil aggregates in subtropical forests. Organically complexed Fe oxide and fulvic acid could directly serve as organic and inorganic colloids to facilitate the stability of soil aggregates. In subtropical forest conversion, the pH and bulk density indirectly but positively affected the soil aggregate stability by directly influencing the organically complexed Fe oxide and fulvic acid. The organic soil colloid was the primary contributor to the stability of soil aggregates in the native and bamboo forests. In contrast, the inorganic soil colloid was main contributor to soil aggregate stability in the mixed and Chinese fir forests. Finally, the inorganic soil colloid gradually replaced the organic soil colloid as the main contributor to the stability of soil aggregates with soil depth. In summary, these findings suggest that specific management strategies are required for different forest types to increase the stability of soil aggregates. After land-use conversion, management practices such as rational fertilization and natural sod cultivation (which increased organic C input into soil) are recommended to improve the soil aggregate stability of the bamboo forests.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13040546/s1, Figure S1: Soil properties at depths of 0–30 cm for different forest types; Figure S2: Soil properties at depths of 0–30 cm for different forest types; Figure S3: Soil enzyme activities at depths of 0–30 cm for different forest types; Figure S4: Soil enzyme activities at depths of 0–30 cm for different forest types; Figure S5: Water-stable aggregate size distribution at depths of 0–30 cm for different forest types; Figure S6: SOC, POC, and MOC contents at depths of 0–30 cm for different forest types; Figure S7: The humic substance contents in bulk soil at depths of 0–30 cm for different forest types; Figure S8: The contents of Fe oxides at depths of 0–30 cm for dif-ferent forest types; Figure S9: The contents of Al oxides at depths of 0–30 cm for different forest types; Table S1: Two-way ANOVA analysis (p values) of the different forest types (F) and differ-ent soil depths (S) for all indexes; Table S2: Pearson correlation between soil physical–chemical properties, soil enzyme activities, soil aggregates, and organic and inorganic soil colloids; Table S3: The contribution of soil organic and inorganic colloids to MWD under different forest types and soil depths.

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