Article

Effect of Forest Management Operations on Aggregate-Associated SOC Dynamics Using a ^{137}Cs Tracing Method

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Abstract: Although forest conversions have long been a focus in carbon (C) research, the relationship between soil erosion and the dynamic change of soil organic carbon (SOC) has not been well-quantified. The objective of this study was to investigate the effects of converting CBF (coniferous and broad-leaved mixed forests) to economic forests, including CF (chestnut forest), HF (hawthorn forest), and AF (apple forest), on the soil structure and nutrient loss in the Huaibei Rocky Mountain Areas, China. A ^{137}Cs tracer method was used to provide soil erosion data in order to quantify the loss of aggregate-associated SOC. The results showed that forest management operations caused macro-aggregates to decrease by 1.69% in CF, 4.52% in AF, and 3.87% in HF. Therefore, the stability of aggregates was reduced. The SOC contents in each aggregate size decreased significantly after forest conversion, with the largest decreases occurring in AF. We quantified the loss of 0.15, 0.38, and 0.31 Mg hm^{-2} of aggregate-associated SOC after conversion from CBF to CF, AF, and HF, respectively. These results suggest that forest management operations have a negative impact on soil quality and fertility. CF has better vegetation coverage and less human interference, making it more prominent among the three economic forests species. Therefore, when developing forest management operations, judicious selection of tree varieties and appropriate management practices are extremely critical. In addition, measures should be taken to increase surface cover to reduce soil erosion and achieve sustainable development of economic forests.

Keywords: forest management operations; ^{137}Cs ; soil aggregate; soil erosion

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1. Introduction

Soil is the largest terrestrial carbon (C) pool in the world, and it contains at least three times as much C as the atmosphere [1]. It was reported that the terrestrial C stock releases about 4% of its pool into the atmosphere each year [2]. Therefore, the potential CO_2 emissions from terrestrial ecosystems are of great importance to the continental- and regional-scale C balance [3]. The distribution of aggregate and aggregate-associated soil organic carbon (SOC) determines the capacity of the soil to store and retain C [4]. Aggregates are the structural units of the soil, and SOC is the critical binding material of aggregates. The differences in size distribution and the stability of aggregates control the changes of microbial activities and nutrient cycling, which in turn affects the soil biogeochemical and biophysical processes [5,6]. Aggregate formation is considered as one of the most important mechanisms of SOC sequestration [7]. Hence, understanding SOC dynamics in aggregates is crucial for developing effective management strategies to mitigate global warming and improve soil quality, which can contribute to the sustainable development of the environment.

Forest soils have great potential for C fixation [8,9]. The global forest ecosystem C storage is 861 ± 66 Pg, and the soil C pool (to 1 m depth) accounts for 44% of this storage [10]. Numerous studies have demonstrated that forest conversion has significant impacts on the stability of aggregates and dynamics of aggregate-associated SOC and other nutrients in soils [11–13]. The forestry management practice, such as tillage scheme, the removal of litter, intermediate cutting, fertilizer treatment, and other measures, destroys macro-aggregate and breaks into small particles, and thus increases the amount of micro-aggregates, which in turn facilitates the transport of SOC between size classes [14,15]. As a result, the forestland is susceptible to water erosion, and aggravates the loss of carbon enriched in micro-aggregates. The effect of changes in land-use on SOC sequestration is mainly responsible for the changes in the renewal and transformation of micro-aggregates, thus altering the mechanism of SOC. Recent research mainly focused on the effects of agricultural management practices on the stability of aggregates and related SOC at the global scale [16–18]. However, reports on the effects of forest conversion on the distribution of aggregates and associated SOC content at the catchment scale are relatively few. Furthermore, the total soil C is not very sensitive to the effects of forest management operations in the short term. As many researchers suggested, the content of TC in soils is high and it is subject to a series of factors, not only the land-use change, tillage practice, and other factors. More importantly, TC is also affected by its intrinsic mechanism [18–22]. In contrast, the smaller C fractions such as the aggregate-associated SOC is more effective to the changes in land-use, and the aggregate-associated is a sensitive indicator to characterize the change in soil carbon pools and soil erosion. Therefore, a greater understanding of the effects of the forest management practices, especially forest conversion, on aggregate-associated SOC dynamics during the forest construction process is needed to characterize the SOC contents that result from changes in land-use.

Since the implementation of the “Grain for Green” program in 1999, planted forests in China have developed rapidly to become the world’s largest planted forest storage area [23]. Large-scale afforestation improves the stability of soil aggregates and increases the SOC content of aggregates [8,11,24]. Afforestation, the conversion of non-forested land into forest, protects the surface soils from wind and water erosion, and enhances the stability of aggregate and aggregate-associated SOC by generating macro-aggregates through mycorrhizal interaction with plant roots and microbes [25]. In addition, forest conversion could sequester CO₂ from the atmosphere and store it into plants via vegetation photosynthesis, eventually transforming it into soil organic matter through humification [11]. However, over the past two decades, native forests have increasingly been converted into economic forests to meet the increasing demands for timber, as well as for raw material for pulp, paper, fuel, and other forest products [26–28]. Forest management practices, such as fertilizer treatments, reduced tillage, and mulching, have been used to manage plantations to obtain better soil structure, and increase forest productivity and biomass C storage in forest ecosystems [29]. Thus, improved understandings of the conversion of forests to economic forests is necessary. However, numerous studies have shown that forest management would decrease SOC storage or stability [11,30,31]. For example, understory vegetation removal results in the reduction of SOC storage or stability due to decreased C input into the soil [32,33]. Simultaneously, soil aggregate size significantly impacts soil bacterial and fungal communities. The breakdown of aggregates exerted an apparent influence on the respiration of soil bacteria (such as *Psathyrellaceae*, *Bacillaceae*, and *Rhizophlyctidaceae*), and soil fungi (such as *Nectriaceae*) lived in aggregate, which in turn inhibited the binding of clay- and silt-sized particles to form micro-aggregates within macro-aggregates, thereby influencing the stability of SOC [8,34]. The effects of forest conversion on soil quality have been extensively studied [17,35–37]. However, the relationships between soil structure stability and dynamic changes of SOC from the perspective of soil erosion have not been fully investigated following the economic forest conversion, especially in Huaibei Rocky Mountain Area, China. Tillage practices, fertilizer treatments, land-use change, and other forestry management measures contribute to the breakdown of original soil structure, and

the decline of soil quality, resulting in the decrease in the anti-erosion function. Effects of soil erosion on soil profile interception and carbon stocks are often overlooked, although soil erosion is the most widespread event accompanying forest conversion [38]. Worldwide, soil erosion redistributes approximately 75 Pg of soil and 1–5 Pg of SOC annually [39]. Thus, studying the stability of soil aggregates and the dynamic changes of associated SOC in response to soil erosion is essential for sustainable forestry management and yield.

The formation and destruction of soil aggregates are both closely related to soil erosion [19]. Increasing the content of >0.25 mm aggregates contributes to a better soil structure and enhances soil erosion resistance [40]. Previous studies have focused on the qualitative description of the effects of soil erosion on the aggregate-associated SOC content [14,22,40]. Little research has been carried out to quantify the amount of aggregate-associated SOC loss caused by soil erosion, which is vital for calculating the global C balance. The isotope ^{137}Cs is a unique artificial radionuclide produced by nuclear tests, and it has been widely used in soil erosion research at different spatial scales around the world since the 1990s [41]. This method is simple, highly quantitative, low cost, and reliable. It has proven to be the best method to study soil erosion [38,42]. Studies have reported that ^{137}Cs has similar migration patterns as SOC in soil aggregates [3,14,43]. Therefore, exploring the relationship between the SOC content in aggregates of different sizes and ^{137}Cs content can further reveal the internal relationship between the two. In summary, soil aggregation is a critical mechanism for the stability of soil organic matter (SOM), especially SOC. Soil aggregation affects many of the key properties of soil, such as physicochemical properties, and microbial activities in that it shapes the habitats available to the microorganisms. Consequently, aggregates are conducive to the SOC sequestration and soil structural stability and improve the soil ability to resist erosion. Although there are studies to investigate the effect of erosion on SOC, there are few studies that have quantified the dynamic changes of aggregate-associated SOC induced by soil erosion, especially by means of Cesium 137. Therefore, even fewer studies have investigated these changes in the context of forest conversion. To quantify this relationship, a ^{137}Cs isotope tracer technology was selected in this study. The aims of this study are (i) to investigate the effects of forest conversion on soil aggregate composition and stability, (ii) to quantify soil erosion and aggregate-associated SOC loss after forest conversion, and (iii) to compare different types of economic forests and management practices to identify reasonable forestry management patterns that can serve as a basis for sustainable development of economic forests, which reduces ecological and environmental problems.

2. Materials and Methods

2.1. Site Description

Soil samples were collected from the Dawu Mountain, situated in the northwest of Ganyu District of Lianyungang City, Jiangsu Province, China (35°0′39.7″ N, 118°57′55.2″ E) (Figure 1). The full site description and experimental design are described by Zhu et al. [38]. Briefly, this region has a humid warm temperate maritime monsoon climate with a mean annual temperature (MAT) of 13.9 °C. The mean annual precipitation (MAP) is 976.6 mm, concentrated from May to September. The annual average sunshine period is 2534 h and the annual average period free of frost is 216 days. Topographically, the slopes in this area generally range from 11° to 15° and the altitude of the region ranges from 190 to 364.4 m above sea level (ASL).

The soils at the experimental site were classified as Alfisols using the FAO soil classification system [44]. Bulk density (BD) ranged from 1.34 to 1.27 g cm⁻³. Soil pH was all acidic at 4.47–5.18, and the specific surface area (SSA) in soils ranged from 1.57 to 3.50 m² g⁻¹, which shows no remarkable difference between forest land-use types. Detailed information about the soil physical and chemical conditions is listed in Tables 1 and 2. The soils in this region have a silty loam texture and the soil layers are thin, which are very vulnerable to water and tillage erosion [38].

The study area is a temperate deciduous broad-leaved forest region, with forest plantations dominating, and a minority of natural deciduous broad-leaved forests and evergreen coniferous forests were supplemented prior to the 2000s, which included secondary vegetation such as *Masson massoniana* Lamb., *Celtis sinensis* Pers., and *Quercus* L., and other economic trees such as hawthorn and chestnuts. By the early 21st century, some of the forest plantations were in a state of natural regeneration, and others were converted into economic forests by the locals to obtain economic profits. According to the field survey, coniferous and broad-leaved mixed forests (CBF) are the dominant stand types of forest plantations, and the dominant tree species are *Pinus massoniana*, *Platycladus orientalis*, and *Metasequoia glyptostroboides*. There are herbaceous plants and humus layers in the understory trees or shrubs. CBF has a complex structure with shrub, grass, and litter in the understory, and has a prosperous root system. The hawthorn forest (HF), the chestnut forest (CF), and the apple forest (AF) are all economic forests transformed from CBF, among which the CF was covered with litter on the surface, the AF was bare on the surface with obvious traces of artificial tilling, and understory vegetation of HF was removed each year [38]. In addition, through the inquiry with the local farmers, significant amounts of fertilizers (P_2O_5 : $109 \text{ kg ha}^{-1} \text{ year}^{-1}$ as ordinary superphosphate, N: $214 \text{ kg ha}^{-1} \text{ year}^{-1}$ as urea and ammonium bicarbonate) were generally applied into the economic forests in May of each year.

Figure 1. Location of the study site.

Table 1. Basic information of the study area.

Forest	Human	Age [38]	LAI [38]	Litter Thickness [38]	Slope [38]	Aspect [38]	¹³⁷ Cs Content [38]	Percentage ¹³⁷ Cs Loss [38]	Soil Erosion Modulus	Soil Loss Thickness
Types	interference	(year)		(mm)	(°)		(Bq m ⁻²)	(%)	(t km ⁻² a ⁻¹)	(mm)
CBF	None	25	3.2	1.3	13	SE	546.92	68.4	1113.73	0.79
CF	Weak	13	2.5	1.1	11	SE	495.89	71.4	1275.35	0.87
AF	Strong	10	2.2	0	13	SE	60.6	96.5	3328.2	2.31
HF	Strong	11	2.1	0	15	SE	123.89	92.9	2606.7	1.84

Note: All the data were calculated on the basis of three replicates and represented as average ± SE (standard error).

Table 2. Soil physicochemical properties of different forest types.

Parameters	CBF	CF	AF	HF
BD (g/cm ³) [38]	1.44 ± 0.12A	1.43 ± 0.05A	1.47 ± 0.18A	1.42 ± 0.12A
pH [38]	5.67 ± 0.27AB	5.95 ± 0.34A	5.48 ± 0.26B	5.67 ± 0.27A
Sand (%) [38]	36.59 ± 7.53AB	31.57 ± 7.83BC	41.07 ± 8.65A	30.84 ± 5.05C
Silt (%) [38]	60.21 ± 6.96AB	64.66 ± 6.66A	56.63 ± 4.36B	65.00 ± 5.63A
Clay (%) [38]	3.20 ± 0.41AB	3.77 ± 0.18AB	2.29 ± 0.23B	4.16 ± 0.36A
SSA (m ² g ^{−1})	2.14 ± 0.17A	2.26 ± 0.23A	3.07 ± 0.43A	2.57 ± 0.82A
TN (g kg ^{−1})	2.57 ± 0.32A	1.35 ± 0.11B	1.21 ± 0.03B	1.52 ± 0.10B
C/N	9.10 ± 0.26A	7.03 ± 0.67BC	6.66 ± 0.16C	7.73 ± 0.26BC
C/H	4.06 ± 0.20A	2.03 ± 0.30B	2.17 ± 0.12B	2.56 ± 0.13B
SOC (g kg ^{−1})	30.86 ± 4.87A	18.87 ± 1.50B	11.55 ± 2.18B	13.83 ± 1.78B
DOC (g kg ^{−1})	0.27 ± 0.02A	0.26 ± 0.02A	0.27 ± 0.06A	0.23 ± 0.06A

Note: Values are means ± SE (*n* = 3). The different capital letters indicate significant differences in the topsoil among different forest types (*p* < 0.05). SSA: specific surface area.

2.2. Experimental Design and Soil Sampling

After evaluation of the site and consultation with the owners of the forest, a series of sites were selected in the Dawu Mountain watershed. The CBF serves as the control. The comparison between CBF and the other three economic forests (CF, HF, and AF) allows us to evaluate the effect of forest management operations. Different soil erosion sequences allow us to assess the impact of intensive management on the soil. Each of these stand types were replicated three times, and the distance between each plot was over 50 m. The forests selected exhibited similar site conditions, such as soil type, elevation, slope gradient, and aspect. Site data for the four forest types are included in Table 1, and for more detailed information, refer to Zhu et al. [38]. Within each stand, a 400 m² (20 × 20 m) plot was established in July 2016. A total of 12 plots were established in this study. An “S” strip sampling strategy was chosen for each sub-quadrant plot to ensure the representativeness of soil samples in each plot. Soil samples were collected from 0 to 30 cm depth from three randomly selected points in each plot and were thoroughly mixed to form a composite sample for determination of basic physical and chemical properties. Samples were also collected from each plot to measure bulk density using a corer, with a 200 cm³ volume. For aggregate analyses, samples were collected with a hard aluminum box following the previous steps and transported to the laboratory for further analyses. In addition, based on the results of our research group, two sampling points on the top of Dawu Mountain were determined, and their average value of ¹³⁷Cs (1732.48 Bq/m²) was chosen as the background value. Soil nuclide ¹³⁷Cs sampling and calculation were conducted according to the study of Zhu et al. [38].

2.3. Soil Analysis

Soil samples were air-dried, crushed, and then passed through a 2 mm mesh sieve to filter out coarse materials after removing all the visible plant materials for the measurement of subsequent analyses. Soil bulk density (BD) was calculated as the ratio of oven-dried undisturbed core weight to container volume on the basis of a core method (at 105 °C for 24 h). The soil pH was determined by a soil–water ratio of 1:2.5 using a HI 3221 pH meter (Hanna Instruments Inc., Woonsocket, RI, USA). The particle size distribution of soil samples was determined by a Mastersizer 2000 laser diffraction particle size distribution analyzer (Malvern Instruments Ltd., Malvern, UK). The specific surface area (SSA) value was determined by physical absorption of nitrogen gas using an automatic apparatus—ASAP 2020 HD 88 analyzer (Micromeritics Instrument Corp., Norcross, GA, USA), operated at 77 K. More details on the experimental instruments and procedures were

reported by Zhao et al. [45]. Afterwards, the samples were then passed through a 0.15 mm mesh, and the total nitrogen (TN), C/N, and C/H ratios were measured by way of the dry combustion method via a Vario Max elemental analyzer (Elementar, Langenselbold, Germany). Soil organic carbon (SOC) content was tested with the vitriol acid-potassium dichromate wet oxidation method [46]. Dissolved organic carbon (DOC) was determined using the Shimadzu TOC-VCPH analyzer (Shimadzu Corp., Kyoto, Japan). The detailed procedures follow Jones' procedure [47]. Three replicates were completed for each sample.

2.4. Soil Aggregate Fractionation

Soil aggregation was characterized by the water aggregate size distribution, and aggregates were separated following the modified method described by ISSAS [48]. Four water-stable aggregates were manually fractionated by sieving 100 g soil through a set of sieves with apertures of 1.0, 0.5, and 0.25 mm. The top sieve was equipped with a cover prior to submerging the sieves in water. The three size fractions at the macro-aggregate scale (>1.0, 0.5–1.0, and 0.25–0.5 mm) and one fraction aggregate at <0.25 mm (micro-aggregate) were obtained. Briefly, all the sieves were immersed in deionized water and were moved up and down approximately 6 cm for 5 min, with 25 repetitions per minute. After 30 min of oscillation, the aggregate fractions remaining on each sieve were transformed from the sieves for four size classes with the deionized water into an Al container and dried at 105 °C for 24 h and weighted to calculate the mean weight diameter (MWD) and geometric mean diameter (GMD). The equations of MWD and GMD refer to [49,50].

2.5. Calculations

Using the mass of the soil particle distribution and the above calculation results, the fractal dimensions (FD) and the soil erodibility factor (K) to characterize soil erosion resistance [51] were calculated by the following equations:

$$\lg \left[\frac{M(r < R_i)}{M_T} \right] = (3 - FD) \left(\frac{R_i}{R_{\max}} \right) \quad (1)$$

$$K = 7.954 \times \left\{ 0.0017 + 0.0494 \times \exp \left[-0.5 \times \left(\frac{\log GMD + 1.675}{0.6896} \right)^2 \right] \right\}, \quad (2)$$

where R_i (mm) is the mean aggregate diameter of all size classes, $R_{\max}$ (mm) is the mean diameter of the largest aggregates, $M(r < R_i)$ (g) is the cumulative soil mass of particle sizes smaller than R_i , M_T (g) is the total mass of all size fractions, FD is the soil fractal dimension, and K is the soil erodibility factor.

2.6. SOC Storage Estimation

Area-based estimates of elements (Mg hm^{-2}) have been commonly accepted as the most appropriate means to describe standing stocks of C in soils. Element masses in genetic horizons were calculated from the thicknesses and bulk densities of the horizons [52]:

$$M_{\text{soil}} = BD \times T \times 0.01 \times 10000 \quad (3)$$

$$M_{\text{element}} = M_{\text{soil}} \times \text{conc} \times 0.001 \quad (4)$$

where M_{element} (Mg hm^{-2}) is the element mass per unit area, conc (g kg^{-1}) is the soil aggregate organic C content, M_{soil} (Mg hm^{-2}) is the soil mass per unit area, $1 \text{ Mg} = 10^3 \text{ kg}$, BD (g cm^{-3}) is field bulk density, T (m) is the soil layer thickness or soil loss thickness, and 0.001, 0.01, and 10,000 are unit conversion factors.

2.7. Statistical Analysis

The data presented in this paper are the average of three replications. A one-way analysis of variance (ANOVA) was conducted to test the effects of forest conversion and subsequent intensive management on the physical and chemical properties, aggregate

distribution and stability, and related organic C dynamics. Before performing the ANOVA, the normality and homogeneity of variance were tested, and data were log-transformed if homogeneity of the variance was not met. When the ANOVA indicated a significant treatment effect, the least significant difference (LSD) test was used to separate the means. An alpha level of 0.05 for significance was used in all statistical analyses, unless otherwise mentioned. A stepwise correlation analysis was applied to investigate the correlation between ^{137}Cs and aggregate-associated SOC content. All of the statistical analyses in this study were performed using the SPSS software (SPSS 25.0 for windows, SPSS Inc., Chicago, IL, USA). The figures were created with the Origin Pro 2016 software (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Soil Physicochemical Properties after Forest Conversion

Total SOC concentrations in CF, AF, and HF decreased by 38.9%, 62.6%, and 55.2% respectively, as compared to levels in CBF (Table 2). The soil total N concentration ranged from 1.21 to 1.52 g/kg among economic forests, and these levels were significantly lower than those in CBF (Table 2). A similar trend was observed for the C/N and C/H ratios (Table 2). The lowest value for pH and silt + clay contents was observed in AF. The specific surface area (SSA) exhibited an increasing trend after forest conversion, especially in the conversion from CBF to AF. There were no significant differences in *BD* and *DOC* regardless of forest conversion and subsequent intensive management.

3.2. Soil Aggregate Fractions and Stability

The economic forest management clearly increased the proportion of micro-aggregates (<0.25 mm). After forest conversion, there was a decrease in the proportion of macro-aggregates (>0.25 mm) and an increase in micro-aggregates (<0.25 mm). Macro-aggregate content for CBF (72.11%) was significantly higher than CF (70.42%), AF (67.59%), and HF (68.14%). The proportion of micro-aggregates for AF was 32.41%, approximately 1.16 times higher than CBF. Results show that 3.39% of macro-aggregates were broken down into micro-aggregates due to the conversion from CBF to economic forests (Table 3).

Table 3. Soil aggregate distribution and stability for different forest types.

Parameters	CBF	CF	AF	HF
>1 mm (%)	21.56 ± 2.08A	19.6 ± 1.21B	16.35 ± 1.81C	14.81 ± 1.56C
1–0.5 mm (%)	26.64 ± 2.65A	24.31 ± 1.64A	23.86 ± 1.17A	25.81 ± 1.44A
0.5–0.25 mm (%)	23.91 ± 2.02B	26.52 ± 1.45A	27.38 ± 0.90A	27.52 ± 1.47A
<0.25 mm (%)	27.89 ± 2.73C	29.58 ± 1.79B	32.41 ± 2.13A	31.86 ± 2.49A
<i>MWD</i> (mm)	0.82 ± 0.08A	0.80 ± 0.02A	0.66 ± 0.04B	0.67 ± 0.02B
<i>GMD</i> (mm)	0.51 ± 0.03A	0.47 ± 0.01B	0.42 ± 0.02C	0.43 ± 0.02C
<i>FD</i>	2.14 ± 0.06C	2.19 ± 0.07B	2.24 ± 0.07A	2.23 ± 0.07A
<i>K</i>	0.06 ± 0.01C	0.07 ± 0.02B	0.08 ± 0.01A	0.08 ± 0.02A

Note: Values are means ± SE ($n = 3$). The different capital letters indicate significant differences in the same aggregate size among different forest types ($p < 0.05$). *MWD*: mean weight diameter, *GMD*: geometric mean diameter, *FD*: fractal dimension, *K*: soil erodibility factor.

Forest conversion significantly ($p < 0.05$) decreased *MWD* and *GMD* values, indicating that aggregate stability declined. The *MWD* values for CF, AF, and HF decreased by 2.43%, 20.51%, and 18.29% respectively, compared with CBF (Table 3). The *GMD* followed a similar pattern to that of *MWD*. Among economic forests, the values of *MWD* and *GMD* in CF (0.80 mm, 0.47 mm) were significantly higher than those in AF (0.66 mm, 0.43 mm) and HF (0.67 mm, 0.43 mm) after forest conversion. The *FD* and *K* values for CBF were significantly lower than those of CF, AF, and HF. However, there were no significant differences between AF and HF. This indicates that long-term intensive management can reduce soil stability and aggravate the negative impacts caused by forest conversion, especially in forest types with severe erosion.

3.3. Aggregate-Associated SOC Contents

SOC contents in the macro-aggregate fraction were significantly higher than those in the micro-aggregate fraction (Figure 2). The SOC contents in each aggregate fraction decreased significantly after conversion to economic forests, with the largest decreases occurring in AF. The decreases in macro-aggregate SOC content were greater than the decreases in micro-aggregate SOC. For example, the SOC content in >1 mm aggregates decreased by 46.47% after conversion from CBF to AF. This was a larger decrease than in CF (33.51%) and HF (34.03%). In addition, we also found that the SOC content of micro-aggregates among three economic forests appeared to follow the pattern: CF (14.97 g kg⁻¹) > HF (14.32 g kg⁻¹) > AF (12.7 g kg⁻¹).

Figure 2. SOC for each aggregate fraction of the different forest types. Note: The different capital letters indicate significant differences in the same aggregate size among different forest types ($p < 0.05$). Values are means $\pm$ standard errors.

The stepwise correlation analysis indicated that the ^{137}Cs activity in the soil showed an extremely significant positive correlation with the aggregate-associated SOC content of water-stable aggregates less than 0.25, 0.25–0.50, and 0.5–1.0 mm ($R^2 = 0.77, 0.68$, and 0.67 , $p < 0.001$), and showed a significant positive correlation with the aggregate-associated SOC content of water-stable aggregate with greater than 1.0 mm ($R^2 = 0.48$, $p < 0.05$) (Table 4).

Table 4. Correlation between ^{137}Cs and organic carbon content of aggregates.

Parameters	>1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm
^{137}Cs	0.48 *	0.67 **	0.68 **	0.77 **
>1 mm		0.76 **	0.72 **	0.54 **
1–0.5 mm			0.84 **	0.69 **
0.5–0.25 mm				0.81 **
<0.25 mm				1

Note: * Correlation significant at $p < 0.05$, $n = 24$. ** Correlation significant at $p < 0.01$, $n = 24$.

3.4. SOC Sequestration of Soil Aggregates

The shift of forest type significantly reduced the SOC storage of soil aggregates (Figure 3). Compared with CBF (82.23 Mg hm⁻²), the storage of SOC in CF, AF, and HF were decreased by 41.4%, 47.96%, and 43.78%, respectively. Macro-aggregates represent the major pool of SOC in forest soil. As a form of SOC storage, macro-aggregates reveal the rising or falling trends of SOC pools. The SOC storage of macro-aggregates for CBF was

59.92 Mg hm⁻², accounting for 68.94% of total SOC storage. Macro-aggregate-associated SOC stocks decreased significantly after conversion of CBF to economic forests. Compared with CBF, the SOC storage of macro-aggregates in CF, AF, and HF decreased by 44.57%, 48.74%, and 46.36%, respectively. Meanwhile, we also found that the SOC storage of aggregates decreased with increasing particle size. However, we observed that the relatively large macro-aggregate SOC storage did not notably change between each forest type. This suggests that after the conversion of CBF into economic forests, the redistribution of SOC shifted from macro-aggregates (>1 mm) to micro-aggregates (<0.25 mm), with little effect on relatively large macro-aggregates (0.25–1.0 mm).

Figure 3. SOC storage for each aggregate fraction in the different forest types. Note: The different capital letters indicate significant differences in the same aggregate size among different forest types ($p < 0.05$). Values are expressed as means $\pm$ standard errors.

As shown in Figure 4, the average annual loss of SOC in aggregates for CBF was 0.24 Mg hm⁻². In economic forests, the aggregate-associated SOC loss in AF, HF, and CF was 1.57, 1.30, and 0.64 times that of CBF, respectively. Moreover, we observed that SOC is mainly stored in macro-aggregates and was subsequently lost, accounting for approximately 60% of the total loss. In economic forests, the lost SOC storage of macro-aggregates followed the pattern: CF (0.09 Mg hm⁻²) < HF (0.19 Mg hm⁻²) < AF (0.24 Mg hm⁻²). This suggests that CF are conducive to the accumulation of SOC and resistant to soil erosion when compared with the three types of economic forests.

Figure 4. SOC loss for each aggregate fraction of the different forest types. Note: The different capital letters indicate significant differences in the same aggregate size among different forest types ($p < 0.05$). Values are means $\pm$ standard errors.

4. Discussion

4.1. Effect of Forest Conversion on the Distribution and Stability of Soil Aggregates

Forest transformation will alter the soil microhabitat and affect soil physicochemical properties, which in turn contributes to the distribution of soil aggregates [6,53]. The proportion of aggregates not only has an impact on soil fertility, but is also the cornerstone of soil structural stability [22,54]. This study showed that when converting CBF into AF, HF, and CF, the content of macro-aggregates was significantly higher in CBF (72.11%) than that in CF (70.42%), AF (67.59%), and HF (68.14%), showing that forest management operations accelerate the breakdown of macro-aggregates. The values of *MWD* and *GWD* of AF, HF, and CF significantly decreased, while the values of *FD* and *K* significantly increased, suggesting that the stability of aggregates declined following the forest conversion. The possible explanation would be that the structure of CBF was complex, with shrub, grass, and litter in the understory, and the root system was also more prosperous, which can effectively prevent the splashing of raindrops and the scouring of surface runoff, protecting the macro-aggregates from being destroyed, thereby improving the stability of soil structure [19,55,56]. CF suffers little anthropogenic interference, and the humus layer is copious, which reduces the scouring force by rainfall, making it less vulnerable to water erosion and more resistant to external disturbances. On the other hand, the organic residues of CF could activate the microbial community during decomposition and lead to an increase in species of fungi and bacteria [57], while the root exudates and enzymes produced by those fungi and bacteria could provide a material basis for the formation of macro-aggregates, thereby augmenting the stability of soil aggregates and improving soil quality [9,57–59]. Conversely, in order to prevent the occurrence of insects and diseases, tillage treatment and removal of understory vegetation were annually performed in AF, and the litter of HF was removed. These management practices greatly increase anthropogenic disruption, which accelerates the destruction of macro-aggregates and increases soil aeration, resulting in a poorer protection of soil particles, looser soil structure, lower content of SOM, and a decrease in the abundance of fungi and bacteria [60–62]. AF and HF were also subjected to a greater

destruction degree under the same external force conditions, and thus their stability of soil aggregates was less stable. Overall, management measures such as minimizing the surface disturbance and increasing the ground coverage should be implemented in economic forest construction to improve the SOM content and microbial populations, which enhance the stability of soil aggregates and improve soil structure [52,63].

4.2. Effect of Forest Conversion on Aggregate-Associated SOC Storage

Soil aggregation has a significant effect on the stability of SOC, and it promotes a suitable microbial environment for the physical protection of soil and absorption of particulate organic matter [54,64]. The soil physicochemical properties, such as the clay content, water content, and temperature, will also change following the forest conversion, and these changes will in turn impact the SOC mineralization and accumulation [30,65]. In this study, compared with CF, the soil erosion modulus was significantly higher in AF and HF after intensive management (Table 1), and the content of clay particles, SOC in macro-aggregates, and C/N ratio were lower in AF and HF, indicating enhanced SOC mineralization and reduced cementing substances. This is because macro-aggregates will break down by intensive management, and soil organic matter was exposed, making it easier to be mineralized and decomposed by microorganisms [66–69]. Conversely, SOC in micro-aggregates is generally difficult to decompose [62]. Accordingly, in contrast to CF, SOC in AF and HF is more concentrated in micro-aggregates. This is consistent with the findings of Six et al. [70], who found that tillage practices and their intensity significantly influence the accumulation of soil organic matter, and intensive management will accelerate its transformation and reduce the formation of aggregation.

The soil erosion modulus was significantly higher after conversion from CBF to these three economic forests and remarkably differed between stand types (Table 1). AF is susceptible to the most severe soil erosion, followed by HF, while soil erosion and water loss would be relatively mild in CF. After forest transformation, aggregate-associated SOC stocks differed in the order of CF > HF > AF, which was exactly the opposite of the soil erosion modulus (Table 1, Figure 2). These results were also consistent with the results of Chen et al. [71], who found that converting from CBF to economic forests reduced the SOC storage related to aggregates. Previous literature reported that forest-type shifts and their subsequent intensive management will increase soil erosion, disrupt the stability of aggregates, and increase soil C loss. Although the rainfall and topography of CBF, AF, HF, and CF were similar, the aggregate-associated SOC stock of CBF was significantly higher than the three economic forests. This can be attributed to the increase in SOM export from economic forests and the increase in erosion intensity that takes away more SOC. Although the SOC content was increased through human input to a certain extent, the soil structure was destroyed, leading to the decline of soil aggregate stability [72]. Additionally, the content of SOC was the least in AF, with strong anthropogenic disturbance and bare surface, mainly due to the difference in depletion of forest growth, soil erosion, and some human disturbances. For example, the understory condition of CF was superior, and its humus-rich surface featured a high organic matter content, which had a supplementary effect on SOC via microbial decomposition, and undoubtedly, the SOC loss induced by erosion was smaller than AF and HF. Accordingly, the content of aggregated-associated SOC in CF was higher than that of AF and HF.

However, the responses of different economic forest species to intensive management were different. Both HF and AF were intensively managed, but the soil erosion modulus and the amount of aggregate-associated SOC lost from AF were higher than in HF (Table 1 and Figure 4), which was mainly related to different tree species [8]. Several studies [73–75] have confirmed that apple trees are deep-rooted plants that require higher moisture, and this demand increases with stand age, which could partly explain why the SOC storage in AF was lowest. Furthermore, in this study, rainfall is abundant in this region, but there is insufficient soil water storage and high evaporation due to the high content of sand particles and the shallow soil layer [38]. Apple trees grow roots that can obtain deeper

levels of moisture, which can have a drying effect on the surrounding soil [75]. When rainfall occurs, soil dryness exacerbates soil erosion induced by intensive management, which was in line with our findings. Consequently, CF's pattern was the optimum choice compared to AF and HF in the process of developing economic forests. Meanwhile, some measures, such as planting tea, grass, or medicine in the understory, fungicide application, less-tillage, and no-tillage to increase the ground cover [55,57,66], can be taken to control soil erosion and enhance the SOC content and its stability, thereby promoting the formation of soil macro-aggregates.

4.3. Estimation of SOC Loss Using ^{137}Cs

The results of correlation analysis demonstrated that ^{137}Cs and SOC related to aggregates were significantly positively correlated, indicating that ^{137}Cs and aggregate-associated SOC have similar patterns in the context of soil erosion, which is consistent with the previous study [4]. It was observed that SOC varies with the migration of soil particles, and thus ^{137}Cs and SOC have similar patterns in the process of erosion and deposition. This was mainly attributed to the fragmentation of macro-aggregates by soil erosion, especially water erosion, resulting in the migration of carbon along with fine particles, thereby causing the loss of SOC from in-situ soils [65]. Thus, under the changes in land-use, differences in the process of separation, translocation, and deposition of erosion will lead to differences in C transport [76].

In addition, the SOC loss in surface soil aggregates decreased by 0.15, 0.38, and 0.31 Mg hm^{-2} following the conversion from CBF to CF, AF, and HF respectively (Figure 3), implying that CF mode is more conducive to SOC accumulation. It is estimated that the conversion to intensively managed economic forests would result in a decrease of 6.47×10^6 kg of SOC in the soil surface layer of the Huaibei Rocky Mountain Areas, which would cause losses of soil and water resources and nutrients [69]. The decrease in aggregate-associated SOC stock demonstrated that the stable structure of soil is destroyed, which led to land degradation, water eutrophication, and a decrease in soil productivity of economic forests, in turn jeopardizing the development of local agroforestry [77–79]. Therefore, soil erosion caused by forest conversion and intensive management cannot be ignored when exploring the effect of soil erosion on aggregate-associated SOC using ^{137}Cs .

5. Conclusions

Conversion of CBF to three economic forests and subsequent intensive management reduced aggregate stability, accelerated aggregate fragmentation, and decreased the proportion of macro-aggregates, which in turn produced decreases in the storage of SOC in aggregates. Macro-aggregates are the main storage forms of SOC in aggregates, and the decrease in macro-aggregates adequately explains the loss of SOC in aggregate fractions. Among economic forests, CF exhibits higher aggregate stability and SOC storage compared to HF and AF. This is mainly due to better vegetation cover and low human disturbance. Intensive management in AF and CF has led to the intensification of soil erosion and accelerated the loss of soil aggregates, which is not conducive to the accumulation of SOC. According to the results of the quantitative relationship calculation, the SOC losses in the aggregates of CF, AF, and HF were 0.15, 0.38, and 0.31 Mg hm^{-2} , respectively. In the study area, soil erosion induced the loss of approximately 6.47×10^6 kg of aggregate-associated SOC, on average, due to intensive management in AF and HF. These results will provide support for monitoring land degradation and preventing soil erosion in the area. Overall, our research indicates that soil erosion induced by forest management operations has a negative impact on soil structure and nutrient storage. Therefore, when developing economic forests in the Huaibei Rocky Mountain Area, we should choose appropriate tree species and adopt proper forest management practices, such as growing tea or medicinal plants to increase surface cover, to reduce soil erosion and achieve sustainable development of economic forests. In addition, seeking a balance between economic benefits and the ecological environment should be an urgent topic for future research.

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