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Intensive Management Increases Phytolith-Occluded Carbon Sequestration in Moso Bamboo Plantations in Subtropical China

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Abstract: Plantation management practices could markedly change the sequestration of phytolith-occluded carbon (PhytOC) in plants and soils. However, for Moso bamboo (*Phyllostachys pubescens*) plantations, the effect of intensive plantation management (including fertilization, tillage, and removal of understory vegetation) on the accretion rate of PhytOC in the soil-plant system is much less understood than extensive management (without fertilization, tillage, and removal of understory vegetation). The objectives of this study were to investigate the effect of intensive and extensive management practices on the production, accumulation, and runoff of PhytOC and their distribution in physical fractions in Moso bamboo plantations. Our results showed that intensive management (1) increased PhytOC production mainly due to increased forest productivity; (2) increased PhytOC storage in the heavy fraction but decreased its storage in the light fraction of organic matter, resulting in the lack of effect on soil PhytOC storage; (3) increased the rate of dissolution of phytolith and the loss of PhytOC in runoff; and (4) promoted PhytOC sequestration in the soil-plant system, mostly in the plants, due to the greater rate of PhytOC production than the rate of loss. We conclude that intensive bamboo plantation management practices are beneficial to increasing long-term PhytOC sequestration in the soil-plant system.

Keywords: PhytOC; phytolith; plantation management; Moso bamboo forest

1. Introduction

Phytoliths are ergastic siliceous substances abundantly present within intercellular spaces and inside the cells of numerous plants [1,2]. During the formation of phytoliths, between 0.2% and 5.8% of organic carbon (C) can be occluded within the phytoliths [3,4]. Phytolith-occluded C (PhytOC) in terrestrial ecosystems is highly resistant to decomposition [5,6] and may accumulate in the soil for centuries and millennia. The PhytOC can contribute 15–37% of long-term biogeochemical C sequestration [7]. In forest ecosystems, studies about PhytOC sequestration have mainly been focused on plants, especially aboveground plant components [4,8–13]. However, little is known about PhytOC sequestration in the soil-plant system and PhytOC storage in the soil has been overlooked.

Forest management is an effective approach to increasing forest net primary productivity (NPP) and PhytOC sequestration (e.g., increasing PhytOC production by increasing vegetation production through afforestation and reforestation, fertilization, and mulching) in forests [4,9,14–16]. However, there have been inconsistent results on the impact of management intensity on plant or soil PhytOC pool sizes [14–17], causing uncertainties in the potential of intensive management to affect PhytOC sequestration in soil-plant systems.

Fertilization, tillage, and removal of understory vegetation to control competition are regarded as three important plantation management practices. For example, Song et al. [18] reported that PhytOC sequestration in croplands doubled since 1978 due to fertilizer application and irrigation. Fertilization would increase forest productivity [19] and subsequently increase PhytOC production. Tillage practice can improve soil properties (e.g., soil moisture and nutrient availability), resulting in increased forest productivity and PhytOC production [20]. Removal of understory vegetation can reduce the competition for nutrients between trees and understory vegetation [21] and may improve the absorption of soluble silicon by plant roots, and consequently increase the formation of phytolith and PhytOC in plant tissues, even though the removal of forest understory vegetation can decrease the PhytOC input to the soil from the understory vegetation.

The PhytOC contained in plant tissues is released into the soil after plants die and plant litter decays. However, forest management can affect the distribution and storage of PhytOC in the soil by changing the balance of PhytOC input and output. Management practices alter soil physical, chemical, and biological properties, and subsequently affect the environment for PhytOC accumulation. For example, inorganic fertilizer application decreases pH [22,23] and subsequently decreases phytolith dissolution as the dissolution of phytolith increases with increasing soil pH between pH 3 and 8 [24]. The separation of physical fractions of soil organic matter (SOM) into meaningful and measurable pools that differ in C turnover rate has been proven to be invaluable to advancing our understanding of SOM dynamics [25]. The SOM, where the PhytOC resides in the soil, can be separated into fractions that are not firmly associated with soil minerals (a light fraction of organic matter, LFOM) and those that are present in organo-mineral complexes (a heavy fraction of organic matter, HFOM) [26]. The PhytOC contained in those fractions is designated as LFOM- and HFOM-PhytOC, respectively. The LFOM is sensitive to forest management practices, while HFOM is much more stable in the soil because of physical protection [27–30]. However, little information is available about the effect of forest management practices on soil PhytOC distribution in physical fractions. Theoretically, LFOM-phytolith is temporarily trapped in the litter and is sensitive to forest management practices. Once the LFOM decomposes, the PhytOC is released into the soil and may form HFOM-PhytOC, including PhytOC protected by clay [31]. However, there has been little study on the effect of intensive management on PhytOC distribution in physical fractions of soil.

A pioneering study of soil phytoliths suggested the soil PhytOC might be influenced by phytolith output through soil erosion [32]. However, one potential deficiency with the work of Zuo et al. [32] is that the phytolith loss is estimated by the topsoil phytolith concentration rather than phytolith concentration in the runoff. In reality, only the phytolith that migrates to rivers through runoff can be considered as phytolith loss by soil erosion. When the soil is not properly managed, soil erosion enhances the loss of phytolith from soils to rivers [32]. Tillage and removal of understory vegetation can increase soil erosion [33] and subsequently phytolith loss through runoff. However, the rate of PhytOC loss in runoff into rivers under different management practices remains largely unknown.

Bamboo forests cover an area of about 6.01 million hectares in China, of which 73.8% is Moso bamboo (*Phyllostachys pubescens* Mazel ex H.de Leh.) forests [34]. It has higher forest productivity (6–22 mega gram (Mg) C ha^{−1} year^{−1}) and higher concentrations of phytolith in its tissue than other vegetation types [9]. But in bamboo ecosystems, studies about PhytOC sequestration have mainly been focused on plants. The impact of fertilization, tillage, and removal of understory vegetation on PhytOC accretion rate in the plant-soil system in bamboo forests remains unclear. The objective of this study was to investigate the effect of intensive and extensive management practices on plant PhytOC

sequestration, soil PhytOC pools, PhytOC dissolution, and loss through runoff in Moso bamboo forests. We tested the following hypotheses: intensive management (1) increases PhytOC sequestration in plant tissues, because intensive management increases forest productivity; (2) increases the soil PhytOC stock and alters its distribution in physical fractions; (3) increases the dissolution of phytolith and loss of soil PhytOC from soils into rivers through runoff due to intensive management exposing more phytolith surfaces and boosting soil erosion; and (4) promotes PhytOC sequestration in the soil-plant system due to greater PhytOC production than loss.

2. Materials and Methods

2.1. Study Site

The study site was located in Qingshan Township, Lin'an County (30°19' N, 119°22' E), Zhejiang Province, in southeastern China. This area has a central-subtropical climate, with a mean annual precipitation of 1422 mm and a mean annual temperature of 15.8 °C based on climatic data available between 2000 and 2009, with minimum and maximum temperatures of −13.3 °C and 41.7 °C, respectively. The mean annual sunshine hours and frost-free days between 2000 and 2009 were 1946 h and 239 days, respectively [15,35]. The study site had a slope of 25° and was 100–150 m above sea level. The soils in the experimental area were classified as Ferralsols in the FAO soil classification system. The basic chemical properties of the soil are listed in Table 1. The Moso bamboo plantation in the study site was converted from a natural evergreen broadleaf forest to a bamboo forest by planting after harvesting the broadleaf forest. The Moso bamboo plantation in this study was 21 years old in 2015.

Table 1. Soil pH, soil organic carbon and total soil SiO₂ concentration (means ± standard deviations) under *Phyllostachys pubescens* stands with different management intensities ($n = 3$).

Management Intensity	Soil Depth	pH	Soil Organic Carbon	Total Soil SiO ₂	Water Soluble Silicon
Extensive	0–10 cm	5.14 ± 0.19a ¹	23.07 ± 3.83a	558.2 ± 14.99a	12.65 ± 4.12a
Intensive	0–10 cm	4.36 ± 0.13b	16.13 ± 1.82b	565.02 ± 14.50a	6.33 ± 1.85b
Extensive	10–30 cm	5.23 ± 0.18a	18.09 ± 0.89a	561.4 ± 28.54a	13.52 ± 2.82a
Intensive	10–30 cm	4.59 ± 0.18b	12.91 ± 2.25b	532.11 ± 25.30a	5.31 ± 1.82b
Extensive	30–60 cm	5.34 ± 0.29a	12.94 ± 0.51a	527.07 ± 50.50a	9.15 ± 3.51a
Intensive	30–60 cm	5.05 ± 0.20a	9.43 ± 1.13b	507.87 ± 39.10a	6.24 ± 0.63b
Extensive	60–100 cm	5.27 ± 0.14a	5.91 ± 1.38a	528.52 ± 21.87a	5.56 ± 2.76a
Intensive	60–100 cm	5.09 ± 0.09a	4.85 ± 1.27a	523.84 ± 29.98a	6.92 ± 3.52a

¹ Different letters within a column indicate significant differences between the different management intensities within the same soil layer at the $p = 0.05$ level.

2.2. Bamboo Forest Management Practices

The experiment included three paired-plots and two small watersheds (Figure 1). The two treatments were intensive management and extensive management. The three paired-plots included two treatments with three replications were used to investigate the effect of management intensity on plant and soil PhytOC. Each paired-plot included two adjacent plots, i.e., one with intensive management and the other with extensive management. We selected three different locations in the area described above to establish three different paired plots in June 2015; the plot size was 20 × 20 m (400 m²). Within a paired-plot, the distance between the two plots (one under intensive management and the other under extensive management) was less than 100 m. The two small watersheds included two treatments, which were adopted to investigate the effect of management intensity on the loss of PhytOC in runoff. The small watershed in adjacent intensively and extensively managed bamboo plantations was 2.67 and 3.67 ha, respectively, in size. Each plot and watershed had the same planting method, planting time (21 years), management time (20 years) and geographic factors, including soil type, slope (15–21°), and aspect (south). The bamboo plantation was intensively managed by annual application of inorganic fertilizers, deep tillage, and removal of understory vegetation. In May of each year, fertilizers including urea (200 kg N ha^{−1}), super phosphate (60 kg P ha^{−1}), and potassium chloride (70 kg K ha^{−1}) were widely applied, followed by deep tillage to ~30 cm depth. The understory

vegetation was manually removed annually. The extensively managed bamboo plantation received no fertilizer, tillage or understory removal, and the understory vegetation was dominated by *Isatis indigotica* Fortune and *Vaccinium bracteatum* Thunb. that typically covered 90% of the soil surface.

Figure 1. Location of three paired-plots and two small watersheds.

2.3. Plant and Soil Sampling and Preparation

In each plot, the height and diameter of all bamboo plants were measured. Three bamboo plants were randomly selected and harvested from each sampling plot, and the biomass of leaves, branches, culms, and stump was determined. At the same time, four 1×1 m subplots were set up at random locations in each sampling plot, and the below-ground bamboo component in 0–60 cm soil layers in the subplots was dug up. The fresh mass of each bamboo component was determined, and about 1000 g of fresh sample was collected for each component for further analysis. In each plot, four 1×1 m litter traps were set up and litterfall was collected every month from June to June of the next year and then weighed. To find whether the two management practices can affect the PhytOC distribution in soil layers, soil samples (2 kg) were collected from seven points per plot from the 0–10, 10–30, 30–60, and 60–100 cm depths. The samples collected from multiple points in each plot were mixed to form a composite sample for each depth. Soil bulk density samples were collected in all four layers using a bulk density corer with a volume of 100 g cm^3 .

Once the samples were brought back to the laboratory, about 100 g of litter was washed in deionized water using an ultrasonic vibrating machine (500W) for 1 min, dried at 105°C for 20 min to quickly remove the excess water, and then dried at 70°C for 48 h in a forced-air oven. The plant samples were then ground to pass through a 0.25 mm mesh for chemical analysis. Soil samples were air-dried. Each soil sample was divided into two parts. One part was ground to pass through a 0.5 mm screen and used to determine phytolith and PhytOC concentrations, and the other part was passed through a 2 mm screen and used for other soil chemical analyses.

In each small watershed, a weir was set up to collect outflow water, to measure water flow rate, and to determine sediment loss under natural rain conditions. Within each weir, 2 sedimentation tanks were set up for settlement of sediment. Sediments were collected every 4 months from October 2015 to October 2016, air-dried, and ground to pass through a 0.5 mm screen. The sediment samples were then used to determine phytolith and PhytOC concentrations.

2.4. Plant and Soil Analysis

Soil pH was determined by a pH electrode on a 1:2.5 (m:v) soil to water ratio. Organic C concentrations in plant and soil samples were determined by an elemental analyzer (model CHN-O-RAPID, Heraeus, Germany). The total silicon concentrations in soil samples were determined by an Optima 7000 DV ICP-OES (PerkinElmer, Inc., Waltham, Massachusetts, United States of America) after pretreatment with the lithium metaborate melting method [22]. Water-soluble silicon was extracted by 0.02 mol L^{-1} CaCl_2 solution and measured with silicon-molybdenum blue spectrophotometer [36].

The determination of LFOM- and HFOM-PhytOC: 10 g of dried soil sample was transferred to a 100 mL graduated centrifuge tube. After adding 40 mL of NaI solution (specific gravity = 1.80 ± 0.02) [27], the suspension was dispersed for 30 s using a homogenizer and for 15 min using an ultrasound (300 W). After standing overnight, each sample was centrifuged at $1250 \times g$ for 60 min [37]. The suspended material (LF) was removed and transferred directly onto a filtration unit that had a filter paper. The LF was then washed under suction with three successive aliquots of 100 mL 0.01 M CaCl_2 and three aliquots of 100 mL distilled water. The HF was washed in 50 mL graduated centrifuge tube with three aliquots of 100 mL 0.01 M CaCl_2 and three aliquots of 50 mL distilled water and each washing was centrifuged at $1250 \times g$ for 30 min. After drying overnight (approximately 17 h at 70°C), the LF from the filter paper and HF in the centrifuge tube were recovered, weighed, and used to determine phytolith and PhytOC concentrations.

A microwave digestion method was used in this study to isolate phytoliths from plant [1], soil, as well as light and heavy fraction and sediment samples [38]. Soil as well as light fraction, heavy fraction, and sediment phytoliths were isolated using the heavy liquid (ZnBr_2 , 2.3 g cm^{-3}) suspension method [32,39]. Duplicates were analyzed for each plant and soil sample. This process was followed by a Walkley–Black type digestion to ensure that the extracted phytoliths were free of extraneous organic material [40]. The extracted phytoliths were oven-dried at 75°C for 24 h and then weighed. Finally, each sample was further checked on an optical microscope (Olympus CX31, Olympus Corporation, Tokyo, Japan) to confirm that all extraneous organic materials on the surface of the phytoliths were thoroughly removed. The C concentration in phytolith was determined using the PhytOC alkali spectrophotometry method [41].

2.5. Calculations and Statistical Analysis

The following calculations were performed:

$$\text{Leaf PhytOC production flux (kg ha}^{-1} \text{ yr}^{-1}) = \text{PhytOC concentration in leaves (g kg}^{-1}) \times \text{leaf litter mass (kg ha}^{-1} \text{ yr}^{-1}) \times 10^{-3} \quad (1)$$

The leaf PhytOC production flux was calculated by reference the ratio of living leaf biomass to annual litter amount [9].

$$\text{Plant PhytOC storage (kg ha}^{-1}) = \text{PhytOC concentration (g kg}^{-1}) \times \text{biomass (kg ha}^{-1}) \times 10^{-3} \quad (2)$$

$$\text{Branch or culm PhytOC production flux (kg ha}^{-1} \text{ yr}^{-1}) = \text{PhytOC concentration in Branch or culm} \times \text{Branch or culm biomass (kg ha}^{-1}) \times 10^{-3} / \text{The age of Moso bamboo} \quad (3)$$

$$\text{Above-ground PhytOC production flux (kg ha}^{-1} \text{ yr}^{-1}) = (\text{leaf} + \text{branch} + \text{culm}) \text{ PhytOC production flux (kg ha}^{-1} \text{ yr}^{-1}) \quad (4)$$

$$\text{Below-ground PhytOC production flux (kg ha}^{-1} \text{ yr}^{-1}) = \text{PhytOC concentration in below-ground biomass} \times \text{Below-ground biomass (kg ha}^{-1}) \times 10^{-3} / \text{stand age (yr)} \quad (5)$$

$$\text{Soil PhytOC storage (kg ha}^{-1}) = \text{Soil PhytOC concentration} \times \text{bulk density (Mg m}^{-3}) \times \text{thickness of the soil layer (m)} \times 10,000 \quad (6)$$

$$\text{LFOM-PhytOC storage (kg ha}^{-1}) = \text{LFOM-PhytOC concentration} \times \text{bulk density (Mg m}^{-3}) \times \text{thickness of the soil layer (m)} \times 10,000 \quad (7)$$

$$\text{HFOM-PhytOC storage (kg ha}^{-1}) = \text{HFOM-PhytOC concentration} \times \text{bulk density (Mg m}^{-3}) \times \text{thickness of the soil layer (m)} \times 10,000 \quad (8)$$

$$\begin{aligned} & \text{Phytolith dissolution} - \text{PhytOC decomposition flux (kg ha}^{-1} \text{ yr}^{-1}) = \\ & \quad \text{Litter PhytOC return flux (kg ha}^{-1} \text{ yr}^{-1}) \\ & - \text{Soil PhytOC accumulation flux (kg ha}^{-1} \text{ yr}^{-1}) - \text{PhytOC stream output flux (kg ha}^{-1} \text{ yr}^{-1}) \end{aligned} \quad (9)$$

$$\begin{aligned} & \text{Plant-soil system accretion flux (kg ha}^{-1} \text{ yr}^{-1}) = \text{Biomass production flux (kg ha}^{-1} \text{ yr}^{-1}) \\ & - \text{Equation (6)} - \text{PhytOC stream output flux (kg ha}^{-1} \text{ yr}^{-1}) \end{aligned} \quad (10)$$

The data presented in this paper are mean values of three replicates. A one-way analysis of variance (ANOVA) and the least significant difference (LSD) test was used to determine the significance of the effect of different management intensities on different parameters. Unless otherwise mentioned, a significance level of 0.05 was used in all statistical analyses. All statistical analyses in this study were performed using the SPSS software (SPSS 13.0 for Windows, SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Effects of Plantation Management Intensity on Soil Chemical Properties

Intensive management decreased soil organic C concentration in bamboo forests by 43.0, 40.1, and 37.2% in the 0–10, 10–30, and 30–60 cm soil layers, respectively, as compared to extensive management (Table 1). Intensive management also decreased soil pH in the topsoil (0–30 cm) and water-soluble silicon concentration in the 0–10, 10–30 and 30–60 cm soil layers, compared to extensive management. Intensive management decreased the mean value of total soil SiO₂ concentration in the 0–10, 10–30, and 30–60 cm soil layers, but was not as significant as compared to extensive management (Table 1).

3.2. Effects of Plantation Management Intensity on Plant PhytOC Production

The phytolith and PhytOC concentrations were not different in above-ground of Moso bamboo and understory vegetation between the two management intensities, while intensive management decreased phytolith and PhytOC concentrations in below-ground plants by 42.0% and 44.6%, respectively, as compared to extensive management (Figure 2).

The PhytOC storage in Moso bamboo plantations ranged from 8.3 to 38.7 kg ha^{−1} in different tissues under two management intensities (Figure 2). Management intensity did not affect PhytOC storage in below-ground of Moso bamboo, but intensive management significantly increased PhytOC storage in above-ground of Moso bamboo and understory vegetation by 58.6 and 94.5%, respectively (Figure 2). The PhytOC production flux of Moso bamboo plantations under intensive management was 29.5 kg ha^{−1} yr^{−1}, which was 1.5 times higher than that under extensive management (20.2 kg ha^{−1} yr^{−1}) (Figure 2).

Figure 2. (a) phytolith concentration, (b) PhytOC concentration, (c) PhytOC storage and (d) PhytOC production flux in different part of *P. pubescens* stands and understory with different management intensities. Different letters within a column indicate significant differences between the different management intensities within the same plant tissue at the $p = 0.05$ level.

3.3. Effects of Plantation Management Intensity on Soil PhytOC Accumulation and Its Distribution in Physical Fractions

Management intensity did not affect the concentration and storage of PhytOC in different soil layers (Table 2). Intensive management decreased LFOM-PhytOC storage in the 0–100 cm soil depth by 50.8% as compared with extensive management (Figure 3). Intensive management increased the mean values of HFOM-phytolith and HFOM-PhytOC concentration and storage in 0–10 and 10–30 cm soil layers but failed to reach a significant level ($p < 0.05$). Intensive management increased the amount of HFOM-PhytOC stored in the 0–100 cm soil layer by 25.2%, compared to extensive management (Figure 4).

Table 2. Soil phytolith and PhytOC concentrations and storage (means $\pm$ standard deviations) in different soil layers under *P. pubescens* stands with different management intensities ($n = 3$).

Management Intensity	Soil Depth	Phytolith Concentration (g kg ⁻¹)	PhytOC Concentration (g kg ⁻¹)	PhytOC Storage (kg ha ⁻¹)
Extensive	0–10 cm	8.79 $\pm$ 3.05a ¹	0.118 $\pm$ 0.047a	119.56 $\pm$ 47.21a
Intensive	0–10 cm	10.25 $\pm$ 1.35a	0.131 $\pm$ 0.010a	135.27 $\pm$ 8.88a
Extensive	10–30 cm	6.04 $\pm$ 0.81a	0.065 $\pm$ 0.013a	144.65 $\pm$ 31.92a
Intensive	10–30 cm	6.21 $\pm$ 0.40a	0.079 $\pm$ 0.036a	176.43 $\pm$ 80.49a
Extensive	30–60 cm	5.26 $\pm$ 0.86a	0.064 $\pm$ 0.011a	225.97 $\pm$ 39.76a
Intensive	30–60 cm	5.43 $\pm$ 0.72a	0.064 $\pm$ 0.004a	228.68 $\pm$ 13.06a
Extensive	60–100 cm	3.84 $\pm$ 1.00a	0.038 $\pm$ 0.014a	184.22 $\pm$ 66.87a
Intensive	60–100 cm	3.88 $\pm$ 0.84a	0.039 $\pm$ 0.010a	192.07 $\pm$ 44.35a
Extensive	Total	-	-	674.42 $\pm$ 27.63a
Intensive	Total	-	-	730.36 $\pm$ 70.78a

¹ Different letters within a column indicate significant differences between the different management intensities within the same soil layer at the $p = 0.05$ level.

Figure 3. Light fraction organic matter (a) phytolith concentration, (b) PhytOC concentration and (c) PhytOC storage (mean $\pm$ SD, $n = 3$) of different soil layers from *P. pubescens* stands with different management intensities. Abbreviations: LFOM- = Light fraction organic matter. Different letters within a column indicate significant differences between the different management intensities within the same soil layer at the $p = 0.05$ level.

Figure 4. Heavy fraction organic matter (a) phytolith concentration, (b) PhytOC concentration and (c) PhytOC storage (mean $\pm$ SD, $n = 3$) of different soils layers from *P. pubescens* stands with different management intensities. Abbreviations: HFOM = Heavy fraction organic matter. Different letters within a column indicate significant differences between the different management intensities within the same soil layer at the $p = 0.05$ level.

3.4. Effect of Plantation Management Intensity on Soil PhytOC Dissolution and Loss in Runoff

The amount of sediment loss, phytolith and PhytOC runoff derived from Moso bamboo plantations was 49.4, 0.3, and 0.004 $\text{kg ha}^{-1} \text{yr}^{-1}$, respectively, under intensive management, and was 34.8, 0.2, and 0.003 $\text{kg ha}^{-1} \text{yr}^{-1}$, respectively, under extensive management (Table 3). Intensive management increased the phytolith dissolution (PhytOC decomposition) rate by 1.3 $\text{kg ha}^{-1} \text{yr}^{-1}$, but increased PhytOC accretion rate in the plant-soil system by 7.8 $\text{kg ha}^{-1} \text{yr}^{-1}$ (Figure 5).

Table 3. Phytolith and PhytOC concentration in sediment, and sediment, phytolith and PhytOC loss rate (means $\pm$ standard deviations) under *P. pubescens* stands with different management intensities ($n = 3$).

Management Intensity	Sediment Loss Rate (kg ha ⁻¹ yr ⁻¹)	Phytolith Concentration (g kg ⁻¹)	PhytOC Concentration (g kg ⁻¹)	Phytolith Loss Rate (kg ha ⁻¹ yr ⁻¹)	PhytOC Loss Rate (kg ha ⁻¹ yr ⁻¹)
Extensive	34.77	5.80 $\pm$ 0.36	0.08 $\pm$ 0.01	0.20 $\pm$ 0.01	0.003 $\pm$ 0.000
Intensive	49.36	5.99 $\pm$ 0.91	0.09 $\pm$ 0.01	0.30 $\pm$ 0.05	0.004 $\pm$ 0.001

Figure 5. Plant-soil system PhytOC cycles model from *P. pubescens* stands with different management intensities.

4. Discussion

4.1. Plantation Management Intensity Affected Plant PhytOC Production

The lower phytolith concentration in the below-ground but the lack of difference in phytolith concentration in the above-ground plant component under intensive management, compared to extensive management. The result suggests that the phytolith concentration in the below-ground plant component is more sensitive to changes in management practices. This study is a step further from previous studies that only reported on the effect of management practices on phytolith concentration in above-ground plant components in croplands and grasslands [16,42].

Intensive management practices increased PhytOC production in above-ground components of Moso bamboo due to increased above-ground productivity rather than PhytOC concentration in above-ground components (Figure 2), but did not affect PhytOC production in below-ground components due to decreased phytolith concentration even though below-ground productivity also increased (Figure 2), supporting our first hypothesis. Generally, PhytOC sequestration in plants is mainly determined by NPP, both above- and below-ground [32,43], the rate of production of phytolith [3,9,10], and the efficiency of C encapsulation during the formation of phytoliths in plants [6,32,44]. Recent studies have shown that intensive management can enhance the growth of Moso bamboo [15,20]. However, it should be noted that intensive management did not change the phytolith and PhytOC concentration above-ground, but decreased them below-ground in this

study. Those were the net result of both positive and negative effects induced by fertilization, tillage, and removal of understory vegetation. High rates of inorganic fertilizer application can limit silicon absorption by plants [16]. On the other hand, tillage can improve water use efficiency [20], increase transpiration, and promote the formation of phytolith in above-ground plant components. Also, removal of understory vegetation can decrease the competition for nutrients between Moso bamboo and understory vegetation [21] and consequently increase the productivity of Moso bamboo and the concentration of PhytOC in plant tissues.

Fertilization may have positive or negative effects on PhytOC production [14,16,18]. For example, Zhao et al. [16] suggested that appropriate nitrogen fertilization increased the PhytOC sink in grasslands, while high levels of nitrogen fertilization decreased the PhytOC concentration in plants. Huang et al. [15] suggested that nitrogen—phosphorus—potassium compound fertilization enhanced PhytOC production in Lei bamboo. Therefore, the effect of fertilization on PhytOC production depends on rate and type of fertilizer application.

4.2. Plantation Management Intensity Affected Soil PhytOC Sequestration

Plantation management, especially long-term intensive management, will change both the concentration and storage of soil PhytOC [15]. However, our results suggest that management intensity did not affect soil PhytOC concentration and storage in Moso bamboo plantations (Table 2). The possible explanation would be (1) intensive management practices increase forest NPP and PhytOC input to the soil (Figure 2); (2) intensive management practices decrease soil organic matter and water-soluble silicon concentration (Table 1), which might result in the increased dissolution of phytolith due to organic anions decrease silicon release from phytolith, as compare to the effect of inorganic anions [45] and higher water-soluble silicon concentration is beneficial to PhytOC accumulation [46] and (3) intensive management practices led to soil acidification (Table 1), which favor the preservation of phytoliths [24,47]. Possible mechanisms involved in the none-change of both soil PhytOC concentration and storage would be (1) inorganic fertilizer input under intensive management would decrease pH but increase the decomposition of SOC [22], which resulted in affect PhytOC output. In addition, inorganic fertilizer affected PhytOC input and would contribute to changing PhytOC storage; (2) tillage would strengthen the aeration and water available condition [48] and increase the potential of phytolith dissolution and PhytOC decomposition; (3) removal of understory vegetation decreased the PhytOC input (Figure 2), and may subsequently contribute to reduced PhytOC storage.

Some studies, however, showed that management practices may have positive or negative effects on the soil phytolith and PhytOC pools [15,17]. For example, long-term mulching of organic residues in bamboo forests significantly increased soil PhytOC storage [15], while long-term harvesting of organic residues decreased soil PhytOC storage by removing litterfall and decrease PhytOC input into the soil [49]. The discrepancy among different studies in the change of soil PhytOC caused by different management practices would be mainly attributed to variations in type of management practices and the duration under different management practices [50].

The light fraction organic C (LFOM) has been used to assess the change of soil organic C pools by different management practices, as this fraction is more sensitive to perturbations than the total soil organic C. Our results showed that intensive management markedly decreased LFOM-PhytOC storage (Figure 3), while increased HFOM- PhytOC storage in the soil (Figure 4), suggesting that intensive management increased the decomposition of LFOM and released more LFOM-PhytOC into the soil to form HFOM-PhytOC. A possible mechanism is that the deep tillage applied in intensive management would break up and mix plant residue into the soil and increase aeration and biological activity, and subsequently increase LFOM decomposition and formation of HFOM-PhytOC. Our results suggest that the LFOM-PhytOC responded faster to different management practices than the total soil PhytOC content.

4.3. Management Intensity Effects on Soil PhytOC Dissolution and Loss Through Runoff

The geochemical stability of phytoliths is controlled by phytolith properties [5,23], and soil properties such as pH [24,47], dissolved silicon concentration, and the soil moisture regime [5]. Intensive management increased the phytolith dissolution-PhytOC decomposition rate by $1.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in Moso bamboo plantations as compared to extensive management practices, suggesting that management practices can alter the rate of PhytOC accumulation. Alternative management regimes may be developed for increasing the geochemical stability of phytolith, and increasing long-term organic C storage in soils to mitigate global climate change [51,52].

Intensive management of bamboo plantations increased the migration of soil phytolith and PhytOC from the forest to the river, due to increased sediment loss. The possible explanation would be tillage and removal of understory vegetation can strengthen soil erosion [33] and subsequently increased the loss of sediment in the runoff, which resulted in phytolith output into river. In this study, the soil phytolith runoff rate ($0.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$) in the intensively managed Moso bamboo plantation (Table 3) was far lower than the estimated rate for phytolith in the Chinese Loess Plateau ($40 \text{ kg ha}^{-1} \text{ yr}^{-1}$) [32], despite a higher phytolith concentration in the sediment but a lower rate of soil erosion in the present study. The total area of bamboo in China is $7.2 \times 10^6 \text{ ha}$ (including 50% with intensively management and 50% with extensively management) [21], and the averaged soil erosion rate in China was $300 \text{ kg ha}^{-1} \text{ yr}^{-1}$ [53]. Using the phytolith and PhytOC concentration in the sediment (Table 3), the rate of phytolith and PhytOC loss into the river was estimated to be 1.74 and $0.03 \text{ kg ha}^{-1} \text{ yr}^{-1}$, respectively, and about 12.5 and 0.2 Mt year^{-1} , respectively, from bamboo forests.

5. Conclusions

As a conclusion, intensive plantation management (including fertilization, tillage, and removal of understory vegetation) promoted PhytOC storage in the plant-soil system in Moso bamboo plantations in subtropical China. This management can increase PhytOC productivity in plant biomass in light of increased forest productivity. It can also change soil PhytOC storage by providing increased PhytOC storage in the HFOM but decreased storage in the LFOM, even after increasing soil phytolith dissolution and PhytOC runoff. To achieve the maximum PhytOC sequestration potential, we need to develop sustainable Moso bamboo plantation management practices such as appropriate fertilization to increase the PhytOC input to and decrease PhytOC output from the soil in the future.

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