Cheng *et al. Ecological Processes* (2023) 12:62
https://doi.org/10.1186/s13717-023-00476-3

Ecological Processes

RESEARCH

Open Access

The phytolith carbon sequestration in terrestrial ecosystems: the underestimated potential of bamboo forest

Xuekun Cheng[1,2,3,4], Huiru Lv[1,2,3,4], Shuhan Liu[1,2,3,4], Chong Li[1,2,3,4], Pingheng Li[1,2,3,4], Yufeng Zhou[1,2,3,4], Yongjun Shi[1,2,3,4] and Guomo Zhou[1,2,3,4*]

Abstract

Background Terrestrial ecosystems contain significant carbon storage, vital to the global carbon cycle and climate change. Alterations in human production activities and environmental factors affect the stability of carbon storage in soil. Carbon sequestration in plant phytoliths offers a sustainable method for long-term carbon stabilization. Carbon occluded in phytoliths (PhytOC) is a kind of carbon that can be stable and not decomposed for a long time, so it is crucial to conduct more in-depth research on it.

Results We undertook a meta-analysis on PhytOC across global terrestrial ecosystems, analyzing 60 articles, encapsulating 534 observations. We observed notable differences in phytolith and PhytOC contents across various ecosystems. Bamboo forest ecosystems exhibited the highest vegetation phytolith and PhytOC content, while soil phytolith content was most prominent in bamboo forests and PhytOC content in croplands. Human activities, such as grassland grazing, had a lesser impact on soil PhytOC transport than actions like cutting and tillage in croplands and forests. Our study separated bamboo ecosystems, analyzing their PhytOC content and revealing an underestimation of their carbon sink capacity.

Conclusions Notwithstanding our findings, phytoliths' intricate environmental interactions warrant further exploration, crucial for refining ecosystem management and accurately estimating PhytOC stocks. This deepened understanding lays the foundation for studying phytoliths and the carbon sink dynamics.

Keywords Carbon sequestration, Phytoliths, PhytOC, Terrestrial ecosystem, Soil carbon

Background

With the increasing concentration of CO_2 in the atmosphere, the greenhouse effect has seen a remarkable enhancement. Biological carbon sequestration serves as an effective approach to reduce these rising CO_2 concentrations in terrestrial ecosystems. Its role in global climate change and the carbon cycle has been documented by multiple studies (Alexander et al. 2006; Law and Harmon 2011). Terrestrial ecosystems possess a vast capacity for carbon storage. However, changes in human activities, combined with the continuous influence of environmental factors, mean that carbon stored in these ecosystems often doesn't remain stable for extended periods (Tang

*Correspondence:
Guomo Zhou
zhougm@zafu.edu.cn
[1] State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Lin'an, Hangzhou 311300, China
[2] Zhejiang Province Key Think Tank: Institute of Ecological Civilization, Zhejiang A&F University, Lin'an, Hangzhou 311300, China
[3] Key Laboratory of Carbon Cycling in Forest Ecosystems and Carbon Sequestration of Zhejiang Province, Zhejiang A&F University, Lin'an, Hangzhou 311300, China
[4] School of Environmental and Resources Science, Zhejiang A&F University, Lin'an, Hangzhou 311300, China

et al. 2018; Nadeau et al. 2022). For years, scholars have sought methods that ensure the long-term stability of carbon sequestration (Rogers et al. 2019; Chmura et al. 2003). Carbon sequestration within plant phytoliths has emerged as a promising biogeochemical method to achieve this (Li et al. 2013; Hodson 2019, 2016; Song et al. 2017a; Tan et al. 2021). Most of the carbon occluded in phytoliths (PhytOC) is derived from atmospheric CO_2 that is fixed by photosynthesis (Hodson 2016; Yang et al. 2020). During the process, some organic carbon is encapsulated within the silicon body, forming PhytOC. This PhytOC exhibits significant physical resistance, and both phytoliths and PhytOC can persist stably in soil for extended durations after a plant's death (Hodson 2016; Song et al. 2012; Zuo et al. 2017). Research by Zhang et al. (2017) highlighted that this stability lasts for about 433 to 1018 years in subtropical and tropical regions.

Given the stable nature of phytolith carbon sequestration, numerous scholars have verified the potential of phytolith plants in the long-term sequestration of atmospheric CO_2, contributing significantly to the mitigation of global climate change (Parr et al. 2010; Zuo et al. 2014; Song et al. 2015; Zhang et al. 2020; Anjum and Nagabovanalli 2021). Ultimately, the phytolith carbon sink is viewed as a crucial mechanism for the long-term sequestration of organic carbon on land. It plays a pivotal role not only in the carbon cycle of terrestrial ecosystems but also in the broader global carbon cycle (Conley 2002; Davamani et al. 2022).

In recent years, the carbon sequestration capabilities of phytolith have garnered significant attention within the academic community (Hodson et al. 2020). Researchers have embarked on systematic evaluations of carbon sequestration by phytolith silica across various ecosystems, including croplands, grasslands, and forests (Li et al. 2022; Zhang et al. 2020; Kaczorek et al. 2019; Song et al. 2017a; Tan et al. 2021). The scope of this research has expanded beyond plant-based phytolith carbon sequestration to also consider the effects of subsurface biomass and soil phytolith carbon sequestration (Maguire et al. 2017). In examining the mechanisms behind phytolith carbon sequestration, numerous studies have identified vegetation primary production, genotype, phytolith structure, and stand age as key determinants of PhytOC (Li et al. 2014; Yang et al. 2016; Zuo et al. 2014; Zhao et al. 2016; Huang et al. 2014). Moreover, environmental factors such as temperature, humidity, precipitation, and soil physicochemical properties have been highlighted as influential to phytolith development (Bartoli and Wilding 1980; Hsu et al. 2012; Liu et al. 2013; Zhang et al. 2020). Current estimates of the carbon sequestration potential of phytoliths in forests, croplands, grasslands, and other ecosystems have been derived from measurements of phytolith and PhytOC content in plants, as well as the extant biomass of these plants. Notable advancements have been made in this area (Zhang et al. 2020; Parr et al. 2010; Yang et al. 2018; Song et al. 2013; Tan et al. 2021; Li et al. 2022). Bamboos are acknowledged as superior accumulators of phytoliths compared to other plants (Parr et al. 2010; Yang et al. 2015). In the Indian Himalayas, bamboo forests demonstrate notably high PhytOC content, indicating their effective accumulation of both phytoliths and PhytOC (Debnath et al. 2023). Furthermore, research conducted in subtropical forest regions of China confirms the robust capacity of bamboo forests to accumulate PhytOC (Chen et al. 2018; Yang et al. 2015; Huang et al. 2019, 2020). These findings collectively emphasize the significant role played by bamboo in the accumulation of phytoliths and PhytOC, particularly in diverse geographical locations. However, there is still a gap in the overall analysis of terrestrial ecosystems, and there are few comprehensive analyses of plants with high phytolith content such as bamboo forests, so a comprehensive study and discussion on ecosystem synthesis is urgently needed.

In this study, we analyzed the phytolith and PhytOC content across terrestrial ecosystems. To offer precise estimates of the phytolith carbon sink potential and furnish insights for global carbon cycle research, we consolidated findings on phytoliths in the vegetation, litter, and soil of these ecosystems. By analyzing the variances in PhytOC across different terrestrial ecosystems, we elucidated the unique characteristics of carbon sequestration. This research paves the way for innovative approaches in future PhytOC studies.

Methods

Data collection

We conducted literature searches on the Web of Science (http://apps.webofknowledge.com) and the China National Knowledge Infrastructure (CNKI, http://www.cnki.net) databases to identify peer-reviewed articles related to phytolith and phytolith carbon. Keywords used for the searches included "forest," "bamboo," "grassland," "cropland," "phytolith," and "PhytOC." Our search was restricted to peer-reviewed articles published from January 2000 to August 2023. The obtained articles were meticulously reviewed to ensure they met the criteria for meta-analysis: (1) Publications must focus on terrestrial ecosystems (such as forest, bamboo, grassland, and cropland) and provide essential details like geographic location, environmental context, and ecosystem type. (2) Each publication must present data on at least one target variable related to phytolith or PhytOC, either in vegetation or soil. (3) The standard deviation (SD) or standard

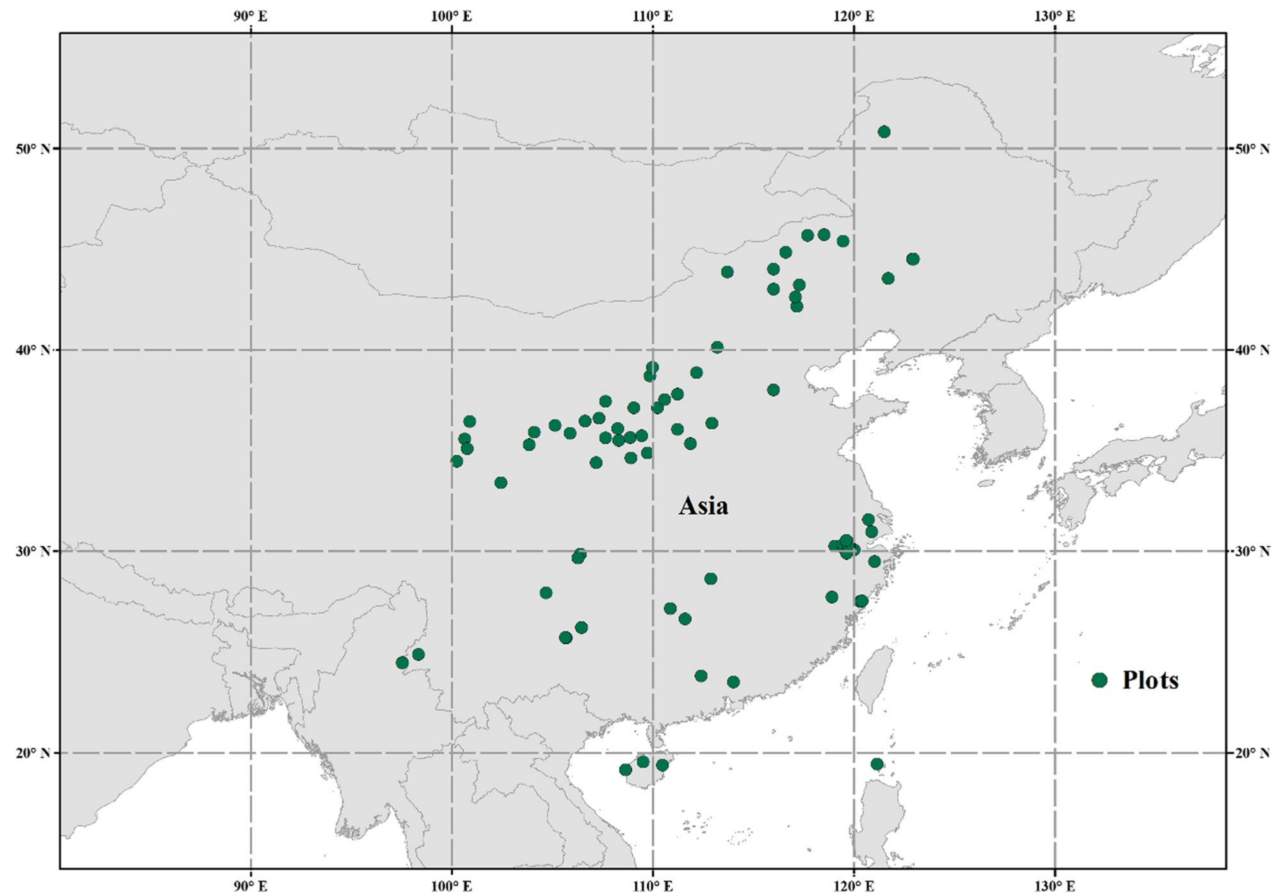

Fig. 1 Research sites on phytolith or PhytOC are included in this meta-analysis

error (SE) of the relevant data should be directly extractable from the publication. (4) Only articles that utilized the measurement techniques detailed by Parr and Sullivan (2005) and Parr et al. (2010) for PhytOC and phytolith data were included. (5) All extracted data should be convertible to a standard unit. (6) We excluded data on carbon sequestration from underground plant parts or wood contributions, focusing primarily on data generated from the aboveground photosynthetic portions of biomes, as suggested by Parr et al. (2010), Parr and Sullivan (2014), and Song et al. (2017a, b). Following these criteria, our database included 60 publications on terrestrial ecosystem phytolith carbon, comprising 534 observations (Additional file 1: Table S1). For enhanced analysis, we categorized the ecosystems. Data on plot coordinates, vegetation types, mean annual temperature (MAT), and mean annual precipitation (MAP) were sourced from the selected articles. When data in the publications were tabulated, we directly extracted it; however, when presented graphically, we employed the Web Plot Digitizer software for extraction. Our focus was on data derived from on-site or laboratory measurements, deliberately excluding model-predicted results. Out of the collected data, 124 entries pertained to grassland ecosystem, 104 to cropland ecosystem, and 306 to forest ecosystem (Fig. 1). Notably, due to the distinctive nature of bamboo forests and their notable phytolith carbon accumulation ability (Parr and Sullivan 2014), we treated bamboo ecosystems as a separate category. A comprehensive list of data sources is provided in the Additional file 1: Table S1.

Data calculation

To characterize the ability of phytolith to sequester carbon, we chose two parameters: one for phytolith content and the other for PhytOC content. Different ecosystem types and different management can affect phytolith content. We uniformly used the following formula to calculate phytolith concentration, PhytOC concentration and PhytOC carbon storage:

$$Phytolith\ concentration\ (g/kg) = phytolith\ weight\,(g)/dry\ weight\,(kg) \tag{1}$$

$$PhytOC\ concentration\,(g/kg) = C\ content\ in\ phytolith\,(g)/dry\ weight\,(kg) \tag{2}$$

$$Plant\ PhytOC\ storage\ (kg/ha) = \frac{PhytOC\ concentration\ (g/kg) \times biomass\ (Mg/ha)}{10^3} \tag{3}$$

Data analysis

We conducted all statistical analyses utilizing Excel and SPSS (version 26.0). Pearson correlation analysis was employed to examine the associations among datasets. To discern the impact of phytoliths on PhytOC, one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test were implemented. The nonparametric Kolmogorov–Smirnov (K–S) test was executed in SPSS. Visualization of the data was achieved using ArcGIS (version 10.7), Excel, and Origin 2021.

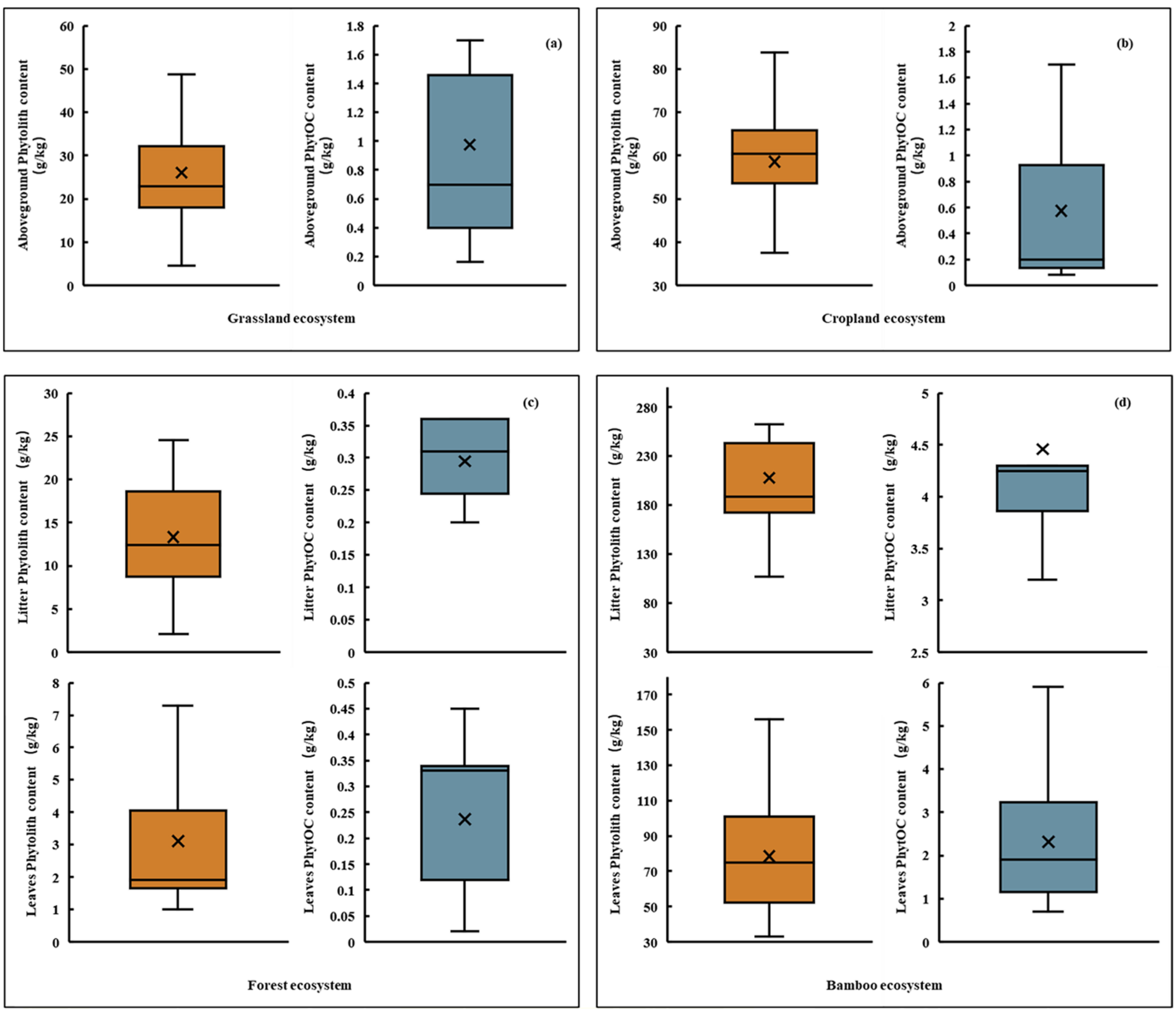

Fig. 2 The phytolith and PhytOC (carbon occluded in phytoliths) contents of vegetation in terrestrial ecosystems. **a**–**d** stand for grassland, cropland, forest, bamboo ecosystems, respectively. The line represents the median of the data, and the x represents the average of the data in the box plots

Results

Vegetation phytolith and PhytOC contents in terrestrial ecosystems

The phytolith content varied significantly among different ecosystems (Fig. 2). For aboveground vegetation, the phytolith content in grassland and cropland ecosystems were 26.024 ± 11.652 g kg^{-1} and 58.564 ± 15.616 g kg^{-1}, respectively. Correspondingly, their PhytOC content stood at 0.975 ± 0.821 g kg^{-1} for grassland and 0.529 ± 0.715 g kg^{-1} for cropland. For leaves in forest and bamboo ecosystems, the phytolith contents were 3.109 ± 2.312 g kg^{-1} and 78.567 ± 32.850 g kg^{-1}, respectively, with PhytOC content of 0.237 ± 0.155 g kg^{-1} for forest ecosystem and 2.319 ± 1.439 g kg^{-1} for bamboo ecosystem. When considering litter content, forest ecosystem recorded a phytolith content of 13.345 ± 7.411 g kg^{-1}, whereas bamboo ecosystem registered a notably higher value at 207.736 ± 72.039 g kg^{-1}. Their respective PhytOC contents were 0.295 ± 0.08 g kg^{-1} for forest ecosystem and 4.455 ± 1.301 g kg^{-1} for bamboo ecosystem.

Soil phytolith and PhytOC contents in terrestrial ecosystems

Soil phytolith content also varied in different ecosystems (Fig. 3). The phytolith content of 0–20, 20–40, 40–60 and 60–100 cm soils in grassland ecosystem was 19.214, 8.921, 8.047, and 11.765 g kg^{-1}, respectively. The phytolith content of 0–20, 20–40, 40–60 and 60–100 cm soil in cropland ecosystem was 13.375, 16.893, 15.987, and 13.397 g kg^{-1}, respectively. The phytolith content of 0–20, 20–40, 40–60 and 60–100 cm soil in forest ecosystem was 15.339, 10.944, 9.364, and 6.877 g kg^{-1}, respectively. The phytolith content in 0–20, 20–40, 40–60 and 60–100 cm soils of bamboo forest ecosystem was 24.549, 18.045, 15.053, and 13.315 g kg^{-1}, respectively. Among them, the soil phytolith content in forest ecosystem decreased with the increase of soil depth ($p < 0.05$), and the soil phytolith content in other three ecosystems did not change with soil depth. The phytolith content in soils from 0 to 20 cm in different ecosystems was significantly different ($p < 0.05$), with bamboo > grassland > forest > cropland.

The PhytOC content of 0–20, 20–40, 40–60 and 60–100 cm soil in grassland ecosystem was 0.422, 0.150, 0.152, and 0.288 g kg^{-1}, respectively. The PhytOC content of 0–20, 20–40, 40–60 and 60–100 cm soil in cropland ecosystem was 0.754, 0.957, 0.833, and 0.840 g kg^{-1}, respectively. The PhytOC content of 0–20, 20–40, 40–60 and 60–100 cm soil in forest ecosystem was 0.434, 0.172, 0.161, and 0.123 g kg^{-1}, respectively. The PhytOC content of 0–20, 20–40, 40–60, and 60–100 cm soil in bamboo forest ecosystem was 0.405, 0.302, 0.350, and 0.290 g kg^{-1}, respectively. The soil PhytOC content in different ecosystems was different ($p < 0.01$), and the soil PhytOC content in cropland ecosystem was higher than that in the other three ecosystems at different soil depths. Cropland ecosystem is the ecosystem with the highest PhytOC content in soil, which is more than twice that of other ecosystems. The soil PhytOC content in the forest ecosystem decreased with the increase of soil depth ($p < 0.01$), and the soil PhytOC content in the other three ecosystems did not change with the soil depth.

The correlation between phytolith and PhytOC content in vegetation and soil

Given the varied structures of different ecosystems, we segmented the aboveground phytolith and PhytOC contents. A significant distinction was observed in phytolith content between grassland and cropland ecosystems ($p < 0.001$). Specifically, the aboveground phytolith content in cropland surpassed that in grassland (Fig. 4). Conversely, the aboveground PhytOC content in cropland was

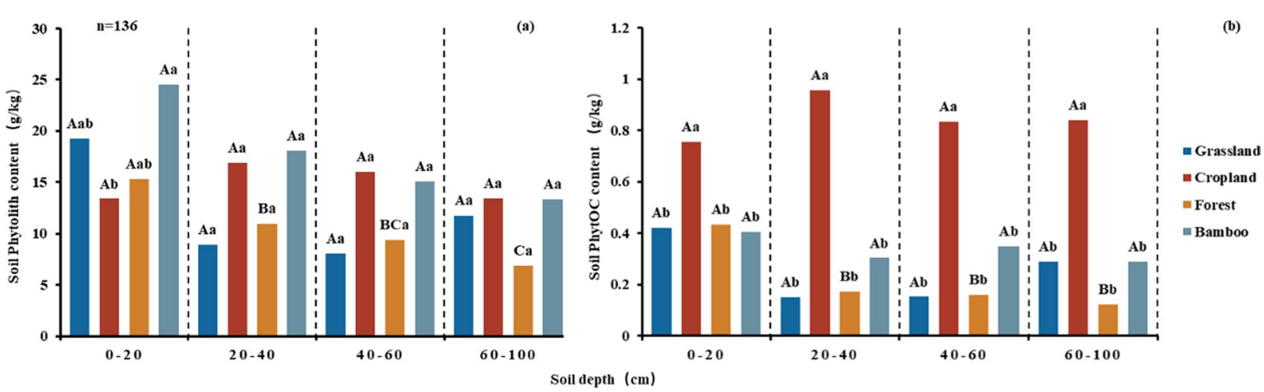

Fig. 3 Soil phytolith (**a**) and PhytOC (carbon occluded in phytoliths) (**b**) carbon content in terrestrial ecosystems. Capital letters represent differences between different soil depths in the same type of ecosystem, and lowercase letters represent differences between the same soil depths in different ecosystems

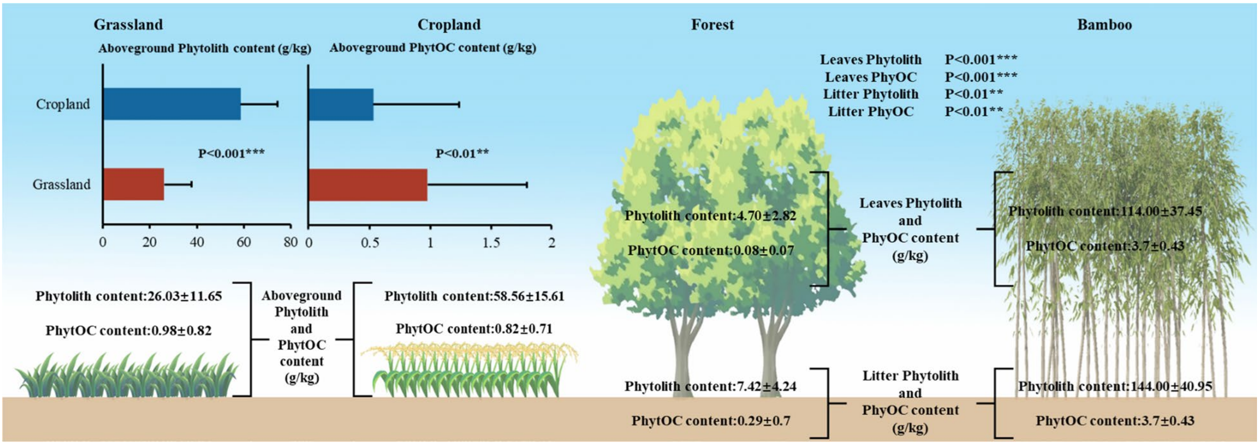

Fig. 4 Comparison of aboveground phytolith and PhytOC (carbon occluded in phytoliths) in different ecosystems. The bar chart represents the difference between cropland and grassland. *, ** and *** denote significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$ levels, respectively

less than in grassland ($p < 0.01$). Even though grassland exhibited a higher phytolith content in their aboveground sections, their carbon content remained inferior to that of cropland. The leaf phytolith contents in forest and bamboo ecosystems were strikingly different ($p < 0.001$), with bamboo leaves containing 24.25 times the phytoliths of forest leaves. Similarly, the PhytOC content in bamboo leaves was 46.25 times greater than in forest leaves. For litter (decomposed leaves and branches from forests), bamboo forests demonstrated significantly elevated phytolith and PhytOC contents compared to regular forests ($p < 0.05$), with values 20.57 and 12.75 times higher, respectively.

Due to the inherent structural differences among ecosystems, we categorized the aboveground phytolith content and PhytOC content into distinct sections. We observed a significant difference in the phytolith content between the grassland and cropland ecosystems ($p < 0.001$). Specifically, the phytolith content in the aboveground part of the cropland ecosystem exceeded that of the grassland (Fig. 4). Conversely, the PhytOC content in the aboveground part of the cropland ecosystem was notably lower than that in the grassland ($p < 0.01$). It is worth noting that while the aboveground part of the grassland ecosystem boasts a high phytolith content, its overall carbon content is comparatively lower than that of the cropland ecosystem. When considering the phytolith content of leaves within the forest and bamboo ecosystems, there was a marked difference ($p < 0.001$). Bamboo leaves presented a phytolith content

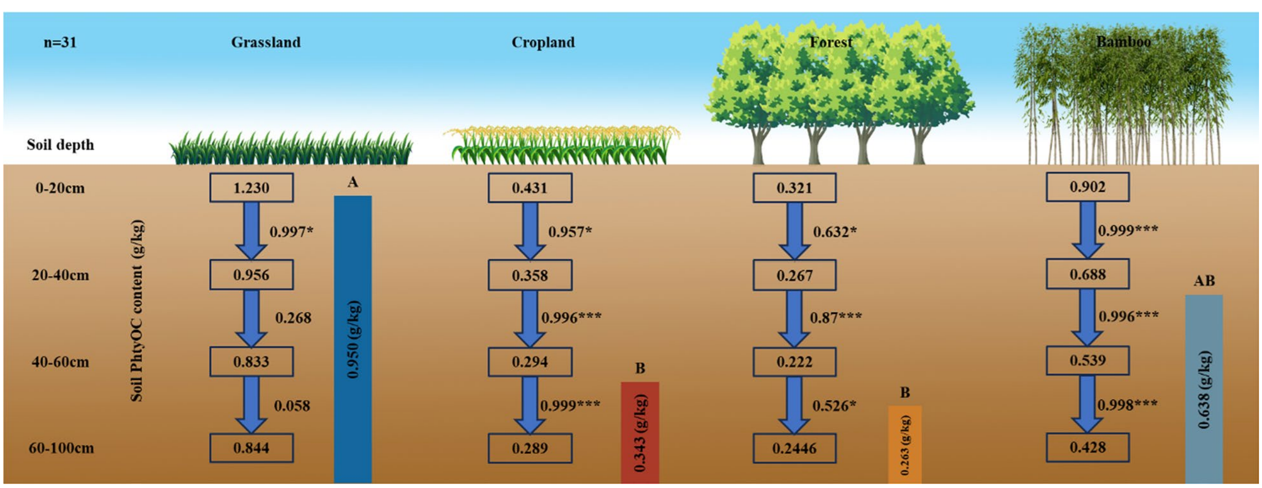

Fig. 5 Comparison of soil PhytOC (carbon occluded in phytoliths) in different ecosystems. The numerical values within each box denote PhytOC content across distinct soil layers. The histogram illustrates the cumulative PhytOC content for soil up to a depth of 100 cm in the given ecosystem. Uppercase letters signify disparities among groups, while values adjacent to the arrows provide the correlation coefficients for neighboring soil layers, *, ** and *** denote significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$ levels, respectively

that was 24.25 times that found in forest leaves. The PhytOC content in leaves demonstrated similar disparities ($p < 0.001$); bamboo leaves had a PhytOC content 46.25 times greater than that of forest leaves. Defining litter as the organic material originating from forest leaves and branches that have fallen and decomposed, we found that the bamboo forest ecosystem exhibited significantly higher phytolith and PhytOC contents in its litter than the forest ecosystem ($p < 0.05$). Specifically, the phytolith and PhytOC contents of litter in the bamboo forest ecosystem were 20.57 and 12.75 times greater than those in the forest ecosystem.

Significant variations were also detected in soil PhytOC contents across different ecosystems ($p < 0.05$). The PhytOC content in the grassland ecosystem, extending to a depth of 0–100 cm, was 0.95 g kg^{-1}, exceeding the content in the other three ecosystems (Fig. 5). Among all ecosystems, the grassland soil at 0–20 cm depth had the highest PhytOC content, boasting a correlation coefficient of 0.997 with the 20–40 cm layer. Nonetheless, as soil depth increased, the PhytOC content in adjacent grassland layers showed no correlation. In the cropland ecosystem, the soil layers of 0–20 cm to 60–100 cm exhibited strong PhytOC correlations, with coefficients of 0.957, 0.996, and 0.999. A similar pattern was found in the bamboo forest ecosystem, where the layers from 0–20 cm to 60–100 cm had correlation coefficients of 0.999, 0.996, and 0.998. In the forest ecosystem, while correlations existed between the 0–20 cm and 60–100 cm layers, they were weaker than in the bamboo forest and cropland ecosystems, with coefficients of 0.632, 0.87, and 0.526, respectively.

China's bamboo forest ecosystem vegetation PhytOC storage estimation

Based on the most recent 2021 data on Chinese bamboo forests (Feng and Li 2021), we calculated the PhytOC storage within Chinese bamboo ecosystem. We segmented the bamboo vegetation into two categories: Leaves and culms, using both PhytOC content and biomass content as metrics for our analysis (Cao et al. 2019; Feng and Li 2021; Additional file 1: Table S1). Our findings reveal that the PhytOC storage in the bamboo forest vegetation of China approximate 252.16 ± 41.65 kg/ha (Table 1). Significantly, bamboo leaves emerge as a substantial PhytOC storehouse, with storage amounting to roughly 205.50 ± 23.88 kg/ha. This represents a staggering 81.49% of the overall PhytOC storage. Conversely, the bamboo stems held PhytOC storage close to 46.66 ± 17.77 kg/ha.

Discussion

Differences in phytolith content of vegetation in terrestrial ecosystems

The total global production of phytoliths in terrestrial ecosystems is estimated to be around 2198 ± 993 Tg/yr^{-1} in dry opal weight (Song et al. 2017a). Within the grassland ecosystem, our findings show average phytolith and PhytOC contents of 26.024 ± 11.652 g kg^{-1} and 0.975 ± 0.821 g kg^{-1}, respectively. For the aboveground vegetation in cropland ecosystems, the values are 58.564 ± 15.616 g kg^{-1} and 0.529 ± 0.715 g kg^{-1}, aligning well with prior studies (Song et al. 2012; Zhao et al. 2016; Tan et al. 2021; Li et al. 2022). Notably, while grassland vegetation possesses lower phytolith content compared to cropland, its PhytOC content approaches 10%, positioning it as a significant global PhytOC reservoir. The global average aboveground PhytOC yield from grassland is 41.4×10^6 Mg CO_2 yr^{-1} (Song et al. 2012), surpassing that of cropland (Zuo and Lv 2011; Song et al. 2017a). Grassland and cropland, being the most widespread vegetation types globally, are pivotal to the worldwide storage of phytoliths in vegetation (Blecker et al. 2006; Song et al. 2017a). In comparing cropland to grassland, it is evident that while the phytolith content is higher in cropland, the PhytOC content is lower than that in grassland. This disparity might be attributed to the prevalent practices of intensive tillage and fertilization in cropland, impacting the absorption and accumulation of silicon by plants. Consequently, the formation of a stable carbon-wrapped structure in phytoliths may be hindered, resulting in carbon loss (Anala and Nambisan 2015; An and Xie 2022; Gu et al. 2013). Additionally, variations in the chemical properties and structure of soils in croplands compared to grasslands could influence the availability of silicon, consequently affecting plants' ability to absorb

Table 1 Carbon storage estimation of bamboo forests in China

	Phytolith content (g/kg)	PhyOC content (g/kg)	Total biomass (Mg)	PhytOC storage (kg/ha)
Leaves	114.00 ± 37.45	3.70 ± 0.43	0.51×10^8	205.50 ± 23.88
Culms	5.43 ± 2.68	0.84 ± 0.32	3.69×10^8	46.66 ± 17.77
Total	119.43 ± 40.13	4.54 ± 0.75	4.20×10^8	252.16 ± 41.65

The total biomass and area of bamboo forests in China came from Feng and Li (2021). The PhyOC represents carbon occluded in phytoliths silicon (Wu et al. 2014). Our research also found that the phytolith and PhytOC contents in forest leaves and litter are modest, consistent with findings from other studies (Song et al. 2013; Yang et al. 2018). Coniferous forests exhibit a limited phytolith carbon sink capacity, predominantly due to their low phytolith content (Song et al. 2013). In contrast, bamboo forests present notably high phytolith and PhytOC contents. Bamboo stands out as a prominent phytolith accumulator with a robust PhytOC fixation capability (Parr et al. 2010). The phytolith content of bamboo forest is higher, which is mainly concentrated in bamboo leaves (Mandlik et al. 2020). Bamboo leaves exhibit a phytolith content approximately 40 times higher than that found in leaves of other forests. However, while the litter produced by bamboo forests is about 13 times greater than that of other forests, the variance in phytolith content arises due to the complex nature of forest litter. Unlike bamboo forests where the litter primarily comprises leaves, forest litter encompasses a mix of components, including trunks, branches of various forest plants, and understory vegetation. This diverse composition contributes to a reduced phytolith content in the overall litter of the forest. Moreover, beyond vegetation type, factors such as climatic conditions, soil environment, and soil nutrients all influence the phytolith and PhytOC content in vegetation (Zhao et al. 2016; Huang et al. 2014; Yang et al. 2016; Song et al. 2017a; Zhang et al. 2020; Tan et al. 2021). Consequently, understanding the causes and mechanisms driving variations in phytolith and PhytOC content in vegetation has emerged as a focal point in phytolith research.

Soil phytolith and PhytOC changes in terrestrial ecosystems

Our study revealed that the bamboo forest soil exhibits the highest phytolith content, with the content in the 0–20 cm layer peaking at 2.45%. The decay of plants releases phytolith, with bamboo litter particularly rich in it, influencing soil phytolith. The proportions of phytolith and PhytOC content in soils vary across ecosystems. We attribute this variance to four factors: (1) Soil PhytOC largely depends on substantial litter input. Given the inherent properties of phytolith and external influences, there are variations in the carbon content and its sequestration potential (Pu et al. 2021). (2) The dissolution dynamics of soil phytolith differ across terrestrial ecosystems, influenced by alterations in soil phytolith's surface properties and elemental composition (Bartoli and Wilding 1980; Puppe and Leue 2018; Zhang et al. 2020). (3) Human interventions, like harvesting methods, affect litter input. In bamboo forests, only stalks are harvested, leaving phytolith-rich leaves behind. The manner of harvesting in cropland and forests contrasts with grassland grazing, impacting PhytOC input (Lu et al. 2002; Parr and Sullivan 2014; Song et al. 2012; Li et al. 2014). (4) Different plants and their organs vary in organic carbon content during phytolith formation. The capability of various plants' phytoliths to envelop organic carbon also differs. While the cropland ecosystem does not have the highest vegetation PhytOC content, its soil possesses the most PhytOC. This suggests cropland phytolith either contains more organic carbon or resists microbial decomposition better than in bamboo forests. This not only influences soil PhytOC content but also underscores the varied PhytOC content across plant types.

Analyzing PhytOC values across soil depths showed a decline in soil phytolith and PhytOC with increasing depth. In grassland, the correlation only extends to 40 cm, but in croplands, forests, and bamboo forests, it reaches 100 cm. Two reasons may explain this: (1) Environmental factors, decomposer community composition, and litter characteristics impact litter decomposition and PhytOC downward movement (Cornwell et al. 2008; Veen et al. 2015; Yang et al. 2021). (2) Human tillage influences PhytOC distribution in the soil, affecting its content and placement (Gao et al. 2017; Krauss et al. 2022; Zhao et al. 2022). The grassland cultivation is less, that impacting downward movement of PhytOC. Although Pan et al. (2017) suggested square grazing modifies grassland phytolith and PhytOC content, we posit that this mainly impacts the surface soil. The strong correlation between bamboo forests and cropland in the 0–100 cm layer indicates that land cultivation can influence downward movement of PhytOC. The weaker correlation in forest ecosystems might stem from our database lacking a distinction between plantation and natural forests, further suggesting cultivation's role in PhytOC movement.

Bamboo ecosystem PhytOC has great carbon sequestration capacity

Phytolith carbon sequestration offers substantial potential as a reliable method for biologically sequestering carbon. Bamboo ecosystem possess extensive phytolith storage, facilitating their stable storage of PhytOC (Song et al. 2013; Huang et al. 2014; Zhang et al. 2017; Liu et al. 2023). Our analysis of aboveground PhytOC indicates that bamboo forest vegetation exhibits robust carbon fixation capabilities. Contrarily, studies on gramineous plants' phytolith content have indicated a hierarchy: Oryzoideae > Bambusoideae > Panicoideae > Pooideae > Eragrostoideae (Jie et al. 2011). However, our findings demonstrate that the bamboo forest's phytolith and PhytOC content surpasses that of the cropland ecosystem, marking the bamboo forest as a paramount carbon sequestrator within terrestrial ecosystems. Bamboo forests are instrumental in addressing climate change and bolstering long-term carbon sinks. The phytolith content within a plant is contingent upon its silicon (Si) absorption capabilities. Typically, Si is absorbed by plant roots in the form of $Si(OH)_4$ via the transpiration stream (Ranganathan et al. 2006; Alexandre et al. 2011). The notably high phytolith content observed in bamboo forests primarily stems from the exceptional silicon absorption and accumulation abilities inherent in bamboo plants, attributable to their distinctive anatomical structure and physiological traits. Bamboo plants possess specialized roots and stems adept at deeper silicon uptake from the soil, while their stems efficiently transport and store silicon. Moreover, being predominantly C_4 photosynthetic plants, bamboos exhibit heightened photosynthetic efficiency, furnishing adequate energy to facilitate the absorption and accumulation of silicon. These collective attributes constitute the primary rationale behind the elevated phytolith content found in bamboo forests compared to other forest types (Tao et al. 2020). Furthermore, bamboo forest soil boasts high phytolith and PhytOC concentrations, primarily sourced from litter. Upon plant decomposition, both phytolith and PhytOC are sustainably retained in the soil (Parr and Sullivan 2005). This soil-based PhytOC serves as a crucial component of the enduring carbon pool in bamboo forests, reinforcing its significance for stable carbon sequestration. The rapid growth, robust regenerative capabilities, and substantial carbon sequestration potential of bamboo forests underscore their significant role in mitigating climate change, often underestimated (Song et al. 2017b). Ouyang et al. (2022) conducted estimations on the biomass of bamboo forests in China, revealing their substantial carbon sequestration capacity, notably highlighting the previously underestimated carbon sequestration potential of bamboo roots underground. The exceptional growth rate and expansive nature of bamboo forests further emphasize their critical significance as carbon sinks. Moreover, beyond their environmental role, bamboo forests serve as crucial sources of wood products, facilitating long-term carbon storage in these bamboo-derived items (Gu et al. 2019).

Deficiencies and prospects

Our investigation into phytoliths within vegetation was limited to the aboveground segments of grassland and cropland and the foliage of forests and bamboo groves, omitting phytolith content in roots and trunks. A scarcity of studies on phytoliths or PhytOC in plant roots and trunks potentially results in underestimations of the carbon sequestration potential of PhytOC in terrestrial settings. Large-scale soil phytolith research often overlooks the influence of environmental heterogeneity. Such heterogeneity can lead to phytolith content variance coefficients reaching up to 30% (Li et al. 2014; Liu et al. 2023). Furthermore, environmental factors can impact phytolith storage in extensive studies, introducing considerable uncertainty into large-scale PhytOC research (Ru et al. 2018).

While prevailing research has predominantly centered on forests, grasslands, croplands, and other ecosystems with minimal human interference, studies on urban ecosystems, especially street trees and landscape plants, remain scarce. Given the significant carbon footprint of

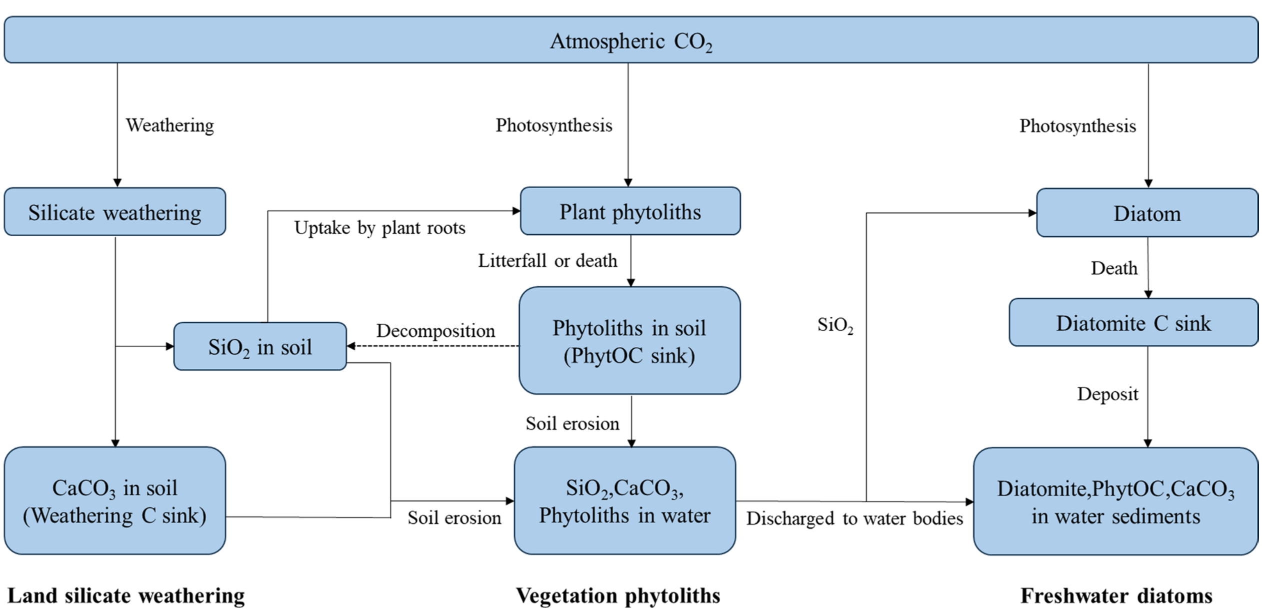

Fig. 6 Carbon sinks produced by silicate weathering, phytoliths, diatoms and their interaction. C represents carbon.

urban areas, examining the carbon sequestration potential of plants within these regions becomes paramount, offering insights for future landscape planning. Despite considerable attention to forests, there remains a gap in our understanding of phytolith distribution across different plant organs and species, necessitating further exploration. A myriad of estimates exists concerning phytolith content and its carbon sink capacity across various ecosystems. The current research pivot leans towards understanding phytolith storage responses to environmental factors, as highlighted by Hodson (2020) regarding future directions in phytolith carbon sequestration. It is essential to intensify studies on how diverse environmental factors influence phytolith carbon sequestration potential and delve deeper into the capabilities of various phytolith species and forms. Moreover, the role of Si—Earth's second most abundant element, which often interacts with carbon in myriad terrestrial biogeochemical processes—is underrepresented in ecosystem process models. This oversight is particularly evident concerning the phytolith-silicate weathering-diatoms interaction (Fig. 6). Therefore, future models should incorporate the Si cycle alongside C, N, and H_2O cycles, paying special attention to the intricate interplay of phytoliths, silicate weathering, and diatoms.

In our analysis of terrestrial ecosystems' phytolith and PhytOC within Asia, we deduced the following: (1) The bamboo forest ecosystem exhibited the highest phytolith and PhytOC contents within vegetation. For soil phytolith concentrations, the 0–100 cm depth in the bamboo forest ecosystem was paramount. However, when it came to the PhytOC levels within the 0–100 cm soil layer, the cropland ecosystem took precedence. It is evident that in cropland ecosystem, phytoliths have a higher propensity to encapsulate organic carbon and demonstrate increased resistance against microbial decomposition. (2) Human interventions undeniably influence the vertical movement of soil PhytOC, although the magnitude of this impact varies across ecosystems. Activities like grazing in grassland predominantly impact the 0–40 cm soil PhytOC depth. In contrast, practices like cutting and tillage in croplands, forests, and bamboo forests resonate more deeply, affecting the 0–100 cm soil PhytOC layer. (3) The carbon sequestration capability of bamboo forests has historically been underappreciated. These forests rank among the most potent carbon sequestration agents within terrestrial ecosystems, holding paramount significance for the broader ecosystem's carbon storage. Our carbon storage estimates for bamboo forest PhytOC vegetation have predominantly centered on aboveground parts. A more comprehensive exploration encompassing underground plant organs and deep soil PhytOC vegetation remains imperative.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-023-00476-3.

Additional file 1. Basic Database of phytolith and PhytOC in Terrestrial Ecosystems.

Acknowledgements

The authors thank Guomo Zhou for his guidance and help in topic selection and manuscript writing. The authors thank the scholars for their efforts in the study of PhytOC. We would like to thank the editors and anonymous reviewers for their valuable comments.

Author contributions

XC and GZ designed the study. XC, HL, and SL have collected literature and data. GZ, YS, PL, CL and YZ revised the manuscript. The paper was written by XC. All authors read and approved the final manuscript.

Funding

This research was funded by the Key Research and Development Program of Zhejiang Province (Grant Number: 2023C02003); the National Natural Science Foundation of China (Grant Number: 32001315; U1809208; 31870618); the Key Research and Development Program of Zhejiang Province (Grant Number: 2021C02005); the Scientific Research Development Fund of Zhejiang A&F University (Grant Number: 2020FR008); the Key Research and Development Pro-gram of Zhejiang Province (Grant Number: 2022C03039).

Availability of data and materials

Detailed data are in the attached Additional file 1: Table S1.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors agreed and approved the manuscript for publication in Ecological Processes.

Competing interests

The authors declare that they have no competing interests.

Received: 5 October 2023 Accepted: 8 December 2023
Published online: 20 December 2023

References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res Atmos 111:D05109. https://doi.org/10.1029/2005JD006290

Alexandre A, Bouvet M, Abbadie L (2011) The role of savannas in the terrestrial Si cycle: a case-study from Lamto, Ivory Coast. Glob Planet Change 78(3–4):162–169. https://doi.org/10.1016/j.gloplacha.2011.06.007

An X, Xie B (2022) Phytoliths from woody plants: a review. Diversity 14:339. https://doi.org/10.3390/d14050339

Anala R, Nambisan P (2015) Study of morphology and chemical composition of phytoliths on the surface of paddy straw. Paddy Water Environ 13(4):521–527. https://doi.org/10.1007/s10333-014-0468-5

Anjum M, Nagabovanalli PB (2021) Assessing production of phytolith and phytolith occluded carbon in above-ground biomass of intensively cultivated rice ecosystems in India. Carbon Manag 12(5):509–519. https://doi.org/10.1080/17583004.2021.1978552

Bartoli F, Wilding LP (1980) Dissolution of biogenic opal as a function of its physical and chemical properties. Soil Sci Soc Am J 44(4):873–878. https://doi.org/10.2136/sssaj1980.03615995004400040043x
Blecker SW, McCulley RL, Chadwick OA, Kelly EF (2006) Biologic cycling of silica across a grassland bioclimosequence. Global Biogeochem Cycles 20(3):GB3023. https://doi.org/10.1029/2006GB002690
Cao L, Coops NC, Sun Y, Ruan H, Wang G, Dai J, She G (2019) Estimating canopy structure and biomass in bamboo forests using airborne LiDAR data. ISPRS J Photogramm Remote Sens 148:114–129. https://doi.org/10.1016/j.isprsjprs.2018.12.006
Chen C, Huang Z, Jiang P, Chen J, Wu J (2018) Belowground phytolith-occluded carbon of monopodial bamboo in China: an overlooked carbon stock. Front Plant Sci 9:1615. https://doi.org/10.3389/fpls.2018.01615
Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC (2003) Global carbon sequestration in tidal, saline wetland soils. Glob Biogeochem Cycles 17:1111. https://doi.org/10.1029/2002gb001917
Conley DJ (2002) Terrestrial ecosystems and the global biogeochemical silica cycle. Glob Biogeochem Cycles 16:1121. https://doi.org/10.1029/2002gb001894
Cornwell WK, Cornelissen JHC, Amatangelo K, Dorrepaal E, Eviner VT, Godoy O, Hobbie SE, Hoorens B, Kurokawa H, Pérez-Harguindeguy N, Quested HM, Santiago LS, Wardle DA, Wright IJ, Aerts R, Allison SD, Van Bodegom P, Brovkin V, Chatain A, Westoby M (2008) Plant species traits are the predominant control on litter decomposition rates within biomes worldwide. Ecol Lett 11(10):1065–1071. https://doi.org/10.1111/j.1461-0248.2008.01219.x
Davamani V, Sangeetha Piriya R, Rakesh SS, Parameswari E, Paul Sebastian S, Kalaiselvi P, Maheswari M, Santhi R (2022) Phytolith-occluded carbon sequestration potential of oil palm plantation in Tamil Nadu. ACS Omega 7(3):2809–2820. https://doi.org/10.1021/acsomega.1c05592
Debnath N, Nath A, Sileshi GW, Nath AJ, Nandy S, Das AK (2023) Determinants of phytolith occluded carbon in bamboo stands across forest types in the eastern Indian Himalayas. Sci Total Environ 857:159568. https://doi.org/10.1016/j.scitotenv.2022.159568
Feng BF, Li YM (2021) China's bamboo resources in 2021. World Bamboo Ratt. https://doi.org/10.12168/sjzttx.2023.02.019
Gao L, Becker E, Liang G, Houssou AA, Wu H, Wu X, Cai D, Degré A (2017) Effect of different tillage systems on aggregate structure and inner distribution of organic carbon. Geoderma 288:97–104. https://doi.org/10.1016/j.geoderma.2016.11.005
Gu Y, Zhao Z, Pearsall DM (2013) Phytolith morphology research on wild and domesticated rice species in East Asia. Quatern Int 287:141–148. https://doi.org/10.1016/j.quaint.2012.02.013
Gu L, Zhou Y, Mei T, Zhou G, Xu L (2019) Carbon footprint analysis of bamboo scrimber flooring: implications for carbon sequestration of bamboo forests and its products. Forests 10:51. https://doi.org/10.3390/f10010051
Hodson MJ (2016) The development of phytoliths in plants and its influence on their chemistry and isotopic composition: implications for palaeoecology and archaeology. J Archaeol Sci 68:62–69. https://doi.org/10.1016/j.jas.2015.09.002
Hodson MJ (2019) The relative importance of cell wall and lumen phytoliths in carbon sequestration in soil: a hypothesis. Front Earth Sci 7:167. https://doi.org/10.3389/feart.2019.00167
Hodson MJ, Song Z, Ball TB, Elbaum R, Struyf E (2020) Editorial: frontiers in phytolith research. Front Plant Sci 11:454. https://doi.org/10.3389/fpls.2020.00454
Hsu JS, Powell J, Adler PB (2012) Sensitivity of mean annual primary production to precipitation. Glob Change Biol 18(7):2246–2255. https://doi.org/10.1111/j.1365-2486.2012.02687.x
Huang ZT, Li YF, Jiang PK, Chang SX, Song ZL, Liu J, Zhou GM (2014) Long-term intensive management increased carbon occluded in phytolith (PhytOC) in bamboo forest soils. Sci Rep 4:3602. https://doi.org/10.1038/srep03602
Huang C, Li Y, Wu J, Huang Z, Chang SX, Jiang P (2019) Intensive management increases phytolith-occluded carbon sequestration in Moso bamboo plantations in subtropical China. Forests 10:883. https://doi.org/10.3390/f10100883
Huang C, Wang L, Gong X, Huang Z, Zhou M, Li J, Wu J, Chang SX, Jiang P (2020) Silicon fertilizer and biochar effects on plant and soil PhytOC concentration and soil PhytOC stability and fractionation in subtropical bamboo plantations. Sci Total Environ 715:136846. https://doi.org/10.1016/j.scitotenv.2020.136846
Jie D, Liu H, Ge Y, Guo M, Li N (2011) Phytolith analysis: morphological characteristics of peatland plant species in Changbai Mountains. Quaternary Sci 31(1):163–170. https://doi.org/10.3969/j.issn.1001-7410.2011.01.20. **(in Chinese)**
Kaczorek D, Puppe D, Busse J, Sommer M (2019) Effects of phytolith distribution and characteristics on extractable silicon fractions in soils under different vegetation – An exploratory study on loess. Geoderma 356. https://doi.org/10.1016/j.geoderma.2019.113917
Krauss M, Wiesmeier M, Don A, Cuperus F, Gattinger A, Gruber S, Haagsma WK, Peigné J, Palazzoli MC, Schulz F, van der Heijden MGA, Vincent-Caboud L, Wittwer RA, Zikeli S, Steffens M (2022) Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. Soil Tillage Res 216:105262. https://doi.org/10.1016/j.still.2021.105262
Law BE, Harmon ME (2011) Forest sector carbon management, measurement and verification, and discussion of policy related to climate change. Carbon Manag 2:73–84. https://doi.org/10.4155/cmt.10.40
Li Z, Song Z, Parr JF, Wang H (2013) Occluded C in rice phytoliths: implications to biogeochemical carbon sequestration. Plant Soil 370(1–2):615–623. https://doi.org/10.1007/s11104-013-1661-9
Li Z, Song Z, Cornelis JT (2014) Impact of rice cultivar and organ on elemental composition of phytoliths and the release of bio-available silicon. Front Plant Sci 5:529. https://doi.org/10.3389/fpls.2014.00529
Li W, Tan L, Peng M, Chen H, Tan C, Zhao E, Zhang L, Peng H, Liang Y (2022) The spatial distribution of phytoliths and phytolith-occluded carbon in wheat (*Triticum aestivum* L.) ecosystem in China. Sci Total Environ 850:158005. https://doi.org/10.1016/j.scitotenv.2022.158005
Liu L, Jie D, Liu H, Li N, Guo J (2013) Response of phytoliths in *Phragmites communis* to humidity in NE China. Quatern Int 304:193–199. https://doi.org/10.1016/j.quaint.2013.03.020
Liu L, Chang SX, Huang C, Yu X, Zhi Y, Jiang P (2023) Controls for phytolith accumulation in Moso bamboo leaves across China. Sci Total Environ 893:164886. https://doi.org/10.1016/j.scitotenv.2023.164886
Lu H, Liu Z, Wu N, Berné S, Saito Y, Liu B, Wang L (2002) Rice domestication and climatic change: phytolith evidence from East China. Boreas 31(4):378–385. https://doi.org/10.1111/j.1502-3885.2002.tb01081.x
Maguire TJ, Templer PH, Battles JJ, Fulweiler RW (2017) Winter climate change and fine root biogenic silica in sugar maple trees (*Acer saccharum*): implications for silica in the Anthropocene. J Geophys Res Biogeosci 122(3):708–715. https://doi.org/10.1002/2016JG003755
Mandlik R, Thakral V, Raturi G, Shinde S, Nikolić M, Tripathi DK, Sonah H, Deshmukh R (2020) Significance of silicon uptake, transport, and deposition in plants. J Exp Bot 71(21):6703–6718. https://doi.org/10.1093/jxb/eraa301
Nadeau KC, Agache I, Jutel M, Annesi Maesano I, Akdis M, Sampath V, D'Amato G, Cecchi L, Traidl-Hoffmann C, Akdis CA (2022) Climate change: a call to action for the United Nations. Allergy 77:1087–1090. https://doi.org/10.1111/all.15079
Ouyang M, Yang C, Tian D, Pan J, Chen G, Su H, Yan Z, Ji C, Tang Z, Fang J (2022) A field-based estimation of moso bamboo forest biomass in China. For Ecol Manag 505:119885. https://doi.org/10.1016/j.foreco.2021.119885
Pan W, Song Z, Liu H, Müeller K, Yang X, Zhang X, Li Z, Liu X, Qiu S, Hao Q, Wang H (2017) Impact of grassland degradation on soil phytolith carbon sequestration in Inner Mongolian steppe of China. Geoderma 308:86–92. https://doi.org/10.1016/j.geoderma.2017.08.037
Parr JF, Sullivan LA (2005) Soil carbon sequestration in phytoliths. Soil Biol Biochem 37(1):117–124. https://doi.org/10.1016/j.soilbio.2004.06.013
Parr JF, Sullivan LA (2014) Comparison of two methods for the isolation of phytolith occluded carbon from plant material. Plant Soil 374(1–2):45–53. https://doi.org/10.1007/s11104-013-1847-1
Parr J, Sullivan L, Chen B, Ye G, Zheng W (2010) Carbon bio-sequestration within the phytoliths of economic bamboo species. Glob Change Biol 16(10):2661–2667. https://doi.org/10.1111/j.1365-2486.2009.02118.x
Pu Y, Wang D, Li M, Zhang S, Li Y, Li T, Wang G, Yuan D, Jia Y, Xu X (2021) Effects of alpine marsh degradation on soil phytoliths and phytolith-occluded carbon on the Zoige Plateau, China. J Soils Sediments 21:1730–1742. https://doi.org/10.1007/s11368-021-02898-y
Puppe D, Leue M (2018) Physicochemical surface properties of different biogenic silicon structures: results from spectroscopic and microscopic analyses of protistic and phytogenic silica. Geoderma 330:212–220. https://doi.org/10.1016/j.geoderma.2018.06.001

Ranganathan S, Suvarchala V, Rajesh YBRD, Srinivasa Prasad M, Padmakumari AP, Voleti SR (2006) Effects of silicon sources on its deposition, chlorophyll content, and disease and pest resistance in rice. Biol Plant 50:713–716
Rogers K, Kelleway JJ, Saintilan N, Megonigal JP, Adams JB, Holmquist JR, Lu M, Schile-Beers L, Zawadzki A, Mazumder D, Woodroffe CD (2019) Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature 567(7746):91–95. https://doi.org/10.1038/s41586-019-0951-7
Ru N, Yang X, Song Z, Liu H, Hao Q, Liu X, Wu X (2018) Phytoliths and phytolith carbon occlusion in aboveground vegetation of sandy grasslands in eastern Inner Mongolia, China. Sci Total Environ 625:1283–1289. https://doi.org/10.1016/j.scitotenv.2018.01.055
Song Z, Liu H, Si Y, Yin Y (2012) The production of phytoliths in China's grasslands: Implications to the biogeochemical sequestration of atmospheric CO_2. Glob Change Biol 18(12):3647–3653. https://doi.org/10.1111/gcb.12017
Song Z, Liu H, Li B, Yang X (2013) The production of phytolith-occluded carbon in China's forests: Implications to biogeochemical carbon sequestration. Glob Change Biol 19(9):2907–2915. https://doi.org/10.1111/gcb.12275
Song A, Ning D, Fan F, Li Z, Provance-Bowley M, Liang Y (2015) The potential for carbon bio-sequestration in China's paddy rice (*Oryza sativa* L.) as impacted by slag-based silicate fertilizer. Sci Rep 5:17354. https://doi.org/10.1038/srep17354
Song X, Chen X, Zhou G, Jiang H, Peng C (2017a) Observed high and persistent carbon uptake by Moso bamboo forests and its response to environmental drivers. Agric For Meteorol 247:467–475. https://doi.org/10.1016/j.agrformet.2017.09.001
Song Z, Liu H, Strömberg CAE, Yang X, Zhang X (2017b) Phytolith carbon sequestration in global terrestrial biomes. Sci Total Environ 603–604:502–509. https://doi.org/10.1016/j.scitotenv.2017.06.107
Tan L, Fan X, Yan G, Peng M, Zhang N, Ye M, Gao Z, Song A, Nikolic M, Liang Y (2021) Sequestration potential of phytolith occluded carbon in China's paddy rice (*Oryza sativa* L.) systems. Sci Total Environ 774:145696. https://doi.org/10.1016/j.scitotenv.2021.145696
Tang X, Zhao X, Bai Y, Tang Z, Wang W, Zhao Y, Wan H, Xie Z, Shi X, Wu B, Wang G, Yan J, Ma K, Du S, Li S, Han S, Ma Y, Hu H, He N, Zhou G (2018a) Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey. Proc Natl Acad Sci USA 115(16):4021–4026. https://doi.org/10.1073/pnas.1700291115
Tao X, Wen M, Li R, Vachula R, Pang L, Li C, Yang K, Jiang N (2020) Phytolith sizes and assemblages differentiate genera and ecotypes of woody bamboos in subtropical Southwest China. Rev Palaeobot Palynol 2020:104129. https://doi.org/10.1016/j.revpalbo.2019.104129
Veen GF, Sundqvist MK, Wardle DA (2015) Environmental factors and traits that drive plant litter decomposition do not determine home-field advantage effects. Funct Ecol 29(7):981–991. https://doi.org/10.1111/1365-2435.12421
Wu Y, Yang Y, Wang H, Wang C (2014) The effects of chemical composition and distribution on the preservation of phytolith morphology. Appl Phys A Mater Sci Process 114(2):503–507. https://doi.org/10.1007/s00339-013-7616-4
Yang J, Wu J, Jiang P, Xu Q, Zhao P, He S (2015) A study of phytolith-occluded carbon stock in monopodial bamboo in China. Sci Rep 5:13292. https://doi.org/10.1038/srep13292
Yang X, Song Z, Sullivan L, Wang H, Li Z, Li Y, Zhang F (2016) Topographic control on phytolith carbon sequestration in moso bamboo (*Phyllostachys pubescens*) ecosystems. Carbon Manag 7(1–2):105–112. https://doi.org/10.1080/17583004.2016.1178398
Yang X, Song Z, Liu H, Van Zwieten L, Song A, Li Z, Hao Q, Zhang X, Wang H (2018) Phytolith accumulation in broadleaf and conifer forests of northern China: implications for phytolith carbon sequestration. Geoderma 312:36–44. https://doi.org/10.1016/j.geoderma.2017.10.005
Yang S, Hao Q, Wang H, Van Zwieten L, Yu C, Liu T, Yang X, Zhang X, Song Z (2020) A review of carbon isotopes of phytoliths: implications for phytolith-occluded carbon sources. J Soils Sediments 20(4):1811–1823. https://doi.org/10.1007/s11368-019-02548-4
Yang X, Wang X, Xiao S, Liu Z, Zhou X, Du G, Liu K, Wang Y, Chen S, Nielsen UN (2021) Dominant plants affect litter decomposition mainly through modifications of the soil microbial community. Soil Biol Biochem 161:108399. https://doi.org/10.1016/j.soilbio.2021.108399
Zhang X, Song Z, Zhao Z, Van Zwieten L, Li J, Liu L, Xu S, Wang H (2017) Impact of climate and lithology on soil phytolith-occluded carbon accumulation in eastern China. J Soils Sediments 17(2):481–490. https://doi.org/10.1007/s11368-016-1527-x
Zhang X, Song Z, Hao Q, Yu C, Liu H, Chen C, Müller K, Wang H (2020) Storage of soil phytoliths and phytolith-occluded carbon along a precipitation gradient in grasslands of northern China. Geoderma 364:114200. https://doi.org/10.1016/j.geoderma.2020.114200
Zhao Y, Song Z, Xu X, Liu H, Wu X, Li Z, Guo F, Pan W (2016) Nitrogen application increases phytolith carbon sequestration in degraded grasslands of North China. Ecol Res 31(1):117–123. https://doi.org/10.1007/s11284-015-1320-0
Zhao H, Qin J, Gao T, Zhang M, Sun H, Zhu S, Xu C, Ning T (2022) Immediate and long-term effects of tillage practices with crop residue on soil water and organic carbon storage changes under a wheat-maize cropping system. Soil Tillage Res 218:105309. https://doi.org/10.1016/j.still.2021.105309
Zhao Y, Song Z, Xu X, Liu H, Wu X, Li Z, Guo F, Pan W (2016) Nitrogen application increases phytolith carbon sequestration in degraded grasslands of North China. Ecol Res 31(1):117–123. https://doi.org/10.1007/s11284-015-1320-0
Zuo XX, Lü HY (2011) Carbon sequestration within millet phytoliths from dry-farming of crops in China. Chin Sci Bull 56(32):3451–3456. https://doi.org/10.1007/s11434-011-4674-x
Zuo XX, Lu HY, Gu ZY (2014) Distribution of soil phytolith-occluded carbon in the Chinese Loess Plateau and its implications for silica-carbon cycles. Plant Soil 374(1–2):223–232. https://doi.org/10.1007/s11104-013-1850-6
Zuo X, Lu H, Jiang L, Zhang J, Yang X, Huan X, He K, Wang C, Wu N (2017) Dating rice remains through phytolith carbon-14 study reveals domestication at the beginning of the Holocene. Proc Natl Acad Sci USA 114(25):6486–6491. https://doi.org/10.1073/pnas.1704304114

Publisher's Note