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# Enhancing phytolith carbon sequestration in rice ecosystems through basalt powder amendment

**Fengshan Guo · Zhaoliang Song · Leigh Sullivan · Hailong Wang · Xueyan Liu · Xudong Wang · Zimin Li · Yuying Zhao**

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**Abstract** Global warming as a result of rapid increase in atmospheric $CO_2$ emission is significantly influencing world's economy and human activities. Carbon sequestration in phytoliths is regarded as a highly stable carbon sink mechanism in terrestrial ecosystems to mitigate climate change. However, the response of plant phytolith-occluded carbon (PhytOC) to external silicon amendments remains unclear. In this study, we investigated the effects of basalt powder (BP) amendment on phytolith carbon sequestration in rice (*Oryza sativa*), a high-PhytOC accumulator. The results showed that the contents of phytolith and PhytOC in rice increased with BP amendment. The PhytOC production flux in different rice plant parts varied considerably (0.005–0.041 Mg $CO_2$ $ha^{-1}$ $a^{-1}$), with the highest flux in the sheath. BP amendment can significantly enhance flux of phytolith carbon sequestration in croplands by 150 %. If the global rice cultivation of $1.55 \times 10^8$ ha had a similar flux of PhytOC production in this study, $0.61 \times 10^7$ to $1.54 \times 10^7$ Mg $CO_2$ would be occluded annually within global rice phytoliths. These findings highlight that external silicon amendment such as BP amendment represents an effective potential management tool to increase long-term biogeochemical carbon sequestration in crops such as rice and may also be an efficient way to mitigate the global warming indirectly.

**Keywords** Phytolith · Carbon sink · Carbon sequestration · Basalt powder amendment · Rice

SPECIAL TOPIC: Land-ocean integrated research and development of carbon sink

F. Guo · Z. Song (✉) · H. Wang · X. Wang · Z. Li · Y. Zhao
School of Environment and Resources, Zhejiang Agricultural and Forestry University, Lin'an 311300, China
e-mail: songzhaoliang78@163.com

Z. Song · X. Liu
State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China

L. Sullivan
Southern Cross GeoScience, Southern Cross University, Lismore, NSW 2480, Australia

Z. Li
Soil Science and Environment Geochemistry, Earth and Life Institute, Université Catholique de Louvain, Croix du Sud 2/L7.05.10, 1348 Louvain-la-Neuve, Belgium

## 1 Introduction

The increase of global $CO_2$ emissions has become an increasingly urgent environmental problem as it may cause climate warming [1–4]. Carbon sequestration in terrestrial ecosystems has been considered as an important process to mitigate global climate warming [5–8]. However, some organic carbon temporarily fixed in terrestrial vegetation will be rapidly oxidized into $CO_2$ and dissolved into water to form water-soluble organic carbon after plant litter decomposition. Therefore, long-time biogeochemical carbon sequestration mechanisms in terrestrial ecosystems remain to be investigated.

Phytoliths, also known as plant opals, are amorphous silica deposited in plant tissues during plant growth [9–11]. Phytoliths are found in most plant species, and their content varies greatly, mostly 0.3 %–12 % [10–16]. Generally, phytolith content in Poaceae and Cyperaceae is much higher than that in other plants [17]. Some organic carbon may be occluded within phytoliths as a result of phytolith formation during plant growth, and the carbon content of phytoliths ranges 0.5 %–6 % [7, 15, 16, 18–21]. Although the annual phytolith carbon sequestration was small relative to the terrestrial vegetation carbon sequestration [22, 23], phytolith-occluded carbon (PhytOC) may be preserved in soils for several thousand years when dead plant materials decompose and the phytoliths are released into the soil [9, 24]. In some soils and sediments after 2,000 years of PhytOC accumulation, PhytOC can even represent up to 82 % of the total organic carbon [9, 15]. Therefore, the potential of phytolith carbon sequestration in soil–plant ecosystems is significant and stable at century time scales.

Cereals (e.g., rice, wheat and maize) and other Si-rich crops (e.g., sugarcane) [18] can produce a large amount of PhytOC and may play a crucial role in the long-term terrestrial carbon sequestration [9, 15, 19, 25–27]. For example, Song et al. [26] indicated that the potential of phytolith carbon sink in the global cropland was 2.6 ($\pm$1.0) $\times$ $10^7$ Mg $a^{-1}$ that may represent about 22 % to 58 % of the global net carbon sequestration in crop soil during 1961–2100. Recent researches on phytolith carbon sequestration in crops mainly focused on sugarcane [18], millet [21], wheat [19] and rice [15], based on analytical data of phytolith and PhytOC contents. For example, Li et al. [15] indicated that PhytOC content in biomass depends not only on the C content of phytoliths but also on phytolith content, implying that external silicon (Si) amendment may also improve PhytOC production through enhancing phytolith production during growth of crops, especially rice. Basalt is widely distributed in the world. Although the content of total $SiO_2$ is lower, minerals such as augite and anorthose in basalt are more abundant and more rapidly weathered, releasing more dissolved silicon than other igneous rocks (such as granite). Although mulching organic matter (e.g., rice straw) has been suggested to increase soil PhytOC accumulation in bamboo forests [28], the total amount of PhytOC does not increase and the regulation mechanisms of phytolith carbon sink through external silicon amendment have not been demonstrated. The objective of this study is to investigate the response of rice phytolith carbon sequestration to basalt powder amendment, to offer references for management of phytolith carbon sequestration in agricultural ecosystems.

## 2 Materials and methods

The pot experiment was carried out at Zhejiang Agricultural and Forestry University, Lin'an, Zhejiang Province, eastern China (29°56′–30°27′N, 118°51′–119°52′E), during April to July, 2012. The site has a subtropical and monsoonal climate, with a mean annual precipitation of 1,000–2,000 mm and a mean annual temperature of 15.8 °C. There are 234 frost-free days.

### 2.1 Pot experiment

Fresh basalt was sampled from Xinchang County, Zhejiang Province, in July 2011 (29°28′N, 120°59′E). The basalt consists of $SiO_2$ 48.15 % $\pm$ 2.84 %, $Al_2O_3$ 13.53 % $\pm$ 0.48 %, $Fe_2O_3$ 13.59 % $\pm$ 1.23 %, $P_2O_5$ 0.61 % $\pm$ 0.42 %, $K_2O$ 1.31 % $\pm$ 0.17 %, CaO 8.48 % $\pm$ 0.71 % and MgO 6.53 % $\pm$ 1.36 %. Basalt blocks were crushed by hammer and machine, and then passed through a 0.85-mm mesh stainless steel sieve. The experimental soil (Gleysols) was taken from a paddy field of an agricultural testing base of Zhejiang Agricultural and Forestry University. The basic physical and chemical properties of the soil were as follows: pH 5.34 $\pm$ 0.02, soil organic matter 30.26 $\pm$ 4.28 g $kg^{-1}$, available Si (silicon that could be easily absorbed and utilized by plant) 155.59 $\pm$ 22.73 g $kg^{-1}$, available phosphorus (phosphorus that could be easily absorbed and utilized by plant) 113.87 $\pm$ 1.35 mg $kg^{-1}$, available potassium 10.33 $\pm$ 1.11 mg $kg^{-1}$ and available nitrogen 87.15 $\pm$ 2.47 mg $kg^{-1}$. The analytical methods were after Lu [29].

Jiayu 253, a widely distributed and high yielding rice (*Oryza sativa*) cultivar, was selected in this study. BP amendment was applied at levels of 0 (non-amendment control), 50, 100, 250 and 500 g $pot^{-1}$ (CK-0, CK-1, CK-2, CK-3 and CK-4, respectively) with three replicates. Each pot had a diameter of 0.24 m and a height of 0.28 m. Each pot contained 8.5 kg soil, and rice was grown in each pot under the same irrigation condition and accurate fertilizer control.

### 2.2 Sample collection and analysis

Plant and surface soil (0–10 cm) samples were collected after 102 days on 26 July, 2012. Soil was removed from the roots. Plant samples were divided into sheath, leaf, flag leaf and stem. Rice samples were washed three times with distilled water, three times with deionized water and oven-dried at 75 °C to a constant weight. Finally, each rice tissue sample was divided into two subsamples: one subsample was ground thoroughly for analysis of rice Si content and the other subsample was cut into small fragments (<5 mm) for the extraction of phytoliths [15].

The analysis of Si content in plant and soil samples was described by Song et al. [11] and Li et al. [15]. Microwave digestion [30] in combination with Walkley-Black digestion [31] was used to extract phytoliths from all rice samples. The purity of phytoliths was checked using the method of Li et al. [15]. The extracted phytoliths were thoroughly dried at 75 °C for 24 h and weighed to obtain the phytolith content of samples. The phytolith sample was dissolved in solution with HF (1 mol $L^{-1}$) at 60 °C for 60 min, and the released carbon was determined using the traditional potassium dichromate method [15, 16, 29]. The carbon data were monitored with standard soil samples of GBW07405 [15]. Precision was <7 % for measurement of C content in phytoliths [10, 15].

### 2.3 Statistical methods

The PhytOC content of the organs (mg $g^{-1}$) was calculated using the following equation [32]:

$$\text{PhytOC content of organs} = \text{Phytolith content} \times \text{C content of phytoliths}/1000, \tag{1}$$

where phytolith content represents the weight of phytolith in unit organ (mg $g^{-1}$) and C content of phytoliths represents the weight of carbon in unit phytolith (mg $g^{-1}$).

PhytOC production flux for rice can be estimated from the data of PhytOC content of organs and the aboveground net primary production of rice organs (ANPP, in Mg $ha^{-1}$ $a^{-1}$) as [11, 32]

$$\text{PhytOC production flux} = \text{PhytOC content of organs} \times \text{ANPP} \times 44/12, \tag{2}$$

where PhytOC production flux is the sum of the PhytOC production from rice organs (not including grain and root) (Mg $CO_2$ $ha^{-1}$ $a^{-1}$). The PhytOC content of organs (mg $g^{-1}$) can be estimated from Eq. (1).

PhytOC production rate can be estimated from data of PhytOC production flux and rice area as

$$\text{PhytOC production rate} = \text{PhytOC content flux} \times \text{area}, \tag{3}$$

where PhytOC production rate is total PhytOC production by rice per year (Mg $CO_2$ $a^{-1}$); PhytOC content flux can be estimated from Eq. (2), and area (ha) is the area of rice production.

The data used for these estimates were the means of the three replicates. Analysis of variance (ANOVA) was applied to compare the different effect of treatments. Duncan's multiple range test (using SPSS 15.0) was used to analyze the rice sample data to determine the significance of difference.

## 3 Results

The dry biomass of rice increased from 162.2 to 257.6 g $pot^{-1}$ with BP amendment. BP amendment increased the phytolith content of each organ, and the increase was clearly related to increasing BP amendment rates (Table 1). The phytolith content in all organs varied significantly from 5 to 37 mg $g^{-1}$ (Table 1) ($P < 0.05$). Generally, the phytolith content in leaf was the highest, ranging 27–37 mg $g^{-1}$ with an average of 32 mg $g^{-1}$. The BP amendment had a significant impact on the C content of phytoliths, which varied significantly in the range of 12–31 mg $g^{-1}$. The C content of phytoliths in flag leaf was the highest with an average of 28 mg $g^{-1}$. The PhytOC contents in the different rice organs for different treatments varied significantly ($P < 0.05$) in the range of 0.10–0.74 mg $g^{-1}$. The highest PhytOC content was in flag leaf, ranging 0.34–0.74 mg $g^{-1}$ with a mean of 0.60 mg $g^{-1}$. The BP amendment clearly increased the flux of PhytOC production in all organs from 0.005 to 0.041 Mg $CO_2$ $ha^{-1}$ $a^{-1}$. The highest increase of PhytOC production flux was in CK-3 and CK-4 treatments. The flux of PhytOC production in the sheath (0.019–0.041 Mg $CO_2$ $ha^{-1}$ $a^{-1}$) was generally much higher than that of other organs.

## 4 Discussion

### 4.1 Effects of BP amendment on rice phytolith carbon sequestration

Previous studies have revealed that the contents of $SiO_2$ and phytoliths of cultivated rice can be increased considerably by supplying Si nutrition (e.g., straw biochar, slag mucks and Si fertilizers) [15, 26, 33–38]. Chemical weathering of primary minerals in basalt powder (BP) may release dissolved silicon [38]. The processes of basalt crushing and rice silicon uptake may enhance chemical weathering of primary silicate minerals in basalt and accelerate the release of dissolved silicon [10, 39]. In addition, Song et al. [10] indicated that plant's growth and their relevant microorganism community can further enhance silicate weathering processes through excreting root exudates. Therefore, it is promising to increase rice Si absorption and phytolith content through BP amendment.

The strong positive relationship ($R^2 = 0.664$–$0.9646$, $P < 0.05$) between the $SiO_2$ content and phytolith contents in all rice organs (Fig. 1a) and the much higher phytolith contents in rice organs with BP amendment than that of the control (Table 1; Figs. 2, 3) support the above hypothesis that BP amendment can enhance phytolith production through increasing Si supply and rice Si uptake though many other factors (e.g., varieties, location, disease resistance and fertilizer requirements) may also influence plant phytolith content [15, 19, 21, 35, 40, 41].

The strong positive correlations between the PhytOC content of organs and the phytolith content ($R^2 = 0.5358$–$0.9829$, $P < 0.05$) (Fig. 1b) and between the Phy-

**Table 1** The contents of phytolith, PhytOC and $SiO_2$ content of organs, and C content of phytoliths in organs for rice amended with BP

| Rice organs | Treatments [a] | Phytolith contents Mean (SD) (mg $g^{-1}$) | C content of phytoliths Mean (SD) (mg $g^{-1}$) | PhytOC content of organs Mean (SD) (mg $g^{-1}$) | $SiO_2$ content Mean (SD) (mg $g^{-1}$) |
|---|---|---|---|---|---|
| Sheath | CK-0 | 26.19 (1.69) | 19.94 (0.12) | 0.52 (0.02) | 31.25 (0.38) |
| | CK-1 | 28.93 (2.98) | 19.60 (1.99) | 0.56 (0.02) | 33.31 (1.78) |
| | CK-2 | 28.76 (3.40) | 19.12 (1.83) | 0.56 (0.02) | 35.16 (1.12) |
| | CK-3 | 31.89 (2.69) | 22.80 (0.29) | 0.73 (0.08) | 35.57 (1.35) |
| | CK-4 | 33.70 (2.66) | 18.68 (0.34) | 0.63 (0.03) | 34.92 (1.27) |
| Leaf | CK-0 | 26.85 (0.06) | 15.52 (1.04) | 0.42 (0.04) | 34.48 (1.10) |
| | CK-1 | 29.50 (0.10) | 14.04 (1.52) | 0.41 (0.06) | 38.27 (4.33) |
| | CK-2 | 31.52 (0.44) | 15.31 (0.28) | 0.48 (0.02) | 40.14 (0.10) |
| | CK-3 | 37.12 (2.69) | 13.60 (1.29) | 0.50 (0.17) | 47.28 (3.00) |
| | CK-4 | 36.90 (0.12) | 12.37 (1.44) | 0.46 (0.11) | 44.51 (0.85) |
| Flag leaf | CK-0 | 13.70 (2.40) | 22.94 (1.35) | 0.34 (0.06) | 27.11 (1.22) |
| | CK-1 | 18.10 (1.56) | 27.39 (1.44) | 0.50 (0.08) | 33.76 (2.23) |
| | CK-2 | 22.55 (5.10) | 30.54 (1.75) | 0.68 (0.10) | 35.37 (4.91) |
| | CK-3 | 25.10 (0.41) | 29.63 (0.63) | 0.74 (0.08) | 37.88 (2.19) |
| | CK-4 | 25.61 (4.56) | 28.83 (3.07) | 0.73 (0.02) | 37.94 (3.36) |
| Stem | CK-0 | 5.20 (0.85) | 19.19 (2.23) | 0.10 (0.00) | 6.97 (1.13) |
| | CK-1 | 6.50 (0.71) | 23.21 (2.80) | 0.16 (0.01) | 10.46 (0.47) |
| | CK-2 | 8.89 (2.40) | 19.24 (0.75) | 0.17 (0.04) | 9.57 (0.54) |
| | CK-3 | 8.20 (0.28) | 21.55 (3.77) | 0.18 (0.06) | 10.75 (0.25) |
| | CK-4 | 11.29 (4.09) | 26.07 (1.14) | 0.30 (0.12) | 13.39 (2.17) |

[a] BP amendment was applied at 0 (non-amendment control), 50, 100, 250 and 500 g $pot^{-1}$ (CK-0, CK-1, CK-2, CK-3 and CK-4, respectively) with three replicates

tOC content of organs and the C content of phytoliths ($R^2 = 0.5245–0.7994$, $P < 0.05$) (Fig. 1c) imply that PhytOC content of organs depends not only on the C content of phytoliths but also on phytolith content. The study of Li et al. [15] also supported the findings of this study.

Considering the complex situation of afforestation, reforestation (e.g., bamboo with high PhytOC content) [7, 26, 42], land use change, location, climatic conditions [7, 15] and the wide variety of crop attributes (e.g., yield, quality, disease resistance, etc.) that are valued by land managers, it is unlikely that crops will be selected solely on the basis of their C content of phytoliths to improve the production flux of PhytOC [15]. Thus, silicon fertilization might be an alternative way to enhance the production flux of PhytOC in crop ecosystems. Recent researches [15, 26] have revealed the possibility to enhance the PhytOC content in crops by regulating silicon nutrient. The rice PhytOC production flux in this study showed an increasing trend under the different BP amendment treatments (Fig. 3), and this trend was much stronger for sheaths than for the other organs, further demonstrating that it is promising to improve the PhytOC content of organ dry biomass in rice by BP amendment, an external silicon amendment.

## 4.2 Potential of phytolith carbon sequestration in rice and other crop: at a national and global scale

Compared to the annual organic carbon sequestration in terrestrial vegetation [22, 23], the quantity of phytolith carbon sequestration is small. However, the potential and ability of phytolith carbon sequestration are significant at a century time scale because PhytOC is highly resistant against decomposition, and may be preserved stably in soils for several thousand years when dead plant materials decompose and the phytoliths are released into the soil [9, 24].

Based on Eqs. (2) and (3) and the yields (for double rice cropping systems) of rice biomass with the different BP amendment rates, this study estimates that BP amendment can enhance the fluxes of PhytOC production in rice from 0.04 to 0.10 Mg $CO_2$ $ha^{-1}$ $a^{-1}$ (Fig. 3) ($P < 0.05$). Using the rice planting area of China in 2012 ($2.96 \times 10^7$ ha) [15] and rice PhytOC production flux, the rates of PhytOC production with BP amendment (CK-0 to CK-4) increased significantly from $0.12 \times 10^7$ to $0.29 \times 10^7$ Mg $CO_2$ $a^{-1}$. If the global rice plantation of $1.55 \times 10^8$ ha had a similar flux of PhytOC production in the present study, $0.61 \times 10^7$ to $1.54 \times 10^7$ Mg $CO_2$ could be occluded annually within phytoliths in global rice ecosystems, being equivalent to

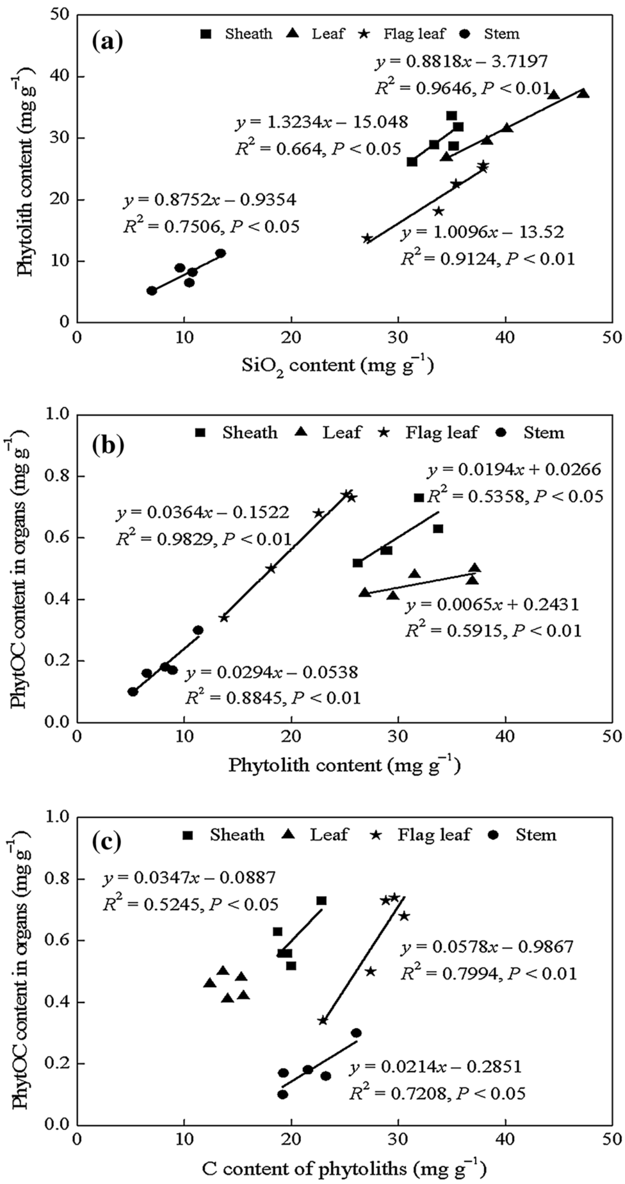


**Fig. 1** Correlations of (**a**) $SiO_2$ content with phytolith content of organs, (**b**) PhytOC content of organs with phytolith content of rice organs, (**c**) PhytOC content of organs with the C content of phytoliths of organs in rice amended with BP

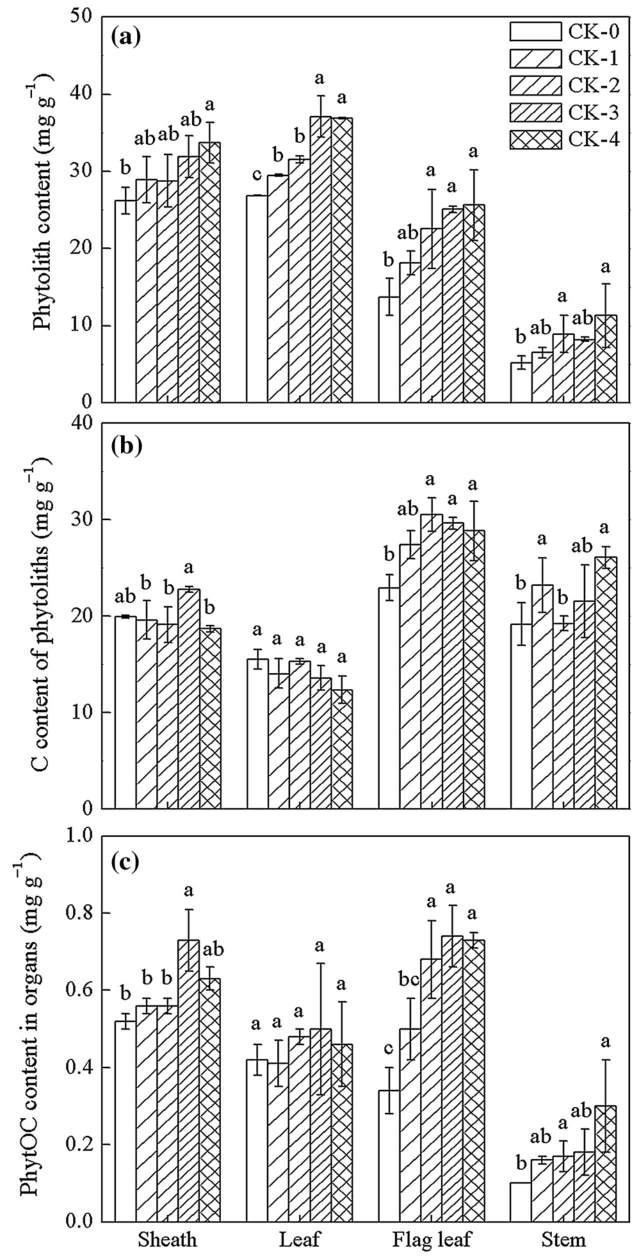


**Fig. 2** Distribution of (**a**) phytolith content of organs, (**b**) C content of phytoliths, (**c**) PhytOC content of organs in rice amended with BP. Error bars represent the standard deviations of the means

0.02 %–0.05 % of the global $CO_2$ emission amounts ($30100 \times 10^6$ Mg) in 2007 [43]. This is slightly lower than $1.94 \times 10^7$ Mg $CO_2$ $a^{-1}$, a value reported by Li et al. [15] as Jiayu 253 has slightly lower phytolith and PhytOC contents than that reported by Li et al. [15]. However, we find a 150 % increase in flux of phytolith sequestration of $CO_2$ with BP amendment compared to controls in this study.

Cereal crops were well known as the high silicon and PhytOC accumulators, especially rice, wheat and maize [15, 19, 26], and there may exist a similar PhytOC increase by BP amendment. If the 150 % increase was applicable to phytolith sequestration of $CO_2$ in world rice [15], wheat [19] and maize [26], the $CO_2$ occluded within phytoliths of these crops would be $4.85 \times 10^7$, $1.80 \times 10^7$ and $1.54 \times 10^7$ Mg $a^{-1}$, respectively. The annual $8.19 \times 10^7$ Mg $CO_2$ occlusion in phytoliths of these cereals would be equivalent to 0.27 % of the global $CO_2$ emission amounts ($30{,}100 \times 10^6$ Mg) in 2007 [43]. Therefore, the stable phytolith carbon sink may be a significant mechanism to mitigate $CO_2$ emission and should not be neglected in the future.

Although there must be certain variation between various trials in terms of dosage, field conditions and

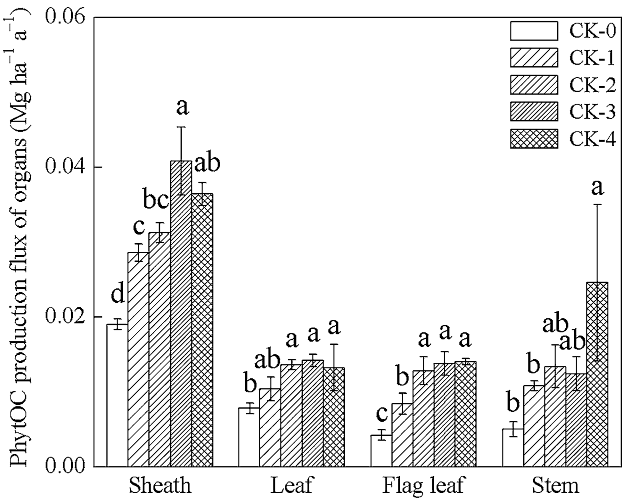


**Fig. 3** PhytOC production flux in different organs of rice amended with BP

management practices, our simple calculation based on area indicates that PhytOC in crops such as rice can be significantly enhanced by BP amendment. This demonstrates that BP amendment is a feasible measure to increase the phytolith carbon sink. However, further works such as the response of phytolith carbon sequestration to crop species and cultivars with different Si accumulation to different fertilization dosage should be done to more precisely estimate phytolith carbon sequestration potential and guide the practices of carbon management in agricultural ecosystems. In addition, while rock powder amendment can be extensively applied in the field to improve phytolith carbon production under different climatic conditions, the impact of rock powder on the accumulation of heavy metal in paddy soil should be further investigated in future research.

## 5 Conclusions

Our research is the first regulation practice of the phytolith carbon sink through external silicon amendments. BP amendment significantly increased the contents of phytolith and the C content of phytoliths in rice ecosystems. The PhytOC production fluxes in organs increased significantly with BP amendment from 0.005 to 0.041 Mg $CO_2$ ha$^{-1}$ a$^{-1}$. The PhytOC production flux of the sheaths was generally higher than that in other organs because of higher PhytOC content. The PhytOC content of organs depends on both the phytolith content and the ability of C occlusion within phytoliths during plant growth. If the global rice with a planting area of about $1.55 \times 10^8$ ha had a similar PhytOC production flux in this study, $0.61 \times 10^7$ to $1.54 \times 10^7$ Mg $CO_2$ could be occluded annually within phytoliths of global rice ecosystems, being equivalent to 0.02 %–0.05 % of the global $CO_2$ emissions ($30{,}100 \times 10^6$ Mg) in 2007. Furthermore, BP amendment resulted in a 150 % increase of PhytOC production flux (CK-0 to CK-4: 0.04–0.10 Mg $CO_2$ ha$^{-1}$ a$^{-1}$). This means that if silicon fertilizer can be efficiently applied to cereals such as rice in the future, atmospheric $CO_2$ emission may be mitigated through increasing phytolith carbon sink in agricultural ecosystems. Thus, our findings highlight that the use of external silicon amendments such as BP amendment provides a novel land management tool to regulate long-term biogeochemical carbon sequestration in crop ecosystems and may contribute to mitigate global climate warming.

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**Conflict of interest** The authors declare that they have no conflict of interest.

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