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RESEARCH ARTICLE

Evaluation of the occluded carbon within husk phytoliths of 35 rice cultivars

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Abstract Rice is a well-known silicon accumulator. During its periods of growth, a great number of phytoliths are formed by taking up silica via the plant roots. Concurrently, carbon in those phytoliths is sequestrated by a mechanism of long-term biogeochemical processes within the plant. Phytolith occluded C (PhytOC) is very stable and can be retained in soil for longer than a millennium. In this study, we evaluated the carbon biosequestration within the phytoliths produced in rice seed husks of 35 rice cultivars, with the goal of finding rice cultivars with relatively higher phytolith carbon sequestration efficiencies. The results showed that the phytolith contents ranged from 71.6 $\mathrm{mg \cdot g^{-1}}$ to 150.1 $\mathrm{mg \cdot g^{-1}}$, and the PhytOC contents ranged from 6.4 $\mathrm{mg \cdot g^{-1}}$ to 38.4 $\mathrm{mg \cdot g^{-1}}$, suggesting that there was no direct correlation between the PhytOC content and the content of rice seed husk phytoliths ($R = 0.092$, $p > 0.05$). Of all rice cultivars, six showed a higher carbon sequestration efficiency in phytolith seed husks. Additionally, the carbon biosequestration within the rice seed husk phytoliths was approximately 0.45–3.46 $\mathrm{kg\text{-}e\text{-}CO_2 \cdot ha^{-1} \cdot yr^{-1}}$. These rates indicate that rice cultivars are a potential source of carbon biosequestration which could contribute to the global carbon cycle and climate change.

Keywords carbon sequestration, seed husks, PhytOC, phytolith, rice cultivars

1 Introduction

The soil carbon pool plays a vital role in the global carbon cycle (Lal, 2004; Liu et al., 2014). The soil carbon storage capacity is influenced by many factors, such as climate (temperature and precipitation), the nature of parent geological materials (i.e., texture and mineralogy), vegetation (crop) type, and land management practices (McCarl et al., 2007). Approximately half of all soil carbon in managed ecosystems has been lost into the atmosphere during the past two centuries due to cultivation. Thus, carbon sequestration in the agricultural ecological system is a popular subject of study (Linquist et al., 2012). Modern crop production technologies are currently being adopted to reduce agricultural greenhouse gas emissions in these rice growing areas, such as early maturing cultivars, high use of inorganic fertilizers and pesticides, and the expansion of irrigation facilities (Pathak et al., 2005). However, potential processes to effectively select and breed high C occlusion efficiency cultivars have been disregarded thus far. Organic carbon can be occluded within phytoliths (i.e., PhytOC) during the course of plant growth (Parr and Sullivan, 2005). The contents of phytoliths generally constitute up to 3% of the total soil mass (Drees et al., 1989). PhytOC has been confirmed to be an important long-term terrestrial carbon fraction in the soil (Parr and Sullivan, 2005; Gu et al., 2012), contributes 15%–37% of the stable soil C sink (Parr and Sullivan, 2005), and represents up to 82% of the soil carbon in topsoils of *in situ* decomposition after 2000 years (Wilding, 1967; Wilding et al., 1967; Mulholland and Prior, 1993; Parr and Sullivan, 2005).

Phytolith, the opaline amorphous silica, is absorbed by plants and is formed in the tissues of most plants (Perry et al., 1987; Piperno, 1988; Song et al., 2012a,b), such as bamboo, rice, wheat, etc. After plants return to the soil, the straws of these plants are decomposed by microorganisms,

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and the phytoliths within these straws can be released directly into the soil. Phytoliths can tolerate extreme environments, such as earthquakes, dust storms, floods, forest fire erosion, etc., and are often retained in the *in situ* environment (Jones and Milne, 1963; Jones and Handreck, 1967; Wilding, 1967; Wilding and Drees, 1974; Sangster and Parry, 1981; Pearsall, 1989; Hart and Humphreys, 1997; Parr, 2006; Bowdery, 2007). However, during phytolith formation in plant tissues, some elements can be occluded (Jones and Milne, 1963), such as C, N, P, K, Ni, Al, Fe, Ca, etc. (Wang, 1998). In this course, phytoliths can occlude 1%–6% organic C (Wilding et al., 1967; Parr and Sullivan, 2005; Parr et al., 2010; Song et al., 2014a). The PhytOC content of plants in different crop species ranges from 0.04% to 0.75% of the dry crop biomass (Parr and Sullivan, 2011; Li et al., 2013). However, the PhytOC content also varies significantly between different cultivars (Parr and Sullivan, 2011; Li et al., 2013) and tissues (Li et al., 2013) of the same crop species. Many studies demonstrate that the PhytOC content in crops depends on the C content of phytoliths (Parr and Sullivan, 2011; Zuo and Lü, 2011) and on the phytolith content of crops (Li et al., 2013).

Rice, which acts as a food source as well as a silica accumulator, has many phytoliths and can occlude more organic C in its organs when compared with other plants (Song et al., 2012a,b). The global rice-planting area was approximately 1.55×10^8 ha in 2010 (IRRI, 2011). Rice is a major crop in Asian countries, such as India and China. From 1950 to 2010, approximately 2.37×10^8 Mg of CO_2 equivalents may have been sequestrated within rice phytoliths in China (Li et al., 2013). Assuming a maximum phytolith C biosequestration flux of 0.13 Mg-e-$CO_2\cdot ha^{-1}\cdot yr^{-1}$, the global annual potential rate of CO_2 sequestrated in rice phytoliths would be approximately 1.94×10^7 Mg (Li et al., 2013), which is greater than bamboo leaf litter (1.56×10^7 Mg-e-CO_2 per year) (Parr et al., 2010), sugarcane leaf (0.72×10^6 Mg-e-CO_2 per year) (Parr et al., 2009), and millet (2.37×10^6 Mg-e-CO_2 per year) (Zuo and Lü, 2011).

The presence of silica phytoliths within cereal crops is well-documented (Yoshida et al., 1962; Ball et al., 1993, 1996; Lux et al., 2002; Song et al., 2014a,b). According to the correlations between phytolith content and PhytOC content in crops, results show that the PhytOC content of plants can be increased by crop species or cultivar optimization (Li et al., 2013; Song et al., 2014a, b). However, the variability of phytolith accumulation within the many cultivars of rice has not previously been examined. In this study, we evaluated carbon biosequestration within the phytoliths produced in the rice seed husks of 35 rice cultivars. The aim of the study is to provide a choice for farmers to plant the rice cultivars with a high efficiency of carbon sequestration in phytoliths as well as high productivity.

2 Methods and materials

2.1 Sample preparation

Seed samples of 35 rice cultivars, which belong to seven varieties, were randomly obtained from six provinces (Jiangxi, Jiangsu, Henan, Heilongjiang, Anhui, and Zhejiang) in China in June 2013. These seed samples were derived from the conventional cultivars within the locality, as presented in Table 1. The seed samples were weighed at 5 g and placed in respective envelopes. The seed samples were then dried in an oven and removed after 8 hours for hulling. The seed husk samples were preserved for extracting phytoliths and analyzing PhytOC and PhytON.

2.2 Phytolith extraction from seed husks

The phytolith extraction method was designed to completely remove all organic material from the seed husk of each rice species (Walkley and Black, 1934; Zuo and Lü, 2011). In this study, a revision to the wet digestion method was implemented to digest the organic matter more completely (Walkley and Black, 1934). The detailed steps are as follows: 1) approximately 1.0 g of dry sample was weighed in a centrifuge tube (to the nearest 0.1 mg); 2) 5 mL of HNO_3 was added to the tube and heated in a water bath at 100°C until the reaction stopped; this was repeated twice, and then the sample was centrifuged at 3,000 r/min for 5 min and the supernatant was decanted; 3) the sample was rinsed with 10 mL of distilled water, centrifuged at 3,000 r/min for 5 min and decanted, followed by two additional rinses; 4) 10% HCl was then added, and the mixture was heated in a water bath at 80°C for 30 min, centrifuged at 3,000 r/min for 5 min, and the supernatant was then decanted; 5) the sample was rinsed with 10 mL of distilled water, centrifuged at 3,000 r/min for 5 min and decanted, followed by two additional rinses; 6) 5 mL HNO_3, was added, and the mixture was heated in a water bath at 100°C until the reaction stopped to ensure the removal of all organic material and then centrifuged twice at 3,000 r/min for 5 min, followed by decanting of the supernatant; 7) 5 mL of H_2SO_4 was added, and the mixture was heated in a water bath at 100°C for 1 h; 8) the mixture was cooled to room temperature, and then 30% H_2O_2 was slowly added until the liquid cleared; and 9) the mixture was centrifuged four times at 3,000 r/min for 5 min, followed by decanting of the supernatant, and finally, the phytoliths were dried in an oven at 70°C for 24 h.

2.3 PhytOC and PhytON measurements

Phytolith residue assemblages were mounted onto glass slides in a Balsam Canada mounting medium. The slides were viewed at 400 × magnification using a Jiangnan XP-

Table 1 The 35 tested rice cultivars collected from six provinces in China (the 35 cultivars belong to seven varieties)

Number	Cultivars	Varieties
1	Zhonghan 35	Indica rice
2	Xinliangyou 6	Indica two line hybrid rice
3	Tianyou 998	Indica three line hybrid rice
4	Gangyou 188	
5	II you 1259	
6	IIyou 501	
7	Fuyou 21	
8	Chuannong 1	
9	Zhongyou 7	
10	Yixiang 2079	
11	IIyou 1313	
12	Yixiang 725	
13	Tenuo 2072	Indica glutinous rice
14	Zhenzhunuo	
15	Huaidao 5	Japonica rice
16	Huaidao 11	
17	Lianjing 11	
18	Yanjing 47−12	
19	Wuyunjing 21	
20	Zhengdao 18	
21	Fengguan 16	
22	Longjing 38	
23	Longdao 12	
24	Longjing 21	
25	Longjing 36	
26	Suidao 3	
27	Jixidao 1	
28	Nanjing 5055	
29	Nanjing 46	
30	Xiushui 09	
31	Zhejing 88	
32	Xiushui 134	
33	8you 682	Japonica three line hybrid rice
34	Sujingnuo 1	Japonica glutinous rice
35	Zhenou 65	

213 microscope fitted with a polarizing filter and a 5.0 MP color CCD camera to ensure that no organic material exists (Fig. 1). The cross-polarized light technique was used here to indicate the absence of cellulose, calcium oxalate crystals, and starch grains, which appear bright white and blue if present (Parr et al., 2010). The PhytOC and PhytON were determined using an Elemental Analyzer 3000 (GmbH Company, Germany).

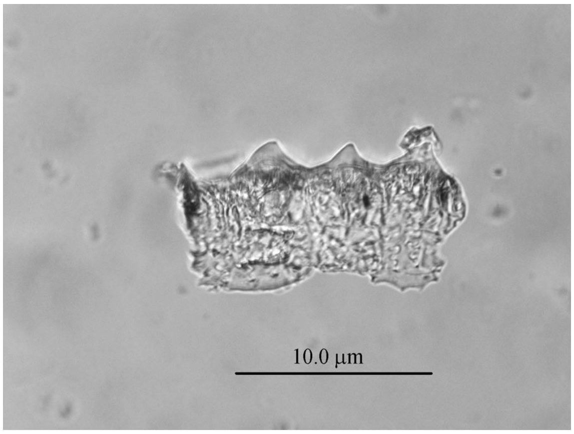

Fig. 1 The phytoliths extracted by the wet Ashing Method followed by Walkley and Black (1934) and Zuo and Lü (2011) from the rice husk samples.

2.4 Statistical analyses

The mean values of all parameters were taken from the measurements of three replicates, and the standard error of the means was calculated. One-way ANOVA was applied to determine the significance of the results between different varieties, and then Turkey's multiple range tests ($p < 0.05$) were performed. All of the statistical analyses were performed using SPSS v.13 for Windows.

3 Results

The results between the husk contents, phytolith contents, and PhytOC content had considerable variation among the 35 cultivars (Table 2). There was an even greater variation in the phytolith contents in the seed husks of the cultivars, ranging from 71.6 $\mathrm{mg \cdot g^{-1}}$ to 150.1 $\mathrm{mg \cdot g^{-1}}$. Similarly, substantial variations were observed in the PhytOC (0.64 $\mathrm{mg \cdot g^{-1}}$ to 3.84 $\mathrm{mg \cdot g^{-1}}$) and PhytON (0.31 $\mathrm{mg \cdot g^{-1}}$ to 0.59 $\mathrm{mg \cdot g^{-1}}$) contents in the seed husks of the 35 rice cultivars. Of all the rice cultivars, the highest carbon sequestration within the phytoliths was observed in the Zhonghan 35 variety, followed by Tianyou 998, Tenuo 2072, Huaidao 5, Yanjing 47−12, and Longjing 38. Their values were (3.22, 3.46, 2.84, 2.92, 2.90, and 2.57) Mg-e-$\mathrm{CO_2 \cdot ha^{-1} \cdot yr^{-1}}$, respectively (Table 2).

The relationships between the seven variables of the 35 rice cultivars are shown in Table 3. No correlation existed between the phytolith content and the PhytOC content in the phytoliths of the 35 rice cultivars ($R = 0.092, p > 0.05$). However, the phytolith content was correlated with the PhytOC content in the seed husks ($R = 0.380$, $p < 0.05$) and with the estimated fluxes of seed husk PhytOC ($R = 0.344$, $p < 0.05$). Additionally, the PhytOC content in the phytoliths exhibited a strong positive correlation with the PhytOC content in the seed husks ($R = 0.865$, $p < 0.01$)

Table 2 Rice cultivars, seed husk content as a percentage of rice, content of phytoliths, PhytON and PhytOC in the seed husk on a dry weight basis, and the estimated fluxes of PhytOC per ha in Mg of CO_2 equivalents (Mg-e-CO_2) for rice (according to gain yields of single rice crops of 9.28 $Mg \cdot ha^{-1}$*)

Cultivars	Husk Weight /%	Phytolith content /($mg \cdot g^{-1}$)	PhytON content in phytoliths /($mg \cdot g^{-1}$)	PhytOC content in phytoliths /($mg \cdot g^{-1}$)	PhytOC content in seed husks /($mg \cdot g^{-1}$)	C/N of phytoliths	Estimated fluxes of PhytOC in seed husks /(kg-$CO_2 \cdot ha^{-1} \cdot yr^{-1}$)
Zhonghan 35	22.46	109.6±22.5	0.33±0.01	3.84±0.44	0.47±0.09	11.83±1.60	3.22±0.37
Xinliangyou 6	22.06	117.8±8.4	0.48±0.05	0.89±0.15	0.11±0.03	1.85±0.43	0.79±0.13
Tianyou 998	24.26	132.2±6.3	0.39±0.03	3.16±0.84	0.43±0.11	9.81±2.83	3.46±0.92
Gangyou 188	18.60	111.2±11.0	0.37±0.03	0.64±0.08	0.07±0.01	1.74±0.25	0.45±0.06
II you 1259	22.15	128.9±16.3	0.36±0.02	0.88±0.15	0.12±0.03	2.43±0.42	0.86±0.15
IIyou 501	25.16	129.3±5.1	0.45±0.02	1.72±0.83	0.22±0.11	3.81±1.71	1.91±0.92
Fuyou 21	22.53	98.8±6.5	0.49±0.03	2.32±0.35	0.23±0.02	4.73±0.51	1.76±0.27
Chuannong 1	19.67	71.6±7.6	0.50±0.09	1.10±0.14	0.08±0.01	2.22±0.19	0.53±0.07
Zhongyou 7	19.79	97.6±8.5	0.53±0.06	1.07±0.46	0.10±0.04	2.00±0.82	0.70±0.30
Yixiang 2079	22.77	118.5±4.9	0.43±0.10	1.07±0.64	0.13±0.08	2.39±1.05	0.98±0.59
IIyou 1313	20.25	110.8±3.1	0.51±0.07	1.26±0.37	0.14±0.04	2.44±0.63	0.96±0.28
Yixiang 725	22.65	132.4±16.2	0.40±0.03	0.66±0.09	0.09±0.02	1.65±0.22	0.67±0.09
Tenuo 2072	19.83	148.5±31.4	0.34±0.06	2.83±0.28	0.42±0.10	8.52±1.09	2.84±0.28
Zhenzhunuo	26.65	113.9±56.9	0.34±0.04	0.89±0.12	0.11±0.06	2.63±0.60	0.92±0.12
Huaidao 5	15.32	150.1±5.5	0.37±0.06	3.73±0.68	0.56±0.14	9.82±2.35	2.92±0.53
Huaidao 11	16.74	138.9±31.8	0.48±0.17	2.22±0.55	1.09±1.01	1.09±1.01	1.76±0.44
Lianjing 11	16.09	127.1±14.4	0.31±0.03	2.62±0.48	0.33±0.04	0.33±0.04	1.83±0.33
Yanjing 47-12	19.57	148.5±2.8	0.32±0.05	2.93±0.30	0.44±0.05	0.44±0.05	2.90±0.30
Wuyunjing 21	13.63	122.5±20.6	0.35±0.01	3.41±0.27	0.40±0.06	0.40±0.06	1.94±0.15
Zhengdao 18	16.60	131.0±55.9	0.37±0.07	0.80±0.09	0.10±0.04	0.10±0.04	0.59±0.07
Fengguan 16	17.84	79.4±6.4	0.54±0.03	3.09±0.49	0.25±0.05	0.25±0.05	1.49±0.24
Longjing 38	17.98	135.0±16.1	0.46±0.05	3.10±0.58	0.42±0.06	0.42±0.06	2.57±0.48
Longdao 12	18.14	149.9±7.9	0.43±0.02	2.01±0.15	0.30±0.03	0.30±0.03	1.86±0.14
Longjing 21	17.26	156.3±21.4	0.38±0.05	1.85±0.57	0.30±0.14	0.30±0.14	1.70±0.52
Longjing 36	16.63	119.8±10.6	0.49±0.03	2.05±0.55	0.25±0.08	0.25±0.08	1.39±0.37
Suidao 3	16.96	141.3±4.2	0.40±0.05	1.74±0.09	0.25±0.02	0.25±0.02	1.42±0.07
Jixidao 1	16.67	140.9±9.9	0.40±0.06	1.45±0.36	0.21±0.07	0.21±0.07	1.16±0.29
Nanjing 5055	15.40	136.2±9.7	0.35±0.05	1.14±0.23	0.15±0.02	0.15±0.02	0.81±0.16
Nanjing 46	14.72	105.7±4.2	0.55±0.07	2.26±0.33	0.24±0.15	0.24±0.15	1.19±0.17
Xiushui 09	15.10	125.5±1.6	0.45±0.07	1.72±0.40	0.22±0.05	0.22±0.05	1.11±0.26
Zhejing 88	15.14	146.5±10.5	0.54±0.07	1.48±0.31	0.22±0.06	0.22±0.06	1.12±0.23
Xiushui 134	17.39	138.4±4.1	0.53±0.04	1.12±0.02	0.16±0.00	0.16±0.00	0.92±0.02
8you 682	19.52	89.5±6.7	0.48±0.01	2.39±0.13	0.21±0.03	0.21±0.03	1.42±0.08
Sujingnuo 1	15.87	124.1±19.8	0.44±0.01	2.01±0.25	0.55±0.59	0.55±0.59	1.35±0.17
Zhenou 65	16.89	134.0±6.4	0.47±0.03	2.35±0.61	0.27±0.01	0.27±0.01	1.81±0.47

*Data offered by the Changshu Agroecological Experimental Station, Chinese Academy of Sciences.

and with the estimated fluxes of seed husk PhytOC ($R = 0.888, p < 0.01$). There was a strong positive correlation ($R = 0.855, p < 0.01$) between the PhytOC content in the seed husks and the estimated fluxes of the seed husk PhytOC (Table 3).

The husk content of Indica varieties ranged from 21.78% to 23.24%, and that of the Japonica varieties varied between 16.38% and 19.52%. Additionally, the PhytOC content in the phytoliths of four Indica varieties varied greatly between (0.89±0.15) $mg \cdot g^{-1}$ and (3.84±

Table 3 Correlation coefficients between the seven variables of the 35 rice cultivars

Variables	Husk weight	Phytolith content	PhytON content in phytoliths	PhytOC content in phytoliths	PhytOC content in seed husks	Estimated fluxes of PhytOC in seed husks	C/N of phytoliths
Husk weight	1						
Phytolith contents	−0.237	1					
PhytON content in phytoliths	−0.127	−0.428*	1				
PhytOC content in phytoliths	−0.204	0.092	−0.180	1			
PhytOC content in seed husks	−0.268	0.380*	−0.287	0.865**	1		
Estimated fluxes of PhytOC in seed husks	0.074	0.344*	−0.351*	0.888**	0.855**	1	
C/N of phytoliths	−0.148	0.216	−0.143	0.539**	0.582**	0.528**	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

0.44) $\mathrm{mg \cdot g^{-1}}$; significant differences in the PhytOC content of the phytoliths were observed among the seven cultivars of the Indica varieties. However, the PhytOC content in the phytoliths of three Japonica varieties ranged from 2.15 $\mathrm{mg \cdot g^{-1}}$ to 2.39 $\mathrm{mg \cdot g^{-1}}$ (Table 4). Although the husk average content of the Indica varieties was much higher than that of the Japonica varieties, the PhytOC content in the phytoliths of Indica varieties was on average lower than that in Japonica varieties. In summary, the seed husk PhytOC content exhibited no significant differences between the two rice varieties.

The relationships between the phytolith content, the phytolith PhytOC content, the seed husk PhytOC content, the phytolith C/N, and the estimated fluxes of seed husk PhytOC were examined. The results indicated that a weak negative correlation existed between the phytolith content and the PhytOC content in the phytoliths for seven rice varieties ($R = -0.242$, $p > 0.05$), whereas the phytolith content was strongly positively correlated with the seed husk PhytOC content ($R = 0.855$, $p < 0.05$), with the estimated fluxes of the seed husk PhytOC ($R = 0.930$, $p < 0.01$), and with the phytolith C/N ($R = 0.966$, $p < 0.01$). In addition, the seed husk PhytOC content exhibited a strong positive correlation with the estimated fluxes of the seed husk PhytOC ($R = 0.840$, $p < 0.01$) and with the phytolith C/N ($R = 0.833$, $p < 0.05$). There was a strong positive correlation between the estimated fluxes of seed husk PhytOC and the phytolith C/N ($R = 0.990$, $p < 0.01$) (Table 5).

4 Discussion

4.1 Carbon sequestration within the phytoliths of rice seed husks

The PhytOC content in bamboo, wheat, sugarcane, and millet was found to have no direct correlation with the

Table 4 Rice varieties, the seed husk content as a percentage of rice, the content of phytoliths, PhytON and PhytOC in seed husk on a dry weight basis and the estimated fluxes of PhyOC per ha in Mg of CO_2 equivalents (Mg-e-CO_2) for rice (according to gains in yields of single rice crops of 9.28 $\mathrm{Mg \cdot ha^{-1}}$*)

Varieties	*n*	Husk Weight /%	Phytolith content /($\mathrm{mg \cdot g^{-1}}$)	PhytON content in phytoliths /($\mathrm{mg \cdot g^{-1}}$)	PhytOC content in phytoliths /($\mathrm{mg \cdot g^{-1}}$)	PhytOC content in seed husks /($\mathrm{mg \cdot g^{-1}}$)	C/N of phytoliths	Estimated fluxes of PhytOC in seed husks /(kg-CO_2 $\mathrm{\cdot ha^{-1} \cdot yr^{-1}}$)
Indica rice	1	22.46±0.00	109.6±22.5	0.33±0.01	3.84±0.44	0.47±0.09	11.63±1.60	3.22±0.37
Indica two line hybrid rice	1	22.06±0.00	117.8±8.4	0.48±0.05	0.89±0.15	0.11±0.03	1.85±0.43	0.79±0.13
Indica three line hybrid rice	10	21.78±2.13	113.1±19.6	0.44±0.08	1.39±0.80	0.16±0.11	3.16±1.98	1.22±0.92
Indica glutinous rice	2	23.24±4.82	131.2±24.5	0.34±0.05	1.86±1.37	0.26±0.22	5.47±4.03	1.88±1.35
Japonica rice	18	16.51±1.45	132.9±18.4	0.43±0.08	2.15±0.84	0.28±0.12	5.25±2.54	1.59±0.67
Japonica three line hybrid rice	1	19.52±0.00	89.5±6.7	0.48±0.01	2.39±0.13	0.21±0.03	4.98±0.92	1.42±0.08
Japonica glutinous rice	2	16.38±0.72	129.1±7.0	0.46±0.02	2.18±0.24	0.41±0.20	4.78±0.31	1.58±0.33

n, number of plant species samples.
*Data offered by Changshu Agroecological Experimental Station, Chinese Academy of Sciences.

Table 5 Correlation coefficients between the seven variables of the seven varieties

Variables	Husk weight	Phytolith content	PhytON content in phytoliths	PhytOC content in phytoliths	PhytOC content in seed husks	Estimated fluxes of PhytOC in seed husks	C/N of phytoliths
Husk weight	1						
Phytolith content	−0.245	1					
PhytON content in phytoliths	−0.497	−0.261	1				
PhytOC content in phytoliths	−0.054	−0.242	−0.581	1			
PhytOC content in seed husks	−0.261	0.181	−0.550	0.855*	1		
Estimated fluxes of PhytOC in seed husks	0.199	−0.041	−0.824*	0.930**	0.840*	1	
C/N of phytoliths	0.140	−0.130	−0.751	0.966**	0.833*	0.990**	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

phytolith content formed within plants (Parr et al., 2009, 2010; Parr and Sullivan, 2011; Zuo and Lü, 2011). Our results indicated that there was no correlation between the phytolith content or the PhytOC content in the phytoliths of the 35 rice cultivars studied ($R = 0.092, p > 0.05$). These data indicate that for rice, as for wheat, bamboo, and sugarcane (Parr et al., 2009, 2010; Parr and Sullivan, 2011), it is the efficiency by which carbon is encapsulated by silica within the epidermal cell walls (phytoliths), rather than the actual quantity of the silica taken up by the plant, that is most important in determining the relative PhytOC yield in plant materials (Parr and Sullivan, 2011). The finding that the carbon was occluded within rice husk phytoliths was consistent with observations made by the aforementioned researchers. In fact, the PhytOC content depends on the efficiency of the C occluded within the phytoliths during plant growth. Genetic and physiological differences within the rice cultivars may affect the formation and the efficiency of the C occluded within the phytoliths (Parr et al., 2009, 2010; Parr and Sullivan, 2011). Therefore, it is possible to improve the carbon sequestration of the phytoliths by selecting cultivars with high phytolith content and high C occluded in phytoliths from different rice cultivars.

4.2 The efficiency of carbon sequestration within the phytoliths in rice seed husks

The long-term carbon sequestration of soil organic carbon is relatively low (only 0.7% of net primary millennia) (Schlesinger, 1990). In addition, many carbon fractions involved in the carbon cycle, either directly or indirectly, are responsible for environmental issues. However, the occlusion of carbon within phytoliths has been retained in soils for more than a millennium resulting in the formation of a long-term, terrestrial carbon fraction (Parr and Sullivan, 2005). In this study, we estimated that the C fluxes of rice seed husks were 0.45 to 3.46 kg-e-$CO_2 \cdot ha^{-1}$ per year in terms of the PhytOC content of rice seed husk material on a dry weight basis (Wang et al., 2008) and the mean annual grain production (9.3 Mg-ha^{-1}) of single rice cropping systems (Anthoni et al., 2004; Zhang et al., 2010). However, Li et al. (2013) reported that the flux of the rice PhytOC was 0.03–0.13 t-e-$CO_2 \cdot ha^{-1}$ per year, which is much higher than our results. The differences between this study and Li et al.'s findings may be due to the tested cultivars and the organs (i.e., this manuscript only tested the husk, and Li et al. tested four organs). This study used an organ to estimate the PhytOC flux.

The global rice-planting area was approximately 1.55×10^8 ha in 2010 (IRRI, 2011). Assuming that the largest PhytOC flux of rice seed husk was 3.46 kg-e-$CO_2 \cdot ha^{-1} \cdot yr^{-1}$, 5.36×10^5 Mg-e-CO_2 would be globally occluded within rice seed husk phytoliths per year.

5 Conclusions

The carbon content of phytoliths in rice seed husks depends on the efficiency of the carbon occluded within the phytoliths during rice growth periods. The PhytOC content in the husk of 35 rice cultivars ranged from 0.64 $mg \cdot g^{-1}$ to 3.84 $mg \cdot g^{-1}$. It is estimated that the flux of C occluded within the rice husk phytoliths is between 0.45 and 3.46 kg-e-$CO_2 \cdot ha^{-1}$ per year. Of the 35 rice cultivars considered, six exhibited relatively higher phytolith and PhytOC accumulation efficiencies. Therefore, enhancing the carbon sequestration efficiency of rice cultivar phytoliths will provide us with a new approach for increasing the soil organic carbon sink, and selecting/breeding rice cultivars with high PhytOC represents critical work in this domain.

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