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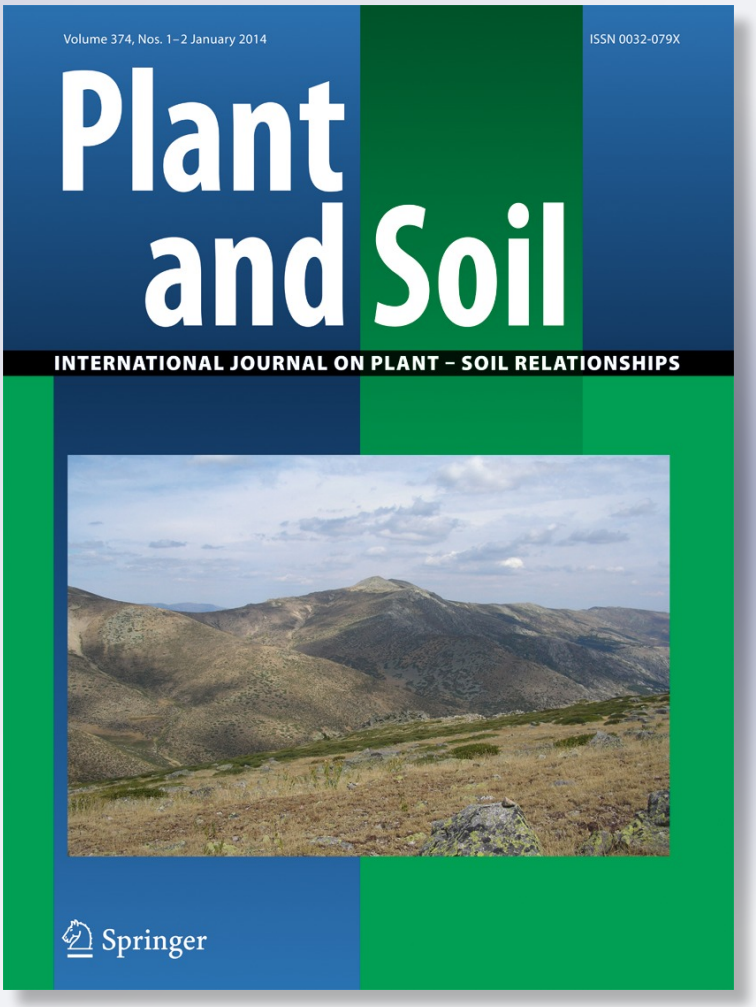

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REGULAR ARTICLE

Distribution of soil phytolith-occluded carbon in the Chinese Loess Plateau and its implications for silica–carbon cycles

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Abstract
Background and aims Plants absorb and carry soluble silica from soils and then deposit $SiO_2 \cdot nH_2O$ within themselves producing amorphous silica particles known as phytoliths. Trace amount of organic carbon is occluded during phytolith formation referred to as phytolith-occluded carbon (PhytOC). This carbon fraction has been recognized as an important way of carbon biosequestration. Previous studies have investigated the PhytOC contents of many crop plants and their contribution to global carbon sink. However, the PhytOC in soil is less focused. In this study, we investigated the distribution of soil PhytOC in the Chinese Loess Plateau (CLP).

Methods Twenty-six soil profiles were collected in the Chinese Loess Plateau. A wet oxidation method was used for phytolith extraction. Occluded carbon was determined by element analyzer.
Results Our results showed that the soil PhytOC density (SPCD) ranged from 0.757 to 23.110 g/m^2 among different soil profiles. The SPCD of profiles in the Southern CLP was generally higher than that in the Northern CLP. It was estimated that 5.35 Mt of PhytOC was stored in the upper soil of the CLP. We also estimated the annual phytolith flux into the Yellow River from the CLP by soil erosion and about 2.5 Mt of phytoliths eroded and transported into rivers per year.
Conclusions Our study indicated that PhytOC was one of the potential biosequestration way and phytoliths had an important influence on biogeochemical cycle of silica. Our results suggested that the soil PhytOC was mainly influenced by different plant communities.

Keywords Soil phytoliths · Carbon sequestration · PhytOC · Silica cycle · Chinese Loess Plateau

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Introduction

Phytoliths, also called silica body, are microscopic particles that deposit inside cells and cell walls of higher plants (Piperno 2006; Ma and Yamaji 2006). Small amounts of organic carbon (usually ranging from 0.2 to 5.8 %) can be occluded during phytolith formation (Wilding et al. 1967; Jones and Beavers

1964; Smith and Anderson 2001). This carbon fraction has been recognized as an important long-term terrestrial carbon sink which sequestrates about 1.5 billion tons of CO_2 per year (Parr et al. 2010). A recent review argued that the phytoliths together with phytolith-occluded carbon (PhytOC) played a crucial role in the coupled silica and carbon cycles (Song et al. 2012a). As one recalcitrant form of organic carbon, PhytOC can be measured while in standing plants; it has thus drawn particular attention from many researchers in the study of the terrestrial carbon cycle (Parr et al. 2010; Oldenburg et al. 2008).

Recently, the PhytOC of some plants, such as bamboo, sugarcane, wheat, and millet has been examined (Parr et al. 2009, 2010; Parr and Sullivan 2011; Zuo and Lu 2011). The potential PhytOC sequestration rates for these four plants were estimated to be 0.7, 0.36, 0.246, and 0.03 t of CO_2 ha^{-1} $year^{-1}$, respectively. Rajendiran et al. (2012) estimated that crops (wheat, rice, sugarcane, barely, and sorghum) might annually contribute about 87 Mt of PhytOC in India. Song et al. (2012b) provided an estimation of 41.4 Mt of CO_2 sink that would be securely sequestrated by the PhytOC production of world grasslands. All these living plants are destined to die and decay in soils. The PhytOC thus becomes one inert form of soil organic carbon and its fate faces many uncertainties. Despite great advances in estimating production of PhytOC for some plants and grassland, few studies focused on the PhytOC in soil and the PhytOC sink in different soils. Moreover, the relation between soil PhytOC and above-ground biomass remains to be tackled. If the part of soil phytoliths are dissolved or transported into rivers, how much does the plant–Si contribute to riverine DSi and global silicon cycle? In this study, we first investigated the distribution of soil PhytOC and estimated the PhytOC stocks of different upper soils (~30 cm depth) in the Chinese Loess Plateau (CLP). We then provided a preliminary estimation of Si flux to the Yellow River by soil erosion and discussed the mechanism of the soil PhytOC accumulation in the CLP.

Material and methods

Study area

The CLP (33.72–41.27°N and 100.9–114.55°E; 1,500–2,000 m above sea level) covers an area of 640,000 km^2 in the upper and middle reaches of the Yellow River. Its present climate belongs to arid and semi-arid temperate zone with annual precipitation ranging from 300 to 500 mm. Natural vegetation of the CLP can be divided into five zones from south to north: (1) broadleaved deciduous forest, (2) forest steppe, (3) steppe, (4) desert steppe, and (5) steppe desert (Wang et al. 1991). However, unsustainable farming practices and overgrazing over thousands of years due to huge population pressures have led to severe vegetation degradation. Many natural forests on the CLP have vanished and been replaced by cultivated land (Fig. 1). Current dominant soil types are Loessi-Orthic Primosols, Hapli Ustic Argosols, and Aridi-Sandic Primosols, which totally account for 80 % area of the Loess Plateau (Integrated Survey of Loess Plateau in China 1992).

Field sampling

We collected 26 upper soil samples in most part of the CLP from July to September 2010. Most of the soil profiles are located in cultivated land (Table 1 and Fig. 1). A field collection protocol was established after Ordóñez et al. (2008). In order to minimize sampling errors due to the effect of heterogeneity in soil conditions, we dug three 20×20×30 cm (length, width, and depth) pits along the circumference of a circle of 500 m^2 (radius=12.6 m). In each pit, about 10 kg of soil was excavated. The soil of three pits was then mixed and sieved (mesh diameter of 2 mm). About 1 kg of soil was sealed in air-tight bags and taken to the lab. All soil samples were air dried. About 10 g of dry soil was finally chosen for phytolith extraction.

Phytolith extraction and PhytOC measurement

A wet oxidation method modified from previous phytoliths extraction processes (Piperno 2006; Carter 2009; Lu et al. 2006, 2007; Santos et al. 2010) was used. Its procedure includes (a) ~10 g of soil was crushed and sieved at 1 mm; (b) the sample was deflocculated with 5 % sodium polyphosphates and the supernatant was washed with distilled water three to four times; (c) organic matter was first oxidized by H_2O_2 (30 %) for 12 h and then heated in a water bath until the reaction stopped; (d) carbonates were excluded by HCl (10 %); (e) the <250 μm fraction was separated with wet sieving, and then disaggregate phytoliths from the organic and clay were processed

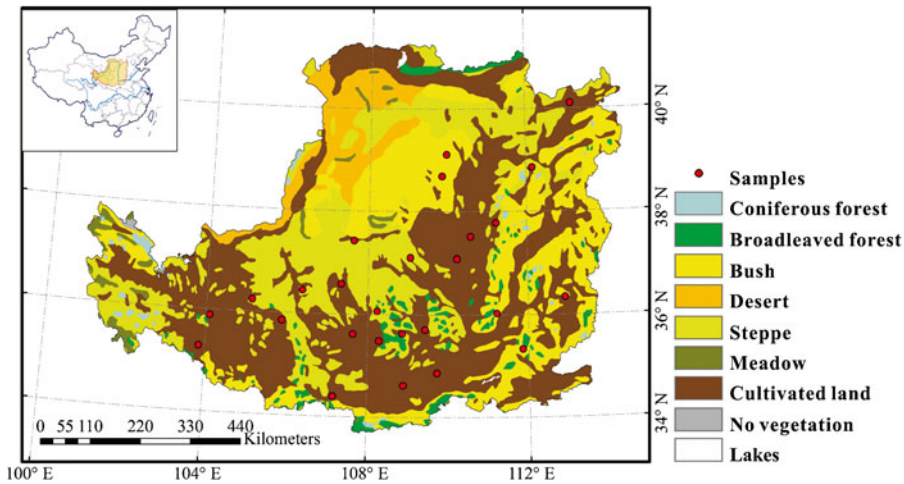

Fig. 1 The location of sampling sites and vegetation types of the CLP (modified from Hou et al. (1979))

by ultrasonic treatment; (f) clay (<5 μm) were removed by sedimentation; (g) the remaining higher-resistant materials were second oxidized by HNO_3 and $KClO_3$ with heating for 1 h, and then centrifuged and decanted; (h) phytoliths were extracted by heavy liquid ($ZnBr_2$) with a specific density of 2.3 and then washed three times with distilled water; (i) extracted phytoliths were further sieved at 7 μm for removal of clay, then $HClO_4$ was added into tube to react for 20 min; and (j) finally, recovered phytoliths were dried at 60 °C for 24 h. The content of PhytOC was measured by PerkinElmer 2400 II in the Institute of Geology and Geophysics, Chinese Academy of Sciences.

Estimation of soil PhytOC density

We plotted all samples on the digital 1:4,000,000 soil map of China. Soil type of each sample was generated from this map. Our soil classification and name were based on the Chinese Soil Taxonomy (Cooperative Research Group of Chinese Soil Taxonomy 2001). The corresponding English translations of soil types were cited from *Soil of China* (National Soil Survey Office 1998).

Soil PhytOC density (SPCD) is estimated using the following formula:

$$\mathrm{SPCD} = t \times \rho \times PC \times 10,000$$

where t is the thickness of soil profile; ρ and PC represent bulky density (in gram per cubic centimeter) and PhytOC in soil, respectively. The equation multiplied by 10,000 is to convert from gram per square centimeter to gram per square meter. In this study, only the upper 30 cm depth was estimated. All of the bulk densities were cited from Soil Species of China (National Soil Survey Office 1995a, b) and other archives (Soil Survey Office of Gansu 1993; Liu and Zhang 1992; Guo 1992).

Estimation of phytolith flux into the Yellow River

The CLP is one of the regions with the most extensive soil erosion. It was estimated that 1.51 billion tons of soil were eroded and exported by rivers in 2008 (Fu et al. 2011). Phytoliths, as a kind of particulate silica, were also eroded and carried by rivers (Dürr et al. 2011). In this study, we determined the upper soil phytolith contents in 26 profiles; the annual phytolith flux into the Yellow River was simply estimated by the average soil phytolith content multiplying the annual total soil loss.

Results

Variations of soil phytoliths, PhytOC, and SPCD in different soil profiles

As shown in Table 2, soil phytolith contents ranged from 0.024 to 0.431 %. Both PhytOC contents within phytoliths and soil PhytOC contents showed significant variation among different profiles. The PhytOC contents within phytoliths for 26 profiles varied from 0.25 to 6.91 %. The soil PhytOC contents and estimated soil PhytOC densities ranged from 0.002 to 0.061‰ and 0.757 to 23.110 g/m^2, respectively. A significant

Table 1 Location, soil type, soil bulk density, and vegetation type of each profile

Sample site	Latitude (°)	Longitude (°)	asl (m)	Soil type (CST)	Bulk density (g/m^3)	Vegetation type
YuanQu	35.33	111.86	606	Hapli Ustic Argosols A	1.22	Broad leaved forest
SanYuan	34.62	108.9	426	Earth-cumuli-Orthic Anthrosols	1.35	Cultivated land
XiFeng	35.61	107.64	1,343	Cumuli-Ustic Isohumosols	1.2	Cultivated land
HuiNing	36.24	105.12	2,030	Calci-Orthic Aridosols	1.26	Cultivated land
XiangNing	36.03	111.22	1,106	Hapli Ustic Argosols A	1.12	Cultivated land
LinTao	35.28	103.85	2,036	Loessi-Orthic Primosols	1.25	Cultivated land
DingBian	37.42	107.63	1,645	Cumuli-Ustic Isohumosols	1.25	Cultivated land
GuYuan	36.45	106.36	1,587	Loessi-Orthic Primosols	1.23	Cultivated land
ShenMu1	38.69	109.85	1,315	Loessi-Orthic Primosols	1.23	Desert steppe
FangShan	37.78	111.22	1,083	Loessi-Orthic Primosols	1.23	Bush
ShenMu2	39.12	109.97	1,254	Aridi-Sandic Primosols	1.37	Desert steppe
QingJian	37.1	110.22	1,191	Loessi-Orthic Primosols	1.23	Cultivated land
ZhengNing	35.49	108.29	1,388	Loessi-Orthic Primosols	1.23	Cultivated land
AnSai	37.11	109.05	1,233	Loessi-Orthic Primosols	1.23	Secondary forest
WeiNan	34.87	109.73	409	Loessi-Orthic Primosols	1.23	Cultivated land
NingWu	38.86	112.16	1,792	Hapli Ustic Argosols A	1.12	Cultivated land
SuiDe	37.51	110.57	1,126	Loessi-Orthic Primosols	1.23	Cultivated land
YanAn	35.63	108.87	1,098	Loessi-Orthic Primosols	1.23	Cultivated land
HeShui	36.07	108.24	1,245	Loessi-Orthic Primosols	1.26	Cultivated land
YuZhong	35.89	104.09	1,943	Hapli Ustic Argosols B	0.98	Cultivated land
BaoJi	34.39	107.17	819	Earth-cumuli-Orthic Anthrosols	1.28	Cultivated land
DaTong	40.11	113.19	1,106	Argic Calci-Ustic Isohumosols	1.46	Steppe
TunLiu	36.34	112.93	943	Hapli Ustic Argosols A	1.12	Cultivated land
HuanXian	36.59	107.32	1,523	Loessi-Orthic Primosols	1.23	Cultivated land
XiJi	35.85	105.87	1,859	Loessi-Orthic Primosols	1.23	Cultivated land
LuoChuan	35.71	109.43	1,085	Cumuli-Ustic Isohumosols	1.25	Cultivated land

asl above sea level

Hapli Ustic Argosols A and B actually are two different soil types. However, their English translations are the same. Here, A and B were suffixed to them, respectively

positive correlation (R=0.593, p<0.01) existed between the PhytOC contents within soil phytoliths and PhytOC contents in soil. This finding supported that the PhytOC content was mostly determined by the efficiency of carbon trapping during the phytolith's deposition in plant (Parr and Sullivan 2011). On the other hand, it implied that it was essential to acquire pure phytolith samples in the procedure of phytolith extraction.

Distribution of soil PhytOC in the CLP

The SPCD values were estimated for the upper soil layers (0–30 cm) in terms of 26 soil profiles in the CLP. As shown in Fig. 2, the SPCD values of different soil profiles were negatively correlated with the latitude of soil profiles, i.e., soil profiles in the Southern Plateau conserved more soil PhytOC than those in the Northern Plateau. It was notable that this correlation occurred not only among profiles with different soil types but also among profiles with the same soil type, such as 13 profiles of the Loessi-Orthic Primosols.

Estimation of current soil PhytOC stocks in the CLP

Table 3 illustrated significant variation of soil PhytOC density among different soil types. The average of SPCD was the highest in Calci-Orthic Aridosols soil (23.11 g/m^2) and the lowest in Aridi-Sandic Primosols soil (0.757 g/m^2). It was certain that variation of soil

Table 2 Phytolith content and estimated soil PhytOC density (SPCD)

Simple site	Dry weight (g)	Phytolith content (%)	PhytOC/phytoliths (%)	PhytOC in soil (‰)	Estimated SPCD (g/m^2)
YuanQu	11.087	0.097	2.840	0.027	10.032
SanYuan	10.347	0.098	2.490	0.024	9.912
XiFeng	10.754	0.214	1.160	0.025	8.931
HuiNing	10.687	0.209	2.930	0.061	23.110
XiangNing	10.535	0.133	2.110	0.028	9.421
LinTao	10.286	0.120	3.580	0.043	16.053
DingBian	10.328	0.024	1.040	0.003	0.944
GuYuan	10.137	0.320	1.030	0.033	12.148
ShenMu1	10.112	0.141	0.250	0.004	1.305
FangShan	10.801	0.259	0.790	0.020	7.557
ShenMu2	10.527	0.036	0.510	0.002	0.757
QingJian	10.098	0.068	1.540	0.011	3.883
ZhengNing	10.939	0.112	1.220	0.014	5.021
AnSai	10.518	0.431	0.570	0.025	9.059
WeiNan	10.065	0.057	6.910	0.039	14.439
NingWu	10.288	0.116	3.220	0.037	12.514
SuiDe	10.351	0.262	0.740	0.019	7.149
YanAn	10.392	0.378	0.540	0.020	7.535
HeShui	10.558	0.064	1.600	0.010	3.895
YuZhong	10.540	0.073	3.470	0.025	7.453
BaoJi	10.164	0.151	2.480	0.038	14.544
DaTong	10.211	0.087	0.790	0.007	2.877
TunLiu	10.231	0.131	0.917	0.012	4.079
HuanXian	10.389	0.215	2.243	0.027	9.797
XiJi	10.360	0.313	1.260	0.039	14.451
LuoChuan	10.802	0.196	1.503	0.029	10.727
Mean±SD		0.166±0.106	1.836±1.430	0.024±0.014	8.754±5.281

PhytOC in soil (‰)=dry weight×phytolith content×PhytOC/phytoliths

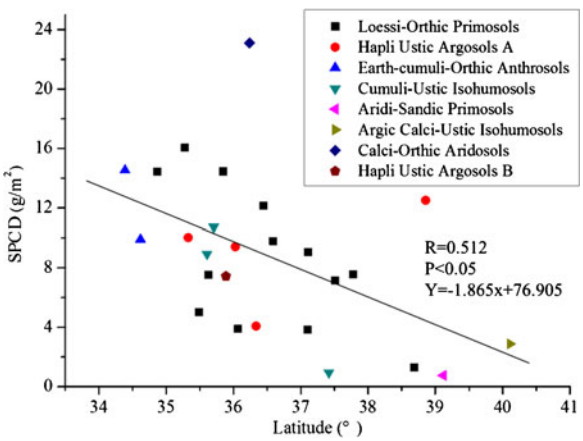

Fig. 2 Variations of the soil PhytOC in different soil profiles

PhytOC density also existed within the same soil type. On the basis of 26 soil profiles from the eight major soil types of the CLP, the total soil PhytOC stock was estimated to be 5.35 Mt for the CLP by assigning an average SPCD of eight major soil types to that of others.

Estimation of phytolith flux into the Yellow River

In the CLP, soil loss has decreased a lot in recent decades as the vegetation cover was improved; however, the rate of soil erosion was still as higher as 2,405 t km^{-2} year^{-1} (Fu et al. 2011). The rate of soil erosion and averaged soil phytolith content (0.166 %) were used to estimate the leached phytoliths with soil. It was estimated that the net phytolith flux into the

Table 3 Soil PhytOC stock of different soil types in the CLP

Soil type	*n*	Percentage of the total area	SPCD±SD (g/m^2)	Soil PhytOC stock (t)
Loessi-Orthic Primosols	13	32.51	8.634±4.594	1,796,425
Hapli Ustic Argosols A	4	24.76	9.012±3.550	1,428,078
Aridi-Sandic Primosols	1	11.77	0.757	57,023
Calci-Orthic Aridosols	1	5.25	23.110	776,496
Hapli Ustic Argosols B	1	5.12	7.453	244,220
Cumuli-Ustic Isohumosols	3	3.72	6.866±5.206	163,466
Argic Calci-Ustic Isohumosols	1	3.67	2.877	67,575
Earth-Cumuli-Orthic Anthrosols	2	3.46	12.228±3.275	270,777
Others		9.76	8.754	546,810
Total stock				5,350,869

The area of different soil types were collected by Integrated Survey of Loess Plateau in China (1992)

n Number of soil profiles

Yellow River was about 4 t km^{-2} $year^{-1}$; about 2.6 Mt of phytolith would be eroded or leached per year for 640, 000 km^2 of the CLP.

Discussion

Possible factors controlling the distribution of soil PhytOC in the CLP

When plants die and decay, phytoliths are released into the soil. Therefore, phytoliths in soil were largely controlled by the production of above-ground plants. However, detailed knowledge on this relationship between phytoliths in soil and the production of above-ground plant was limited. A pioneering study of soil phytoliths suggested the soil PhytOC might be influenced by different plant communities (Drees et al. 1989). Nevertheless, the exact relationship between plant community and PhytOC in soil is still not clear (Parr and Sullivan 2005).

Our soil PhytOC density varied among the sites (Table 2). Generally, the SPCD increased as the altitude of soil profiles decreased (Fig. 2). This fact was consistent with the spatial variation of stimulated net primary production (NPP) of different vegetation zones in the CLP (Gao and Liu 2008). Two sites (Shenmu1 and Shenmu2) covered by desert steppe have SPCD lower than the most of other sites (Table 2). The SPCD also exhibited a general increase southward within different cultivated land in the CLP. Regional analysis of China' croplands indicated that NPP was higher in the southeast than the northwest (Ren et al. 2012). Our results thus suggested that NPP, influenced by different plant communities, probably was the most important in determining the PhytOC in soil. This conclusion was also supported by the study of PhytOC production in Chinese grasslands (Song et al. 2012b). They found that average above-ground PhytOC production rate of China' grasslands (0.3 Mt $year^{-1}$ or 0.7 % of world grasslands) were much lower than those of other grasslands (e.g., North American nonwoody grasslands) mainly because of much lower above-ground net primary productivity.

Except for different plant communities, soil properties were another factor affecting phytolith and PhytOC. The differences in soil properties, such as the soil texture (Hart and Humphreys 2003) and pH (Fraysse et al. 2009) might have influence on preservation and detention of the phytolith in soil. As Table 3 shows, SPCD difference occurred not only between soil profiles of different soil types with the same natural plant community (desert steppe) but different soil types (e.g., soil profiles Shenmu1 and Shenmu2), but also among soil profiles with the same cultivated plant community (e.g., 20 profiles with cultivated land). It was evident that the highest relative ratio of PhytOC between different soil types was as high as 2,400 %. This was probably because the different hydrothermal conditions of cultivated lands resulted in significant difference in soil properties.

Studies of PhytOC in some plants have demonstrated that the PhytOC content was mainly controlled by the efficiency of carbon trapping during the deposition of phytoliths in plant (Parr et al. 2009, 2010; Parr and Sullivan 2011; Zuo and Lu 2011). It implied that the capacity of trapping carbon during plant growth probably was another major factor in determining the PhytOC in plant and soil. As shown in Fig. 3, bamboo and sugarcane occluded more carbon in phytolith than wheat and millet. It is well known that the former two

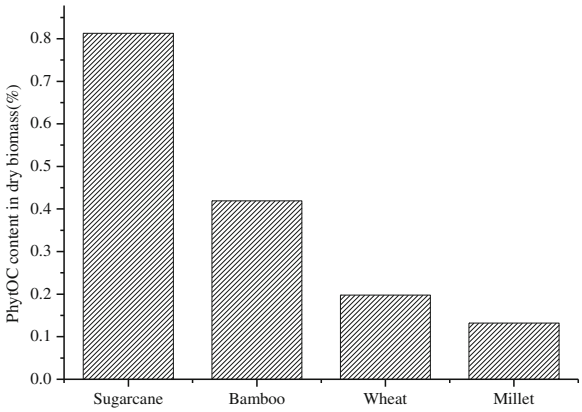

Fig. 3 Average PhytOC content in dry biomass for some plant species (Parr et al. 2009, 2010; Parr and Sullivan 2011; Zuo and Lu 2011)

favored wetter and warmer conditions than the latter two. This suggested that environmental conditions, especially temperature and precipitation, probably had an influence on the PhytOC content in plants. A generally higher SPCD in the Southern Plateau could thus be attributed to the higher capacity of trapping carbon in plants because the mean temperature and precipitation decreased along a gradient from south to north in the CLP. However, this conclusion needed further examination since a limited knowledge of phytolith formation and carbon encapsulation within plant.

Although the SPCD showed a gradient from south to north in the CLP, there were outliers such as soil profiles Huining and Ningwu (Table 2 and Fig. 2). Those outliers were partly explained by the following several reasons. First, a portion of phytolith content in ~30 cm depth of soil profiles probably inherited from the previous vegetation (Blinnikov et al. 2013; Borrelli et al. 2008). Second, other factors such as local topography also had a certain impact on the rate of soil phytolith accumulation. Cary et al. (2005) found that a swamp in low land accumulated as two to three times phytoliths as the high elevations. Third, although we already collected 26 soil profiles generally covering the most part of the Plateau, a further discussion of the distribution of soil PhytOC needed more soil profiles especially from the northern and western parts of the Plateau.

The fate of phytolith and PhytOC in soil

As presented in Table 2, the mean soil PhytOC content was 0.024‰ in the Loess Plateau. It is much lower than the PhytOC in paddy soil (0.203‰; Chen and Zhang 2011). The average soil PhytOC density of the upper 30 cm was estimated to be 8.754 g/m^2. According to a soil profile with 200 years sediment (5 cm) at Numundo in Papua New Guinea, the estimated SPCD was 176 g/m^2 (Parr and Sullivan 2005). Although no exact accumulation rates were estimated for the depth of 30 cm of soil profiles, they certainly might have received a long-term deposition probably up to thousands of years because the upper soil layers generally were developed over the past 3,000 years in the CLP (Tang and He 2004). In contrast to Numundo soil, why was the SPCD from soil profiles in the CLP relatively low? Actual phytolith accumulation rate, phytolith dissolution, and phytolith migration were three major aspects to be considered for possible explanations.

As estimated by Zuo and Lu (2011), Chinese dry-farming crop such as millet accumulated PhytOC at a rate of 1 g/m^2 per year. However, large amount of nongrain dry biomass producing more phytolith were used for forge, industry materials, and bioenergy (Liu et al. 2008). Generally, only about 15 % of total nongrain biomass finally returned to soil (Liu et al. 2008). Once those phytoliths are deposited, they underwent the dissolution as well as the migration. Phytoliths preferred an acid environment (e.g., paddy soils) for good preservation (Fraysse et al. 2006). However, soil pH in the CLP usually ranged from 8 to 9 (National Soil Survey Office 1995b). Alkaline soil with pH above 8 usually increased the dissolution and erosion of phytoliths (Fraysse et al. 2009; Piperno 2006). In addition to a higher soil pH, agricultural practices such as use of N fertilization might accelerate dissolution of phytolith by release of H+ during the nitrification of the applied NH_4+ (Gollany et al. 2006). Both the dissolution and erosion caused few well-preserved phytoliths found in the upper soil of the CLP. As shown in Fig. 4, most of phytoliths were either broken or extensively weathered. Overall, such situation in the CLP not only decreased in situ phytolith accumulation rate but also release CO_2 from occluded carbon in phytoliths.

Besides the erosion and dissolution of phytoliths, phytoliths were also migrated and transported in terrestrial ecosystem. Factors causing phytolith migration mainly include wind (Latorre et al. 2012) and water transportation. Water (precipitation) transportation moved phytoliths downward soil transaction or to redeposit at other places. The CLP is one of the regions with the most severe soil erosion in the world (Feng et al. 2010). According to Chen and Luck (1989), the average rates of soil loss were 150 Mg ha^{-1} year^{-1}, which was

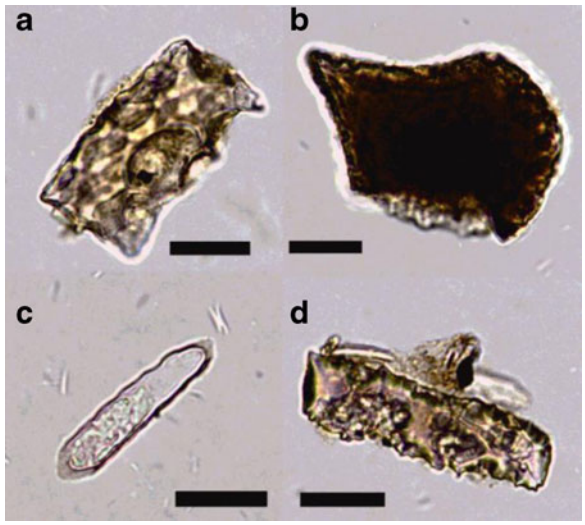

Fig. 4 Extensive excavated phytoliths in upper soil of the CLP **a** elongate, **b** bulliform, **c** trapezoid crenate, **d** elongate (*black bar* 25 μm)

equivalent to a surface lowering of 1.2 cm year^{-1}. Serious soil erosion and leaching on the CLP enhanced the migration and redeposition of soil phytoliths. Crop phytoliths were even recovered in marine sediments because of long-distance transportation by rivers (Lu et al. 2002).

A prolonged tillage history would certainly have great impacts on accumulation rates of phytoliths and PhytOC. As the cradle of Chinese civilization, the CLP has experienced a long history of human activity over 5,000 years (Ren and Zhu 1994). It is evident that long-term export of the nongrain biomass caused that plant Si did not return to the soil and therefore diminished the pool of soil phytoliths (Guntzer et al. 2012). A long agriculture history not only affected vegetation communities (Lu et al. 2003) but also caused the deforestation and degradation of forests and grasslands (Zhou et al. 2011); all of them decreased the annual phytolith and PhytOC production.

Although phytoliths and PhytOC in soil underwent the erosion and transportation, there still were left 5.35 Mt of soil PhytOC in the CLP. They accounted for 0.31 % of soil organic carbon stock in the CLP (Liu et al. 2011). In spite of a relative small stock compared to the total soil organic carbon stock of the Loess Plateau, this carbon fraction, as a kind of the stable soil carbon forms (Parr et al. 2010), really existed in soil and was not determined by the traditional organic analyzed method.

Contribution of phytoliths to biogeochemical cycle of silica

It is well-known that phytoliths have a significant influence on silica biogeochemical cycle through their weathering and migration (Borrelli et al. 2010; Meunier et al. 2008; Street-Perrott and Barker 2008; Lucas 2001). Biogenic silica in river was largely controlled by the production and transportation of phytoliths in terrestrial plants (Struyf and Conley 2009; Blecker et al. 2006). Although the importance of phytoliths to terrestrial silica cycle have been recognized (Ding et al. 2011), their contribution to DSi has not been quantified. For example, about 1.42 Mt SiO_2year^{-1} absorbed by wheat plants was estimated without regard to the retention, dissolution, and actual accumulation of the phytolith (Alexandre et al. 1997). A recent study of global terrestrial silica pump provided the first estimation of silica sink (Carey and Fulweiler 2012); however, they did not take the actual phytolith accumulation rate into their estimation either.

As discussed above, not all above ground biomass were released into soil especially for the cultivated land because of the recycling of crop residues. Additionally, our estimation of the soil phytolith erosion rate was little higher than the global average yield of DSi (3.3 t km^{2}year^{-1}; Dürr et al. 2011). The total phytolith flux into the Yellow River was about 2.5 Mt year^{-1}, in which it was equivalent to about four times of the flux of dissolved SiO_2 carried by the Yellow River (Ding et al. 2011). Therefore, phytoliths had a noticeable effect on the silica balance of rivers and the transport of silica along the land–ocean continuum. Note that our estimation of the contribution of phytolith to riverine silica cycle still had a lot of uncertainties, just provided insights in estimating terrestrial silica cycle on the regional scale.

Conclusion

An increasing number of studies have indicated that the PhytOC was an important long-term terrestrial carbon reservoir. Despite the significant work on the PhytOC in plants, there has been less attention given to the PhytOC in soil. Our results showed relatively large soil PhytOC variation in the CLP. The distribution of soil PhytOC was generally consistent with the spatial patterns of NPP in the CLP, and thus the soil PhytOC in

different soil types was mainly controlled by different plant communities. The average value of SPCD was 8.754 g/m^2, which is lower than paddy soil profiles. This low SPCD was partly attributed to the erosion, dissolution, and transportation of phytoliths and PhytOC. Although a relative low SPCD occurred because a large number of the PhytOC was leached, the CLP had a stock of 5.35 Mt of PhytOC in its upper soil (~30 cm depth). These leached phytoliths finally transported into rivers might have an important influence on riverine DSi and global biogeochemical cycle of silica. To improve our understanding of the mechanisms of PhytOC accumulation and the biogeochemical cycle of Silica, extending our knowledge of phytolith behavior in soil and mechanism of carbon trapping in phytolith is necessary.

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