Role of phytolith occluded carbon of crop plants for enhancing soil carbon sequestration in agro-ecosystems

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Phytolith occluded carbon (PhytOC) which is stable in the soil environment is considered to be an important fraction of soil organic carbon and substantially contributes to the terrestrial carbon sequestration for long periods (millennia). Phytoliths are silica bodies produced by plants as a result of biomineralization process. During this process, occlusion of carbon also takes place within the phytoliths. Some of the major agricultural crops like barley, maize, rice, sorghum, sugarcane and wheat are known to be prolific producers of phytolith and PhytOC. In India, an estimate indicates that these crops may annually contribute about 87 million tonnes (mt) of PhytOC. Hence, a great potential exists to enhance PhytOC accumulation in the soils of various agro-ecosystems. The rate of phytolith production and the carbon occluded in phytoliths vary among the plant community. In India, an estimate indicates that these crops may annually contribute about 87 mt of PhytOC and growing high PhytOC-yielding cultivars of these crops may additionally produce 1.05 mt of PhytOC. Therefore, selection of high PhytOC-yielding cultivars over low PhytOC-yielding cultivars for agricultural production under different agro-ecosystems offers an opportunity to enhance terrestrial carbon sequestration.

Keywords: Biomineralization, phytolith occluded carbon, soil organic carbon, terrestrial carbon sequestration.

GLOBAL warming and rapid increase in the concentration of atmospheric CO_2 have contributed to an increased awareness of carbon sequestration in the soil. Terrestrial carbon sequestration is fundamental to the global carbon cycle and is being utilized to counter increases in anthropogenic CO_2 emissions. So far several approaches are being adopted to mitigate global CO_2 emissions and to sequester carbon in the soil. However, these approaches restore C in the soil only for a short span of time. Long-term (decades to millennia) soil organic carbon sequestration is believed to be mainly by physical protection of chemically recalcitrant organic matter within organo-mineral complexes[1] and charcoal formation[2]. These mechanisms largely require and are dependant on existing forests and hardwood plantations. On the other hand, the land area available for woody plant production has become limited due to the increasing demand for agricultural production. Therefore, a more recent approach to improve phytolith occluded carbon (PhytOC) accumulation in plants and soils was demonstrated to increase the world carbon stocks of soils in various agro-ecosystems[3–6].

PhytOC, an important fraction of soil organic carbon, is stable in the soil environment and substantially contributes to the terrestrial sequestration of carbon for a long period (millennia)[7,8]. PhytOC fractions remain in the soil for a long period (millennia) that results in the reduction of CO_2 emission from agriculture, as against many other soil organic carbon fractions which may decompose over a much shorter time. PhytOC has been widely studied in archaeological, palaeobotanical, palaeoenvironmental and biogeochemical investigations[9–12]. Morphotypes of silicophytoliths were used in the identification of taxonomical groups of plant species[13–15]. However, from the soil carbon sequestration point of view, there is little information available on the utilization of PhytOC of many agricultural crops[3–6]. Hence, an in-depth knowledge of PhytOC and its potential in long-term carbon sequestration is necessary. In recent years, many researchers have demonstrated that phytolith has a potential to sequester carbon in the soil as PhytOC for a long period[3,6]. The objective of this article is to describe phytoliths, PhytOC and their importance, PhytOC content in plants, and the scope of carbon sequestration potential in agricultural systems across the world.

Phytoliths and their importance

Phytoliths (phyto means 'plant' and lithos means 'rocks' in Greek), also referred to as 'plant opal' or 'plant stone', are silica bodies produced by plants as a result of biomineralization. The soluble silica from the soil, particularly in the form of monosilicic acid ($Si(OH)_4$), is absorbed by the roots and carried to different plant parts through the vascular system. During the subsequent process, the silica is deposited in the intra- and extracellular structures of

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the leaf, stem and root systems[16]. Cell wall, cell lumen and intercellular spaces of the cortex are three sites where silica is mainly deposited in the plant tissues[17]. The amount of silica accumulated in the plant tissues ranges from 0.1% to 10% of the dry weight[18]. The size of the silica bodies that are deposited in the plant tissues mostly ranges between 10 and 30 μm and is occasionally up to 200 μm (ref. 19). The cell-wall deposits of silica often replicate the morphology of the living cells. During the biomineralization process, occlusion of carbon takes place within the phytoliths[20]. These PhytOC are most likely the original cytoplasmic organic constituents[7], simple carbohydrates[12] and cellulose[21] depending upon the location of silicification.

Silica phytoliths in plants perform a variety of functions and provide structural rigidity and mechanical strength to the shoot[22–25]. Silica phytoliths help the plants to survive many abiotic stresses such as salt, metal toxicity, nutrient imbalance, drought, radiation, high temperature, freezing and ultraviolet radiation[26] as well as reduce the impact of biotic stress such as insect pests and fungal diseases on plants.

Morphotypes of biomineralized silicophytoliths

In plants, accumulation of calcium carbonate, calcium oxalate and amorphous silica is a common biomineralization process. The study of plant biomineralization has become an important taxonomic approach as oxalate and carbonate crystals and phytoliths help in plant taxon identification[13–15]. In particular, silicophytoliths are widely used as indicators of past plant communities and environmental conditions where these communities were evolved and developed[27–29]. Biomineralization of silicophytoliths is considered to be an important process as it influences the earth carbon cycle by occlusion of carbon during the silicification process[22]. Morphotypes of biomineralized silicophytoliths have been widely studied and reported in aquatic plants[30], woody plants[31], common grasses[32,33], wild and cultivated rice[34], foxtail millet (*Setaria italica*), common millet (*Panicum miliaceum*)[35] and even in some herbarium specimens[36]. The morphological classes and distribution of grass phytoliths that occur in the sediments belong to a particular taxonomic group of Gramineae which falls under four main classes such as festucoid, chloridoid, panicoid and elongated (Figure 1 and Table 1)[13]. The phytoliths extracted from inflorescence of *Triticum* sp. are papillae, trichome base and dendriform phytoliths (Figure 2)[37]. Maize and domesticated squash mostly contain dendriform phytoliths in their leaves (Figure 3)[38].

Evidently, the presence of phytoliths in different plant families is well documented[39,40]. Attempts have been made to distinguish phytoliths in cultivated crops from those of wild plants, especially wild relatives of crop plants[38,41,42]. During the last two decades, phytoliths of 12 domesticated plants and their wild relatives have been widely studied[43]. These domesticated plants include maize, squash and gourd, bottle gourd, cassabanana, arrowroot, rice, banana, ensets, barley, einkorn wheat, emmer wheat and bread wheat. In maize, eight distinct morphological variants of cross-body (quadralobate) phytoliths have been reported[17,38]. This is used to differentiate maize and its wild species utilizing a combination of size and three-dimensional shape attributes. In rice genus *Oryza*, unique type of double-peaked hair-cell phytoliths is reported[44,45]. Wave pattern of the long cell walls in the glumes of wheat and barley has been found useful in discriminating both taxa[46]. Phytoliths of a bamboo genus, *Pleioblastus* have been recorded in parts of soils dated to the last interglacial period (130,000–74,000 BP) from Japan[47]. Phytoliths can be used as palaeoenvironmental markers to understand the past environmental conditions. Such information is valuable in palaeoecological studies on monitoring climate change and reconstructing past vegetation[47–49].

Phytoliths, PhytOC content and their variability in plants

The rate of phytolith production and the amount of carbon occluded in phytoliths vary among the plant commu-

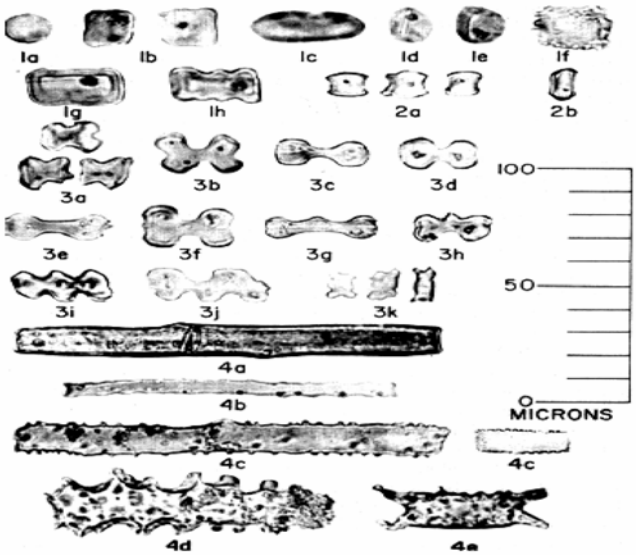

Figure 1. Morphological shapes of grass phytoliths[13]. 1. Festucoid class: 1a, Circular; 1b, Rectangular; 1c, Elliptical; 1d, Acicular, variable focus; 1e, Crescent, variable focus; 1f, Circular crenate; 1g, Oblong; 1h, Oblong, sinuous. 2. Chloridoid class: 2a, Chloridoid; 2b, Thin chloridoid. 3. Panicoid class: 3a, Cross, thick shank; 3b, Cross, thin shank; 3c, Dumbbell, long shank; 3d, Dumbbell, short shank; 3e, Dumbbell, long shank, straight or concave ends; 3f, Dumbbell, short shank, straight or concave ends; 3g, Dumbbell, nodular shank; 3h, Dumbbell, spiny shank; 3i, Regular, complex dumbbell; 3j, Irregular, complex dumbbell; 3k, Crenate. 4. Elongate class (no subfamily characteristics): 4a, Elongate, smooth; 4b, Elongate, sinuous; 4c, Elongate, spiny; 4d, Elongate, spiny with pavement; 4e, Elongate, concave ends.

Table 1. Distribution of phytoliths in common grasses of Gramineae[13]

	Festucoid class 1								Chloridoid class 2		Panicoid class 3											Elongate class 4				
Species of grass	a	b	c	d	e	f	g	h	a	b	a	b	c	d	e	f	g	h	i	j	k	a	b	c	d	e
Bromus inrrmis Ieyss.	C	C	C			C	C	C														A		A		
Festuca elatior L.	R	R	C	C	C																		A	A		
Poa pratensis I.	C	C	C	C	C	C	C															A		A	R	
Triticum aestivum I.	C	C		C	C	C		C														C		A	C	
Aristida sp. L.	C	C	C										C		C							C		A		
Bouteloua curtipendula (Michx.) Torr.									C	C												A	C	A		
Bouteloua gracilis (H. B. K.) Lag. and Steud.									C	C												A		A		
Bouteloua hirsuta Lag.									C	C												A		A		
Buchloe dactyloides (Nutt.) Engeim.									C	C												A	C	A		C
Bambusa sp.									C	C													A	A		
Sorghum vulgare Pers.																						A	C	A	C	
Panicum virgatum L.											C	R	C	C		C	R	R	R			A	C	C		
Andropmon gerardi Vitman											C		C	C	C		R		R			A	A	A		
Andropogon scoparius Michx.											C		C	C	C	C	R	R	R	R	R	A	A	A	R	
Sorghastrum nutans (L.)											C	C	C	C	C	C						R	C	A		
Zea mays L.											C		C	C	C	C	R	R	R		R	C	C	A		
Hilaria mutica (Buck1.)											C			C				R	R					A	A	
Benth.	C	C									R			C	C	C										

A, Abundant; C, Common; R, Rare; No designation, None.

nities and also within the community. Many plant species are considered to be effective silica accumulators in the form of monosilicic acid, whereas other plant species can exclude effectively the uptake of monosilicic acid[50]. Higher plants have been categorized into three groups according to their silicon content (SiO_2, expressed as a percentage of shoot dry weight): (1) members of Cyperaceae and wetland species of Gramineae (e.g., rice) with 10–15%, (2) dryland species of Gramineae (e.g., wheat, sugarcane) and a few dicotyledons with 1–3% and (3) most dicotyledons, especially legumes with less than 0.5% (ref. 50). Although silica occurs in many plants, some tree species and grasses such as Poaceae and Cyperaceae are generally considered as the most prolific producers of phytoliths[51–56]. Most of the cell-wall deposits of silica contain occluded carbon and are generally found in herbaceous plants. The grasses are particularly good at occluding carbon via silica biomineralization processes[6]. As a result, long-term phytolith accumulation rates under grasslands are commonly 5–10 times greater than under forest land[57].

Many studies have been reported on phytolith content and its variability among different cultivars of agricultural crops like wheat, maize, sugarcane and rice, and even in some grasses like bamboo[5]. In rice, SiO_2 accumulation up to the level of 10% of shoot dry weight has been observed[18]. The SiO_2 content and its distribution in different plant parts of rice vary widely and 65.5% of silica is deposited in leafs compared to other plant parts of rice (Table 2)[58]. In wheat and sugarcane, phytolith content varies from 2.68% to 7.85% (ref. 4) and 1.3% to 2.6% (ref. 6) respectively.

The occluded carbon contents in phytoliths also vary widely. For example the carbon content in phytoliths extracted from oats varies from 5.0% to 5.8% (ref. 20) and in sugarcane[6] from 3.88% to 19.26%. Significant variation was reported in PhytOC content of different varieties of sugarcane (Table 3)[6]. It is the efficiency by which carbon is encapsulated within silica, rather than the quantity of silica accumulated by the plant, which is an important factor in determining the relative PhytOC yields[4,6]. The PhytOC yield of a sugarcane crop was 18.1 g C m^{-2} yr^{-1}, an accumulation rate that is substantial over a long period (millennia) and yet comparable to the rates of carbon sequestration that are achievable (but only for a few decades) by land-use changes[6]. The rate of silica accumulation and carbon bio-sequestered within the silica phytoliths of the leaf and stem material of 53 wheat (*Triticum* sp.) cultivars sourced from 25 countries around the world was examined[4], which showed that PhytOC content of wheat cultivars ranged from 0.06% to 0.60% of dry leaf and stem biomass. The phytolith carbon bio-sequestration potential of wheat cultivars is reported to be 0.246 t e-CO_2 ha^{-1} yr^{-1} (ref. 4). These phytolith carbon bio-sequestration rates indicate a substantial potential (~50 mt e-CO_2 yr^{-1}) for increasing the rate of carbon bio-sequestration in wheat (Table 4)[4]. Globally bamboo leaf litter has PhytOC yields of up to 0.7 t e-CO_2 ha^{-1} yr^{-1}.

According to Parr *et al.*[5], bamboo and sugarcane have a global potential to bio-sequestrate PhytOC of about ~1.5 billion t e-CO_2 yr^{-1}, which is equivalent to 11% of the current annual increase in atmospheric CO_2. Hence, this process offers the opportunity to use the plant species that yield high amounts of PhytOC to enhance terrestrial carbon sequestration. There are studies which demonstrate that simply growing high PhytOC-yielding cultivars over low PhytOC-yielding cultivars results in additional sequestration of carbon in the soil by ~0.25 t e-CO_2 yr^{-1} ha^{-1} for sugarcane[6] and ~0.2 t e-CO_2 yr^{-1} ha^{-1} for wheat[4] respectively.

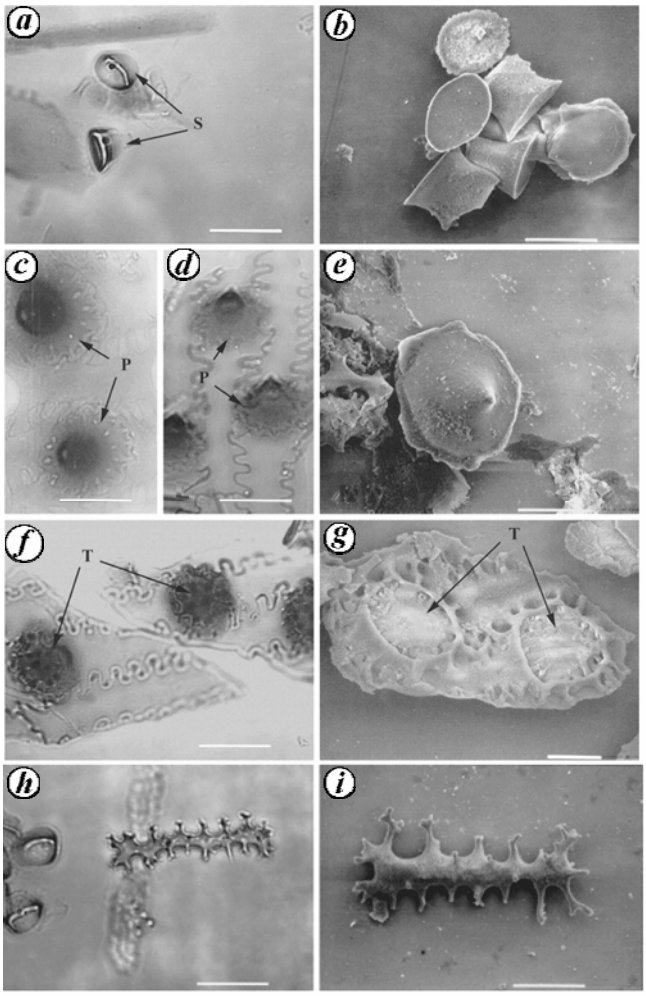

Figure 2. Phytoliths extracted from the inflorescence bracts of *Triticum* sp.[37]. S, Silica cell phytoliths; P, Papillae phytoliths; T, Trichome base phytoliths. ***a***, Light micrograph of silica cell phytoliths from *T. monococcum*; bar = 25 µm. ***b***, Scanning electron micrograph of silica cell phytoliths from *T. aestivum*; bar = 10 µm. ***c***, Light micrograph of papillae phytoliths from *T. aestivum*; bar = 25 µm. ***d***, Light micrograph of papillae phytoliths from *T. monococcum*; bar = 25 µm. ***e***, Scanning electron micrograph of papillae phytolith from *T. aestivum*; bar = 10 µm. ***f***, Light micrograph of trichome base phytoliths from *T. monococcum*; bar = 25 µm. ***g***, Scanning electron micrograph of trichome base phytoliths from *T. aestivum*; bar = 10 µm. ***h***, Light micrograph of dendriform phytolith from *T. aestivum*; bar = 25 µm. ***i***, Scanning electron micrograph of dendriform phytolith from *T. aestivum*; bar = 10 µm.

PhytOC accumulation in soil

On a global scale organic carbon stored in the soil quantitatively dominates the carbon cycle, out-storing the possible carbon stored in the current vegetation cover by at least two-fold[59]. It has the potential to assist in the mitigation of greenhouse gas emissions with appropriate management[60,61]. The carbon occluded in the phytoliths has been demonstrated to be an important long-term terrestrial carbon fraction in the soil. For example, after 2000 years of *in situ* decomposition in Numundo sites of Australia, PhytOC was representing up to 82% of the total soil carbon in buried topsoils of up to 2 m depth, whereas the concentration of the total carbon fraction decreased markedly over this period (Figure 4)[3]. Although PhytOC was a relatively minor fraction of the soil carbon in the young Numundo topsoils (200 years), most of the other soil organic matter components were considerably decomposed in the older topsoils, resulting in PhytOC comprising a mean of 42% of the total carbon pool in these well-drained soils after 1000 years. Moreover, it has been demonstrated that relative to the soil organic carbon fraction that decomposes over shorter timescales, PhytOC is highly resistant against decomposition and persists in the soil environment for a long period[3,7,8,62]. Radiocarbon dating of the phytoliths, extracted from palaeosols and peat sediments, indicated ages of at least 8,000 yrs BP (i.e. before 1950)[3] to 13,300 ± 450 BP (ref. 9).

Phytoliths may experience a range of fates in terrestrial environments. For example, erosion, transportation by wind or water, loss due to burning in a forest fire, or biochemical changes while passing through the digestive systems of animals. Regardless of such fates, the potential of stability and persistence of phytoliths against such

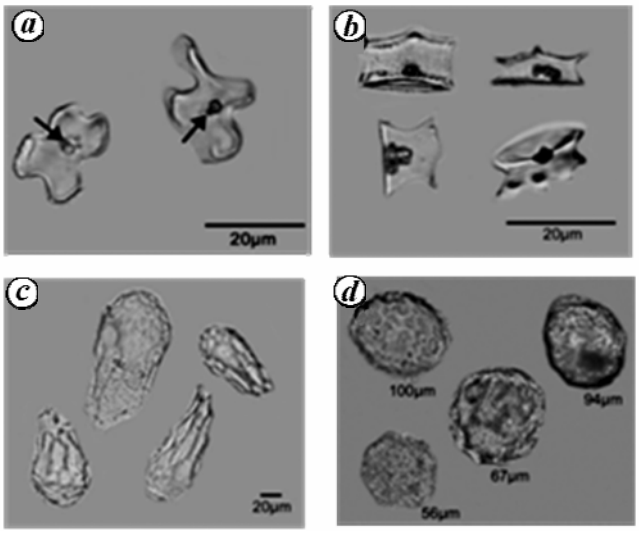

Figure 3. Light micrograph of dendriform phytolith from (***a***) maize leaves, (***b***) maize cobs, (***c***) domesticated squash species *Cucurbita moschata* and (***d***) *Cucurbita maxima*[43].

Table 2. SiO_2 concentration, accumulation and distribution in different plant parts of rice[58]

Plant part	SiO_2 concentration (% dry wt)	SiO_2 accumulation (g per plant)	SiO_2 distribution (% total silica)
Root	4.98 ± 0.84	0.171	3.41
Stem	8.30 ± 1.17	0.686	13.67
Leaf	21.61 ± 1.86	3.290	65.56
Husk	23.22 ± 0.29	0.863	17.20
Grain	0.11 ± 0.01	0.008	0.16

Table 3. Si-phytolith content, carbon content of phytolith, phytolith occluded carbon (PhytOC) content and yield of sugarcane varieties and PhytOC yield in carbon dioxide equivalents (e-CO_2) per hectare per year (for new (N) and ratoon (R) plantations)[6]

Sugarcane cultivar	Phytolith content of plant material (%)	Carbon content of isolated phytoliths (%)	PhytOC content of dry plant material (%)	PhytOC yield (kg ha^{-1} yr^{-1})	PhytOC yield* (t e-CO_2 ha^{-1} yr^{-1})
N-1	1.6	12.35	0.198	79.04	0.290
N-2	2.6	6.06	0.158	63.02	0.231
R-3	1.9	8.51	0.162	64.68	0.237
R-4	2.2	3.88	0.085	34.14	0.125
N-5	2.5	9.56	0.239	95.60	0.350
R-6	1.9	11.81	0.224	89.76	0.329
R-7	1.5	11.21	0.168	67.26	0.247
N-8	2.0	11.66	0.233	93.28	0.342
R-9	1.3	19.26	0.250	100.15	0.368
N-10	2.2	8.40	0.185	73.92	0.271

*Assuming dry biomass production of sugarcane as 40 t ha^{-1} yr^{-1}.

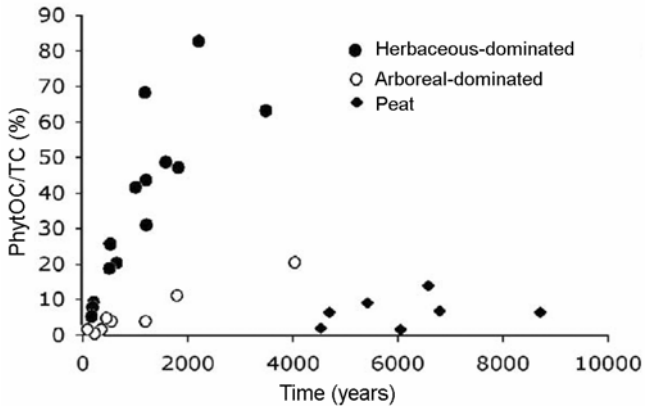

Figure 4. Phytolith occluded carbon (PhytOC) as a proportion of total carbon (TC) over a time for the Numundo (West New Britain) upland buried soils, and a peat wetland soil dominated by Restionaceae and Cyperaceae species[3].

processes has been well documented[63–73]. The rate of phytolith accumulation in the soil is also affected by factors other than plant species, including soil properties, climate and geomorphology[57]. The quantity of phytoliths in the soil varies from several orders of magnitude at the regional scale[57] depending upon the type of phytolith containing above-ground biomass. For example, variations in opal yield in plants ranged from 10 kg ha^{-1} yr^{-1} in conifer forest of arid New Mexico[74] to 300 kg ha^{-1} yr^{-1} in prairie grassland of temperate Oregon[75]. Although the concentration of phytoliths in the soil generally constitutes up to 3% on a total soil basis[57], some soil horizons, particularly the upper layer (5–30 cm) of tropical podsols of biogenic origin are almost completely composed of siliceous phytoliths[76].

Estimated annual PhytOC accumulation rates (0.72–0.88 g C m^{-2} yr^{-1}) in the tropical and subtropical sites are reported to be similar[3]. In the case of temperate soils, the average PhytOC accumulation rate was 15 g m^{-2} yr^{-1} (ref. 9). But in similar soils in Ohio, the average carbon content of phytoliths was 2.40% and PhytOC accumulation rate was 0.36 g C m^{-2} yr^{-1} (ref. 9). PhytOC accumulation rates have contributed about 15% and 37% to the estimated global mean long-term soil carbon accumulation rate of 2.4 g C m^{-2} yr^{-1} over the last 10,000 years[59].

Potential and contribution of PhytOC from agricultural systems

Most of the economically important agricultural plant species, viz. barley, maize, rice, sorghum, sugarcane and wheat are considered to be producers of phytoliths[77–79]. These agricultural crops contain a significant amount of PhytOC in their straws/stovers with considerable variation within cultivars[4,6]. Generally, it is assumed that only about 30% of total non-grain biomass produced from these crops finally reaches the soil through residue incorporation, wastes after feeding the animals, animal excreta, farmyard manure in the form of compost and burnt ash.

Table 5 shows estimate of PhytOC contribution from some of the widely cultivated agricultural food crops like rice, wheat, maize, sorghum, barley and sugarcane

Table 4. Country of origin, accession number, content of phytoliths in dry leaf and stem biomass, PhytOC content, PhytOC content in dry leaf and stem biomass, and estimated PhytOC yield per hectare in t CO_2 equivalents per hectare of wheat[4]

Country of origin	Australian accession number	Phytolith content (%)	PhytOC of phytoliths (%) (sd)	PhytOC of leaf and stem (%)	PhytOC yields t e-CO_2 ha^{-1} yr^{-1}
Afghanistan	13373	3.86	4.03 (0.33)	0.16	0.012–0.064
Australia	15688	6.06	3.58 (0.20)	0.22	0.017–0.089
Australia	1131	6.97	5.65 (0.77)	0.39	0.030–0.161
Australia	25607	4.76	1.63 (0.66)	0.08	0.006–0032
Australia	10398	6.38	1.69 (0.05)	0.11	0.008–0.044
Australia	25271	4.17	4.07 (0.11)	0.17	0.013–0.070
Australia	1924	5.34	11.41 (0.61)	0.59	0.046–0.244
Australia	30434	3.68	3.85 (0.15)	0.14	0.011–0.058
Australia	93	6.39	3.01 (0.05)	0.19	0.015–0.079
Canada	7010	5.25	4.13 (0.23)	0.22	0.017–0.089
China	14011	5.37	4.16 (0.15)	0.22	0.017–0.092
China	13905	4.27	2.25 (0.32)	0.10	0.007–0.039
Croatia	4342	4.12	4.66 (0.17)	0.19	0.015–0.081
Ecuador	20775	5.69	1.80 (0.13)	0.10	0.008–0.042
Egypt	12957	7.85	2.53 (0.22)	0.20	0.015–0.081
Ethiopia	13085	5.29	6.51 (0.51)	0.34	0.026–0.141
Former Soviet Union	20438	7.67	1.29 (0.08)	0.10	0.008–0.04
Greece	4287	4.64	12.91 (0.31)	0.60	0.046–0.246
Iran	19143	3.96	2.68 (0.31)	0.11	0.008–0.044
Iran	19157	2.79	4.65 (0.04)	0.13	0.010–0.053
Iran	19161	3.8	4.41 (0.49)	0.16	0.012–0.064
Iraq	19133	4.19	3.17 (0.19)	0.13	0.010–0.054
Italy	483	5.24	6.97 (0.35)	0.37	0.028–0.150
Italy	12227	7.47	4.89 (0.06)	0.37	0.028–0.150
Japan	21846	4.45	2.03 (0.06)	0.09	0.007–0.037
Kenya	11996	5.49	2.84 (0.01)	0.16	0.012–0.064
Lebanon	4203	4.91	3.48 (0.17)	0.17	0.013–0.070
Lebanon	4205	5.41	3.06 (0.07)	0.17	0.013–0.068
Morocco	5080	5.29	3.88 (0.25)	0.21	0.016–0.084
Nepal	15006	7.63	2.12 (0.03)	0.16	0.012–0.066
Nepal	15028	4.83	5.47 (0.36)	0.26	0.020–0.108
Nepal	15022	5.24	3.32 (0.17)	0.17	0.013–0.071
Nepal	15005	6.72	4.42 (0.31)	0.30	0.023–0.122
Nepal	15025	5.24	3.91 (0.39)	0.20	0.016–0.084
Pakistan	17814	4.67	4.17 (0.38)	0.19	0.015–0.083
Pakistan	17737	3.9	5.17 (0.54)	0.20	0.015–0.083
Pakistan	17741	6.2	4.81 (0.28)	0.30	0.023–0.122
Portugal	3180	2.9	8.79 (1.69)	0.25	0.020–0.104
South Africa	7208	4.75	3.46 (0.25)	0.16	0.013–0.067
South Africa	1844	4.54	1.91 (0.00)	0.09	0.007–0.036
Spain	5639	6.44	4.03 (0.38)	0.26	0.020–0.106
Spain	12091	4.22	2.90 (0.24)	0.12	0.009–0.050
Spain	20103	4.37	2.11 (0.10)	0.09	0.007–0.038
Spain	2088	3.07	6.87 (0.53)	0.21	0.016–0.086
Syria	16132	3.41	4.67 (0.48)	0.16	0.012–0.065
Syria	19111	4.85	4.11 (0.25)	0.20	0.015–0.082
Syria	19114	3.68	2.73 (0.15)	0.10	0.008–0.041
Turkey	5567	3.8	3.87 (1.02)	0.15	0.011–0.060
Turkey	19103	2.68	7.28 (1.32)	0.20	0.015–0.080
Turkey	19189	3.08	1.82 (0.05)	0.06	0.004–0.023
Turkey	19182	3.95	4.53 (0.15)	0.18	0.014–0.073
Turkey	19193	4.29	1.90 (0.02)	0.08	0.006–0.033
The United States	130	4.95	4.41 (0.05)	0.22	0.017–0.089

Note: All the species were grown on the same paddock at the Biloela Agricultural Research Station, Queensland, Australia. Representative leaf and stem samples of the wheat cultivars were collected at a growth stage of 11.3 following Feeke's scale.

based on available data on area of cultivation[80]. Phytolith content in the plant biomass and amount of PhytOC that reaches the soil were estimated based on the information available in the literature[4–6,38]. The estimate showed that the above-said crops globally produce PhytOC to the tune of 5.08–12.01 mt yr^{-1}, of which 1.52–3.60 mt

Table 5. Estimation of PhytOC production of some widely cultivated agricultural crops of the world

Crop	Area (m ha)	Straw/stover yield (t ha^{-1})	Total straw (mt yr^{-1})	Phytolith content of straw (%)		Phytolith production (mt yr^{-1})		*PhytOC production (mt yr^{-1})	
				Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Rice	153	4.0	612	5.0	15.0	30.60	91.80	1.53	4.59
Wheat	218	3.5	763	3.5	6.0	26.70	45.78	1.33	2.29
Maize	145	6.0	870	2.0	7.0	17.40	60.90	0.87	3.05
Sorghum	44	5.0	220	9.0	12.0	19.80	26.40	0.99	1.32
Sugarcane	16	25.0	400	1.3	2.6	52.00	10.40	0.26	5.20
Barley	56	3.0	168	1.2	3.0	20.10	50.40	0.10	2.52

*Calculated taking average carbon content of phytoliths as 5% (refs 3–6).

Table 6. Estimation of total PhytOC production potential in India

Crop	Area (m ha)	Straw/stover yield (t ha^{-1})	Toal straw (mt)	Phytolith content of straw (%)		Phytolith production (mt)		*PhytOC production (mt)	
				Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Rice	44.0	3.0	132.0	5.0	15.0	6.60	19.80	0.330	0.990
Wheat	28.0	4.0	112.0	3.5	6.0	3.92	67.20	0.196	0.336
Maize	8.4	5.0	42.0	2.0	7.0	0.84	29.40	0.042	0.147
Sorghum	9.2	6.0	55.2	9.0	12.0	4.97	66.24	0.248	0.331
Sugarcane	4.3	20.0	86.0	1.3	2.6	1.12	22.36	0.056	0.112
Barley	0.8	4.0	3.2	1.2	3.0	0.04	0.10	0.002	0.005

*Calculated taking average carbon content of phytoliths as 5% (refs 3–6).

PhytOC accumulates in the soil every year. Further, inclusion of high PhytOC-yielding cultivars in agricultural systems may contribute about 2.08 mt C yr^{-1} to the soil[6]. Thus, it contributes substantially to the soil carbon stock.

In India, the major cereal crops grown are rice, wheat, maize and sorghum, and in many parts of the country these crops are cultivated during two or three seasons in a year. The area under cultivation of rice, wheat, maize, sorghum, sugarcane and barley in India is 44, 28, 8.4, 9.2, 4.2 and 0.8 m ha respectively[81]. Considering the reported range of phytolith content and average 5% carbon content of phytolith, total phytolith and PhytOC yields for these crops are approximately 17.48 and 0.87 mt respectively (Table 6). At the same time if we take maximum phytolith content for these crops, the values are 38.41 mt of total phytoliths and 1.92 mt of PhytOC respectively (Table 6). Thus, by replacing low PhytOC yielding cultivars with high PhytOC yielding cultivars, 1.05 mt of additional PhytOC production can be enhanced annually.

Fate of PhytOC and its management in soil

PhytOC is a stable inert carbon fraction which remains in the soil for a long period. But it is transported to different places by wind, water, bioturbation and other mechanical means. However, the biochemical change of this fraction, particularly microbial oxidation, is very low or may not even take place. There are evidences that have revealed that PhytOC is not affected by forest fire, or biochemical changes that occur in the intestine of mammals while it passes through an animal's stomach during digestion. There are many reports on the translocation of this carbon fraction within the soil. Alexandre *et al.*[82] reported translocation to a depth of 2.2 m in a ferrallitic soil, with a slight accumulation in an impermeable clay layer at 1.3–1.4 m. Humphreys *et al.*[83] attributed the distribution pattern in Podzol mainly to translocation with percolating water. In contrast, Piperno[43] pointed out that the magnitude of transport is probably minimal because phytoliths occur commonly only in the upper part of recent soils and their concentration usually decreases in B horizons. The main factor which is responsible for the translocation of PhytOC is its size and shape. Larger sized fractions are mainly remains in the upper layer of the soil[84]. Indeed, the diameter of phytoliths ranges between 5 and 50 μm (equal to the size of silt fractions in the soil). Although silt particles are less mobile than clay particles, the downward translocation of phytolith in the soil has been reported by several workers. Thus, PhytOC is relatively mobile in the soil.

Several soil processes and soil characteristics affect the phytolith distribution in a soil profile other than direct translocation mechanisms. These include the availability of macropore channels, the intensity of phytolith aggregation with clay particles, organic substances and oxides, and phytolith dissolution. A potential key determinant of phytolith transport is soil structure, in particular, continuity of macropore channels[85]. Field experiment on phytolith transport provided direct evidence for significant

downward translocation in a loamy sand (Cambisol) and a silty loam (Luvisol) in southern Germany[86]. The mean travel distance after one year was 3.99 ± 1.21 cm in the Cambisol and 3.86 ± 0.56 cm in the Luvisol. About 50% of the phytoliths were recovered below 5 cm depth in both soils[86]. Transport in intact soil was significantly faster than in packed sand, indicating a crucial role of continuous macropores in transport efficiency.

It was estimated that conversion of cultivated agricultural land to either forest or grasslands contributes about 33.5 g C m^{-2} yr^{-1} (ref. 1) and switching from conventional to no tillage practices resulted in additional carbon sequestered by 50.7 g C m^{-2} yr^{-1} (ref. 87). Carbon sequestration benefits provided by continuous cropping and changes in tillage practices can be further enhanced through PhytOC accumulation in the soil by growing high PhytOC-yielding cultivars.

Conclusions and future perspectives

To sum up, the opportunity exists to enhance both short- and long-term carbon sequestration by cultivation of high PhytOC-yielding plant species of agricultural crops. The carbon sequestration potential of sugarcane varieties ranged from 0.12 to 0.66 t e-CO_2 ha^{-1} yr^{-1}. Therefore, preference of high PhytOC-yielding variety over low PhytOC-yielding variety results in a net increase of 0.54 t e-CO_2 ha^{-1} yr^{-1} of carbon securely sequestered in phytoliths. Phytolith production may vary depending upon the cultivars, which in turn depend on environmental and management conditions. All the phytolith produced in plants may not reach the soil. There may be several factors that control phytolith accretion in the soil. They are crop factors like crop species and age, parts of the plant it accumulated, phytolith content, size and shape of the phytolith and amount of crop residue that reaches the soil, and soil factors like structure, particularly macropore channels, texture, clay content, soil water and microbial communities and its activity in the soil. Hence, PhytOC produced in the plants species under a specific environmental and management situation and the amount that reaches the soil should be quantified. The processes and properties that affect the stability and the losses of PhytOC from the soil need to be studied extensively. The potential of PhytOC fraction for increasing soil carbon sequestration in different crop production systems needs to be re-examined.

In future, studies should be mainly focused on the application of breeding and biotechnological tools for identification of the trait that would result in identification of crop cultivars with much greater PhytOC yields. Such a plant-breeding programme would provide growers with even greater opportunities to securely bio-sequester carbon in their crops than that exists at present. Enhancing the potential of PhytOC production and accumulation in crop species through external application of silica needs to be explored.

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