Science of the Total Environment 603–604 (2017) 502–509

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Phytolith carbon sequestration in global terrestrial biomes

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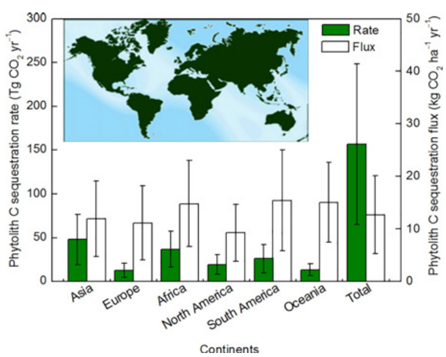
HIGHLIGHTS

- Carbon occluded within phytolith is a stable bio-geochemical C sink mechanism.
- Phytolith C sequestration in global terrestrial biomes is 156.7 ± 91.6 Tg CO_2 yr^{-1}.
- The main contributors are Asia (31%), Africa (24%), and South America (17%).
- Appropriate practices could theoretically double the phytolith C sink in global terrestrial biomes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form 7 June 2017
Accepted 13 June 2017
Available online 20 June 2017

Editor: Jay Gan

Keywords:
Phytolith-occluded carbon (PhytOC)
Biogeochemical carbon sequestration
Carbon sink
Silicon
Terrestrial biomes

ABSTRACT

Terrestrial biogeochemical carbon (C) sequestration is coupled with the biogeochemical silicon (Si) cycle through mechanisms such as phytolith C sequestration, but the size and distribution of the phytolith C sink remain unclear. Here, we estimate phytolith C sequestration in global terrestrial biomes. We used biome data including productivity, phytolith and silica contents, and the phytolith stability factor to preliminarily determine the size and distribution of the phytolith C sink in global terrestrial biomes. Total phytolith C sequestration in global terrestrial biomes is 156.7 ± 91.6 Tg CO_2 yr^{-1}. Grassland (40%), cropland (35%), and forest (20%) biomes are the dominant producers of phytolith-based carbon; geographically, the main contributors are Asia (31%), Africa (24%), and South America (17%). Practices such as bamboo afforestation/reforestation and grassland recovery for economic and ecological purposes could theoretically double the above phytolith C sink. The potential terrestrial phytolith C sequestration during 2000–2099 under such practices would be 15.7–40.5 Pg CO_2, equivalent in magnitude to the C sequestration of oceanic diatoms in sediments and through silicate weathering. Phytolith C sequestration contributes vitally to the global C cycle, hence, it is essential to incorporate plant-soil silica cycling in biogeochemical C cycle models.

1. Introduction

Motivated by rapid increases in global emissions of carbon dioxide (CO_2), many scientists have recently focused on terrestrial carbon (C) sequestration (Heimann and Reichstein, 2008; Pan et al., 2011; Peters et al., 2013; Taylor et al., 2016). Phytoliths are microscopic silica bodies

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http://dx.doi.org/10.1016/j.scitotenv.2017.06.107
0048-9697/

that form inside tissues in living plants and, in doing so, occlude carbon into the silica lattice (Piperno, 2006; Alexandre et al., 2015). Although accumulation of phytolith-occluded carbon (PhytOC) in soils is slow on an annual-decadal scale, it may contribute ~15–37% of the global mean long-term (10,000 years) soil carbon sequestration rate (Parr and Sullivan, 2005). Based on these calculations, it has been suggested that occlusion of C within phytoliths is an important biogeochemical carbon sequestration mechanism (Parr and Sullivan, 2005; Parr et al., 2010; Song et al., 2012a, 2012b).

A wide range of vascular land plants produce phytoliths that occlude carbon (Smith and White, 2004; Strömberg et al., 2016). Soils contain 400–1000 times more PhytOC than the aboveground biomass for most ecosystems, demonstrating that PhytOC is highly resistant to decomposition and may accumulate in soils and sediment for several hundreds or thousands of years (Meunier et al., 1999; Parr and Sullivan, 2005; Blecker et al., 2006)—if not millions of years (Prasad et al., 2005; Strömberg, 2011). Previous work has estimated the amount of PhytOC produced from leaf litters within grassland (Song et al., 2012a), forest (Parr et al., 2010; Song et al., 2013a) and cropland (Zuo and Lü, 2011) ecosystems of a country (China), within different ecosystems of a region (the Chinese Loess Plateau) (Zuo et al., 2014), and within cropland ecosystems across the world (Parr and Sullivan, 2011; Rajendiran et al., 2012; Song et al., 2013b). However, the magnitude and potential of phytolith C sequestration at a global scale and relative to C sequestration as a whole, and how it varies among continents remain unknown.

Here, we present estimates of how much C is sequestered in plant silica within the world's terrestrial biomes based on data of aboveground net primary production (ANPP) of silicon (Si)-rich tissues, phytolith content of vegetation on average in biomes, C contents of phytoliths, and the PhytOC stability factor for terrestrial ecosystems within 100 years (PSF_{100}) estimated from phytolith turnover time ($PSF_{100} = 1 - 100$ / phytolith turnover time) (Materials and methods). Because phytoliths are mainly produced from the aboveground parts of the biomes (Parr et al., 2010; Parr and Sullivan, 2011) and we are mainly interested in potential storage of phytoliths (and hence PhytOC) in soils well beyond the life of the plants, we have only included PhytOC input from aboveground litterfall and subsequent accumulation in soils or sediments. To account for variation among biomes in phytolith C sequestration estimates due to differential vegetation distribution and phytolith production in relevant plant types, we divided each continent into forest (including bamboo), grassland, wetland, cropland, tundra, and desert. We then used the relative areal extent and average phytolith production of each biome type when preliminarily calculating continental phytolith C sequestration (for more details see Appendix A).

2. Materials and methods

2.1. Productivity, phytolith and silica content data

From relevant published papers, we obtained ANPP data of herb and/or tree litter (hereafter referred to as Si-rich tissues) for forests (Feng et al., 1999; Parr et al., 2010; Song et al., 2013a), grasslands (Blecker et al., 2006; Ma et al., 2010; Melzer et al., 2010; Alexandre et al., 2011), and other biomes (Li et al., 2013a, 2013b, 2013c; Song et al., 2013b) (Table 1). Forest ANPP in the form of wood and bark for evergreen and deciduous trees was excluded because the Si contribution to the soil pool from wood/bark is negligible compared to leaf biomass (Bartoli, 1983; Li et al., 2006); although note that because tropical woods often contain a lot of silica (Amos, 1952; Welle, 1976), our estimates for tropical regions are conservative. Phytolith and silica content data were obtained from published monographs (Hou, 1982; Xu et al., 1998) and papers (Ding et al., 2008; Parr and Sullivan, 2011; Li et al., 2013a, 2013b, 2013c; Song et al., 2012a, 2013a, 2013b).

2.2. Estimation of phytolith and PhytOC contents

Because the ratio of phytolith/silica for most plants is approximately 1 (Song et al., 2012a, 2013a, 2013b), the phytolith content of plant biomass was estimated from silica content (weight % of plant dry biomass) (Table 2). As most ecosystems contain different plant functional types and even more species, we arrived at one phytolith content value per ecosystem using different phytolith content for different plant functional types within those ecosystems and then averaged those based on estimated relative ANPP for each plant functional type. Based on our own measurements and data from 22 published papers (up to 199 data points, for more details see Appendix B), the C content of phytoliths mainly extracted by a microwave digestion method varies from 0.1% to >10%. Therefore, we used the average occluded C content in phytoliths of these relevant plants for each ecosystem as a preliminary estimation due to the difficult and extremely labor-intensive measuring of the PhytOC for all plants in different biomes. Based on the analysis of these data, we approximated the average PhytOC content as 2.36% for (sub-) tropical forest, 2.37% for temperate forest, 3.06% for boreal forest, 1.85% for grassland (including tropical savanna and temperate steppe), 1.59% for wetland, 4.21% for cropland, 2.67% for shrubland, and 1.5% for

Table 1
General information on global terrestrial biomes.

Biomes	Area (10^6 ha)	Above ground Si-rich tissues	ANPP of Si-rich tissues ($t\ ha^{-1}\ yr^{-1}$)[c]	References
Forest				
(Sub)tropical forest	1949	Tree leaf litter and herb litter	6.95	*1*
Temperate forest	810	Tree leaf litter and herb litter	6.09	*1*
Boreal forest	1304	Tree leaf litter and herb litter	5.19	*1*
Total or average[a]	4063		6.21	
Grassland				
Tropical savanna	2250	Herb litter	6.89	*2–4*
Temperate steppe	1250	Herb litter	2.06	*2, 3, 5, 6*
Total or average[b]	3500		5.17	
Wetland	330	Herb litter	6.50	*7, 8*
Cropland	1533	Crop straw including sheath, stem and leaf	5.28	*9*
Shrubland	250	Shrub leaf litter and herb litter	3.20	*2, 10*
Tundra	743	Shrub leaf litter, herb litter and moss litter	0.89	*2, 10*
Desert	1925	Shrub leaf litter and herb litter	0.42	*2, 10*
Total or average[b]	12,344		4.52	

1 Song et al., 2013a; *2* Atjay et al., 1979; *3* Melzer et al., 2010; *4* Alexandre et al., 2011; *5* Blecker et al., 2006; *6* Song et al., 2012b; *7* Guo et al., 2008; *8* Zong et al., 2011; *9* Song et al., 2013b; *10* Olson et al., 2001.

[a] Area for different biomes based on Atjay et al. (1979), Costanza et al. (1997) and Pan et al. (2011).

[b] Average weighted by area, calculated from total biome ANPP of Si-rich tissues and total biome area.

[c] ANPP of Si-rich tissues in Shrubland, Tundra, and Deserst was estimated from their NPP data by multiplying an ANPP/NPP ratio of 0.4 (Olson et al., 2001).