Geoderma 312 (2018) 36–44

Contents lists available at ScienceDirect

Geoderma

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

Phytolith accumulation in broadleaf and conifer forests of northern China: Implications for phytolith carbon sequestration

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ARTICLE INFO

Keywords:
Biogenic silica
Long-term carbon sequestration
Phytolith occluded carbon
Soil organic carbon
Silicon-carbon coupled cycle
Temperate forest

ABSTRACT

Carbon (C) occlusion within phytoliths (PhytOC) has a significant potential for long-term C sequestration in forest ecosystems. To unravel the role of forest composition on phytolith production, soil phytolith distribution, and phytolith C sequestration in soils, we investigated community composition and examined phytoliths and PhytOC of mature leaves or needles of dominant trees and understory herbs, as well as soil profiles (50 cm depth) within *Quercus*, *Betula*, *Larix* and *Pinus* forest ecosystems of northern China. Results showed that herb layers contributed 72%, 52%, 40%, and 5% to the flux of phytolith production within *Betula* forest (18.0 ± 1.26 kg ha^{-1} yr^{-1}), *Quercus* forest (28.5 ± 0.77 kg ha^{-1} yr^{-1}), *Larix* forest (37.7 ± 1.80 kg ha^{-1} yr^{-1}) and *Pinus* forest (16.9 ± 0.30 kg ha^{-1} yr^{-1}), respectively. The distribution pattern of soil phytoliths from topsoil to subsoil could be classified into three types: significantly decreasing pattern (*Betula* forest and *Quercus* forest), non-significantly decreasing pattern (*Larix* forest), and initially increasing and then decreasing pattern (*Pinus* forest). Within 0–50 cm soil depth, the PhytOC storage of *Betula* forest, *Quercus* forest, *Larix* forest and *Pinus* forest were 0.29 ± 0.02 t ha^{-1}, 0.67 ± 0.03 t ha^{-1}, 0.46 ± 0.03 t ha^{-1} and 0.37 ± 0.02 t ha^{-1}, respectively. Moreover, the soil PhytOC turnover times of these four forest types were estimated to be 537,503,363 and 560 year, respectively, which were at least 8–20 times slower than soil organic carbon contributing to climate change mitigation. Overall, our findings indicate that composition of the forest community controls the production flux of phytoliths and the distribution of soil phytoliths, and influences the biogenic silica and its coupled carbon cycles.

1. Introduction

Forests store about 90% of all living terrestrial biomass carbon (C) on earth and afforestation/reforestation has been regarded as an effective solution to reduce atmospheric carbon dioxide (CO_2) (Christian, 2003). In China, national-scale projects including afforestation and reforestation have been launched in the past several decades (Fang et al., 2001; FAO, 2010). Although the estimated average CO_2 accumulation rate of Chinese forests is up to 110 t CO_2 ha^{-1} yr^{-1} (FAO, 2010), approximately 95% of the previously sequestered CO_2 will be released to atmosphere with only 5.5 t CO_2 ha^{-1} yr^{-1} captured by soil as organic C (Dewar and Cannell, 1992). The biogeochemical C sequestration by phytoliths provides a longer-term opportunity to sequester atmospheric CO_2 (Parr and Sullivan, 2005; Parr et al., 2010; Song et al., 2016).

Both understory herbs and tree leaves (or needles) in forest ecosystems play a crucial role in the biogeochemical silicon (Si) cycle and subsequent phytolith C sequestration (Zhang et al., 2012; Song et al., 2013), though underground fine roots may also contribute to soil Si content (Maguire et al., 2017). Generally, the leaves accumulate 50%–88% of the Si following root absorption of soil soluble Si (Chen et al., 1997; Carnelli et al., 2001; Feng et al., 1999; Umemura and Takenaka, 2014). In forest ecosystems, leaf litter could contribute between 28 and 87% of the total litter biomass (Chen et al., 1997; Carnelli

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http://dx.doi.org/10.1016/j.geoderma.2017.10.005
Received 4 July 2017; Received in revised form 4 October 2017; Accepted 6 October 2017
Available online 13 October 2017

et al., 2001), meanwhile understory vegetation contributes approximately 28% of the annual net primary production (ANPP) (Chen et al., 1997; Feng et al., 1999; Song et al., 2013; Yang et al., 2015). Therefore, the understory herbs are also indispensable for the structure and function of forest ecosystems, especially for the nutrient cycling (e.g. nitrogen, Si and C) in forests ecosystems (Gilliam, 2007; Song et al., 2013).

Phytoliths are the main products of Si deposition inside cells and cell walls of plant bodies after plant absorption of the dissolved Si in the form of $Si(OH)_4$ or H_4SiO_4 from soil solution (Wilding, 1967; Epstein, 1994). Compared to lumen phytoliths, cell wall phytoliths generally contain less proteins, lipids and possibly nucleic acids (Hodson, 2016). The role of phytoliths in plants is diverse and multi-functional when the plants undergo adverse conditions (Epstein, 2009). For example, phytoliths can enhance the resistance against biotic and abiotic stress of many terrestrial plants, especially grasses (e.g. Cyperaceae and Poaceae) (Epstein, 2009). Furthermore, the morphology and chemical composition of phytoliths and environmental conditions would be expected to affect C sequestration in phytoliths (Song et al., 2016). In the plant kingdom, the phytolith content of plant dry weight varies greatly, being between 0.1% to > 10% (Epstein, 1994; Carnelli et al., 2001). For example, gymnosperms generally accumulate fewer phytoliths than angiosperms, and other monocots within the angiosperms commonly accumulate fewer phytoliths than Poaceae and Cyperaceae (Hodson et al., 2005; Yang et al., 2015). The annual biogenic Si production of terrestrial ecosystems has been estimated to be 60–200 Tmol Si yr^{-1}, equivalent to 3600–12,000 Tg yr^{-1} phytoliths, which may significantly influence global C cycle (Conley, 2002; Song et al., 2012).

As the most important component of terrestrial ecosystems, forest ecosystems not only play a crucial role in the biogenic Si cycle but can also effectively regulate atmospheric CO_2 concentration through the coupled biogeochemical cycles of Si and C (Chen et al., 1997; Meunier et al., 1999; Conley, 2002; Parr et al., 2010; Song et al., 2013). It has been confirmed that approximately 0.1–6% of organic C could be occluded within phytoliths (PhytOC, phytolith-occluded C) during the formation process of phytoliths (Jones and Milne, 1963; Parr and Sullivan, 2011; Zuo and Lü, 2011). During the decomposition of dead plants and annual litterfall, PhytOC will be released into soils or sediments (Bartoli, 1983). Compared with other soil organic C (SOC) fractions, PhytOC is more stable and can be kept in soils for thousands of years under the protection of silica (Piperno, 1985; Strömberg, 2004; Parr and Sullivan, 2005; Zuo et al., 2017). Furthermore, soil PhytOC can contribute to 15–37% of the average annual accumulation rate of the global stable soil C (88 kg CO_2 ha^{-1} yr^{-1}) and can account for 82% of the total C in some about 2000 year-old soils (Parr and Sullivan, 2005). For phytolith C sequestration, past researches mainly focused on sugarcane (Parr et al., 2009), bamboo (Parr et al., 2010), millet (Zuo and Lü, 2011), wheat (Parr and Sullivan, 2011) and rice (Li et al., 2013), and their PhytOC production fluxes significantly ranged from 0.04 to 0.71 t CO_2 ha^{-1} yr^{-1}. Despite great advances in estimating production fluxes of PhytOC for some terrestrial ecosystems (e.g. grasslands, wetlands, and croplands) (Song et al., 2012; Li et al., 2013; Song et al., 2014), few studies have focused on the effects of the community compositions on the production fluxes, distributions and storage processes of phytoliths and PhytOC in forest ecosystems.

In this study, we hypothesized that: i) forest composition controls the quantity and characteristics of above-ground phytoliths; ii) the stability and distribution of under-ground phytoliths are related to forest composition; iii) being protected by phytoliths, the decomposition of soil PhytOC is significantly slower than SOC. These factors are important for the long-term sequestration of C in soils. In order to test our hypotheses, we examined the effects of forest composition on phytolith and PhytOC production fluxes and phytolith distribution in soils, and estimated the long-term phytolith C sequestration potential of *Betula*, *Quercus*, *Larix*, and *Pinus* forest ecosystems in northern China. Our study will offer scientific reference for the global long-term C sequestration practices such as afforestation and reforestation.

2. Materials and methods

2.1. Experimental site

This study was carried out in the mountain area of Northern Hebei (42°09′–42°26′N, 117°09′–117°26′E), China. The experimental area belongs to continental semi-arid sub humid climate with mean annual temperature (MAT) of 0–13 °C and mean annual precipitation (MAP) of 300–800 mm (Yang et al., 2015). The altitude of this area is between 1000 and 1940 m. There are four typical temperate forests in this area: *Betula* forest (dominated by *Betula platyphylla* and *Betula davurica*), *Quercus* forest (dominated by *Quercus mongolica*), *Larix* forest (dominated by *Larix principis-rupprechtii*), and *Pinus* forest (dominated by *Pinus tabulaeformis*). The soils of this area are composed of Haplic Kastanozem according to the Food and Agriculture Organization (FAO) soil classification system (IUSS Working Group WRB, 2015).

2.2. Field investigation and sampling

In the field investigations, we randomly set three 1 m × 1 m quadrats for understory herb layer and 10 m × 10 m quadrats for tree layer as standard plots in each forest type in July 2012. The vegetation information, such as height, abundance, and cover of each plant species, were recorded in each plot (Appendix A). Plant species nomenclature was based on *Flora of China* (http://www.eflora.cn).

Considering that the main production of phytoliths occurs in mature tree leaves (or needles) and above-ground herbs in terrestrial forest ecosystems (Bartoli, 1983; Carnelli et al., 2001; Hodson et al., 2005; Umemura and Takenaka, 2014), this study selected mature leaves (or needles) and above-ground herbs to examine phytolith and PhytOC content. For the tree layer, mature leaves of *Betula platyphylla*, *Betula davurica* and *Quercus mongolica*, mature needles of *Larix principis-rupprechtii*, and mature needles (> two years old) of *Pinus tabulaeformis* in corresponding forest type were sampled from each standard plot (Table 1). For understory herbs, twelve of thirty-two, nine of twenty-seven, eight of twenty-seven, and five of seven dominant plant species in the herb layer in *Betula*, *Quercus*, *Larix*, and *Pinus* forest were also sampled, respectively (Table 1). Each plant sample included approximately 150 g.

Furthermore, soil samples were sampled by soil auger in each forest type. In order to minimize the spatial heterogeneity in soil conditions, we randomly selected three soil sample sites in each forest type. In each site, soil samples (about 500 g) were collected from the layers of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm. Additionally, characteristics (e.g. earthworm channels and earthworms) of each soil layer were also recorded.

2.3. Sample analysis

Plant samples were placed in an ultrasonic bath for 15 min, rinsed three times with ultrapure water, dried at 75 °C for 48 h to a constant mass, and then ground to a coarse and fine powder. Soil samples were dried by air, ground by a mortar and pestle, and then respectively sieved to 10 mesh (2 mm pore size), 40 mesh (0.43 mm pore size) and 100 mesh (0.15 mm pore size).

According to the study of Tian et al. (2011), conversion factors of 0.48, 0.49, 0.44 and 0.54 between biomass and organic C were used to estimate foliage organic C content of *Betula*, *Quercus*, *Larix* and *Pinus* forests, respectively. Moreover, the conversion factor of 0.45 between biomass of herbs and organic C has frequently been used to estimate organic C content of the herbs (Vogt, 1991). To examine total content of plant Si, the fine powder samples of plants were fused by Li-metaborate and dissolved in dilute nitric acid (4%); the Si concentration of the solution was analyzed by molybdenum blue colorimetric method (Lu,