

Phytolith Content In *Larix Gmelinii* Forest Soils And Its Relations With Soil Properties

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Abstract

Aims

Phytolith occluded carbon (PhytOC) has become one of the important mechanisms of long-term carbon sequestration in soil. Ecosystems with higher latitude in the northern hemisphere are expected to face the largest loss of soil carbon due to global warming. The contributions of phytoliths storage in soil layers of cold temperate forest need to be studied in depth.

Methods

We examined soil phytolith contents and other soil physicochemical properties of *Larix gmelinii* forest soils in Daxing'anling. ANOVA was employed to analyze differences in the quantitative characteristics of phytoliths. Bivariate correlation, regression analysis, principal component analysis and redundancy analysis were employed to analyze the relations between soil phytolith and soil properties.

Results

The phytolith in *Larix gmelinii* forest soil was mainly in elongate shape with a mean content of 19.1 g kg^{-1} . The phytolith had a stronger correlation with phosphorus rather than potassium and nitrogen and had no correlation with soil water content, and the dominant factors were Na, Mg and K content. Soil phytolith storage in the cold temperate zone (41.0 t ha^{-1}) was significantly higher than that in the tropical and subtropical zone.

Conclusions

Phytolith is an important way for long-term sequestration of soil organic carbon. Soil phytolith storage is affected by soil physicochemical properties and climate. However, the acid-base level of soil is more important for phytolith preservation. The effects of hydrothermal conditions on the yield and stability of phytoliths on a large spatial scale need to be studied in future.

1. Introduction

In recent decades, greenhouse gases (GHGs) mediated global warming and climate change have become one of the major global environmental issues (Prajapati 2016; Rajendiran et al. 2012). Terrestrial carbon sequestration is fundamental to global carbon cycle and being utilized to cope with CO_2 increases (Rajendiran et al. 2012). As an important component of terrestrial ecosystem, forest plays a key role in slowing down CO_2 concentration rising and maintaining carbon balance (Bonan 2008; Fang et al. 2006; Fang et al. 2001; Goodale et al. 2002; Korner 2003; Pan et al. 2011; Parr et al. 2010; Song et al. 2013a;

Yang et al. 2018). Forest soil has the largest carbon pool in all terrestrial ecosystems (Jin et al. 2000), which is 2 ~ 3 times of terrestrial vegetation carbon pool. A great impact will be observed on atmospheric CO₂ concentration, which then potentially be fed back on climate change, even small changes occur in forest soil carbon pool (Heimann and Reichstein 2008; Kirschbaum 2004). Therefore, characteristics of soil carbon pool are an important prerequisite for understanding the mechanism of carbon cycles in terrestrial ecosystems (Qiao et al. 2014).

Considering global warming, it is urgent to find a long-term carbon sequestration way to reduce atmospheric CO₂ concentration. Terrestrial biogeochemical carbon sequestration is estimated to counteract about 30% of the total anthropogenic CO₂ emissions (Law and Harmon 2011) and thus believed to be a promising way (Parr et al. 2010; Song et al. 2012a). Phytolith, also known as plant opal, is a hydrated silica (SiO₂·nH₂O) mineral (Parr and Sullivan 2011; Piperno 1988), which is the monosilicic acid (H₄SiO₄) absorbed by plants from soil solution (Epstein 1994; Hodson 2016; Wilding 1967), and precipitates in the form of amorphous silicon inside cells and cell walls of plant bodies through transpiration (Ma 2003; Neumann 2003; Wang and Lv 1993). Phytoliths are formed in plants, and the content of phytoliths in soil depends on the amount of biological litter, which is the main way for soil to accumulate phytoliths (Han et al. 2018). However, the distribution of phytoliths in different regions is different due to the differences of vegetation, hydrology, climate, geology and other environmental conditions. Due to the fact that phytoliths are abundant, durable and distinctive, it is used to deduce historic vegetation patterns and human uses across the fields of archeology, paleoethnobotany, paleoecology and historical ecology, particularly at sites with poor preservation of larger plant-derived samples (Alexandre et al. 2012; Hart 2016; Piperno 2006; Rashid et al. 2019).

During the formation process of phytoliths in plants, approximately 0.1% ~ 6% organic carbon could be occluded within phytoliths to form phytolith-occluded carbon (PhytOC) (Jones and Milne 1963; Parr and Sullivan 2011; Zuo and Lü 2011). When plants die or fall, PhytOC will accumulate in soil or sediment (Bartoli 1983). Due to the strong resistance of phytoliths to decomposition, PhytOC is more stable than other fractions of organic carbon in soil and even preserved for thousands of years (Parr and Sullivan 2005; Piperno 1985; Strömberg 2004; Wilding 1967; Yang et al. 2015; Yang et al. 2018; Zuo et al. 2017). It has been shown that soil PhytOC contributes to 15%~37% of annual accumulation rate of global stable soil carbon (88 kg CO₂ha⁻¹ yr⁻¹) and accounts for 82% of the total carbon (Alexandre et al. 2012) in about 2000-year-old soils (Parr and Sullivan 2005), which has become one of the important mechanisms of long-term carbon sequestration in soil (Yang et al. 2018). This long-term form of biogeochemical carbon sequestration is believed to have great potential in reducing atmospheric CO₂ content and mitigating greenhouse effects (Piperno 2002; Wu and Wang 2009). However, Santos and Alexandre (2017) advances that PhytOC in phytolith cavities would participate only to a limited extent in long-term atmospheric CO₂ sequestration, and phytOC fluxes must be quantified to accurately estimate the flux of atmospheric CO₂ sequestered by soil phytoliths. As the PhytOC should be rapidly oxidized when phytoliths start to dissolve and cavities become open, after phytolith deposition in litter, soil or sediment. Therefore, the potential of carbon sequestration in phytoliths has become a hot topic in biogeochemical

carbon sequestration research (Li et al. 2013b; Parr and Sullivan 2011; Parr et al. 2010; Song et al. 2012a).

The content of phytolith closely relates to the accumulated silicon in plants. In general, silicon content is the highest in gramineae, followed by conifer and deciduous broadleaf. Therefore, for PhytOC sequestration, previous work mainly focused on bamboo (Parr et al. 2010) and crops, i.e. sugarcane (Parr et al. 2009), millet (Zuo and Lü 2011), wheat (Parr and Sullivan 2011) and rice (Li et al. 2013b), in which their reported PhytOC production fluxes ranged from 0.04 to 0.71 t CO₂ha⁻¹ yr⁻¹ (Yang et al., 2018). While few studies focus on the production fluxes, distributions and storage processes of phytoliths and PhytOC in forest ecosystems, despite great advances in estimating production fluxes of PhytOC for some terrestrial ecosystems (e.g. grasslands, wetlands, and croplands) (Li et al. 2013a; Song et al. 2012a; Song et al. 2013b). Meanwhile, the production fluxes of phytolith or PhytOC in the above-ground vegetation of various forest types have gained more concerns. Ecosystems with higher latitude in the northern hemisphere have the highest density and storage of soil organic carbon (Scharlemann et al. 2014), and are expected to face the largest loss of soil carbon due to global warming (Kirill et al. 2004), and may become a hot spot of CO₂ flux in the biosphere. Whereas the contributions of phytoliths and PhytOC to carbon storage in soil layers of cold temperate forest have not been studied in depth.

Daxing'anling, located in Northeast China, is the largest primary forest area with the only cold temperate coniferous forest in China, which is also one of the most sensitive regions in response to global climate change. Where *Larix gmelinii* is the dominant tree species with *Betula platyphylla* as the associated species. Accordingly, the forest ecosystem of Daxing'anling plays an irreplaceable role in cold temperate forest carbon sequestration. We hypothesized phytolith distribution to be controlled by vegetation and to be influenced by environmental conditions. To test our hypothesis, we used samples from *Larix gmelinii* soils, (i) to examine the phytoliths content in *Larix gmelinii* forest soil. (ii) to observe the morphotypes of phytoliths in *Larix gmelinii* forest soil; (iii) to discuss the effects of soil physicochemical indexes on phytoliths preservation in the cold-temperate forest soil, such as pH and nutrients. This work will offer a scientific reference for the global long-term carbon sequestration practices such as afforestation and management.

2. Materials And Methods

2.1. Study area

The study area covers an area of 11,000 hm² with a forest coverage rate of 75%, which is located in Chaocha Forest Farm of Genhe Forestry Bureau, Inner Mongolia Autonomous Region, China (50°49'-50°51'N, 121°30'-121°31'E). The altitude varies from 810 m to 1100 m in this area. It belongs to the semi-humid climate zone in the cold temperate zone, with a freezing period of 6 ~ 7 months. Most of the rainfall is concentrated in July and August with annual precipitation of 438 ~ 530 mm. The main soil type in this area is brown coniferous forest soil with large areas of permafrost distributed. There is also a lot of gravel in soil below 30 cm. *Larix gmelinii* is the dominant tree species. The main understory plants

are *Rhododendron simsii*, *Ledum palustre*, *Betula fruticose*, *Vaccinium vitis-idaea*, *Pyrola incarnata*, *Maianthemum bifolium*, *Deyeuxia langsdorffii*.

2.2. Soil sampling and analysis

2.2.1. Soil sampling

Field investigation and soil sampling were conducted during July and August of 2017. Based on the typical plot survey method, 28 sampling sites were selected within in the area of 5km×5km. Soil samples were collected from the profiles of 0–10, 10–20, 20–40 and 40–60 cm depth layer at each site. About 1 kg of soil was collected in each layer. To minimize sampling errors due to soil heterogeneity, three samples in the same layer were mixed as a mixture soil sample for further analysis. The soil samples were air-dried after being taken to the laboratory, then passed through a 2-mm sieve for soil properties determination and passed through a 0.15-mm sieve for phytolith extraction.

2.2.2. Soil properties determination

Soil water content (SWC) and bulk density (BD) were determined by the oven drying method. Soil pH was determined using a pH meter with a soil/water mass ratio of 1:5 (w/v). Soil organic matter content was determined by potassium dichromate oxidation spectrophotometry method (HJ 615–2011); total phosphorus (TP) was determined by acid dissolution spectrophotometry method (Pierzynski 2009); ammonium nitrogen ($\text{NH}_4^+\text{-N}$), available potassium (AK) and available phosphorus (AP) were determined by combined extraction colorimetry method (NY/T 1849–2010); Mineral element contents in soils were determined by XRF analyzers (BRUKER S8 TIGER SERIES 2, Germany).

2.2.3. Phytolith extraction and determination

The air-dried soil (< 0.15 mm) was used to extract phytolith. The modified wet air oxidation method and heavy liquid flotation method were used for separation and extraction of phytolith from soil (Li et al. 2013a; Parr 2002; Zuo et al. 2014). In brief, after organic matter was completely removed, the samples were separated by heavy liquid flotation and centrifugation method using ZnBr_2 (specific gravity of 2.35) as the heavy liquid to obtain pure phytolith samples.

2.3. Data calculation and statistics

Soil phytolith content and phytolith storage were calculated as follows (Huang et al. 2014; Li et al. 2019; Zuo et al. 2014):

Soil phytolith content (g kg^{-1}) = phytolith weight (g)/soil weight (kg) (1)

Soil phytolith storage (t ha^{-1}) = Σ [soil phytolith content (g kg^{-1}) × bulk density (g cm^{-3}) × soil depth(cm) /10] (2)

Phytolith translocation indices were used to determine the phytolith translocation rate in natural soil profiles. The total translocation rate (T_r) and translocation distance (T_d) were calculated as follows (Liu

et al. 2019):

$$T_r = A_0 / (A_0 + A + B + C) \quad (3)$$

$$T_d = B / (A_0 + A + B + C) \quad (4)$$

Where, A_0 , A, B and C are phytolith content in 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm soil layer, respectively. The phytolith translocation increases from surface humic horizon to lower layers of soil profile as T_r increases. The larger the T_r value is, the weaker the soil preservation is (Liu et al. 2019). $T_r < 18\%$ indicates phytoliths better preserved in soil; by contrast, $T_r > 30\%$ indicates phytolith poorly preserved, and $18\% < T_r < 30\%$ represents an intermediate translocation rate. $T_d < 4\%$ indicates that the translocation distance of phytoliths within soil profile is relatively low, whereas $T_d > 12\%$ represents a greater translocation distance, and $4\% < T_d < 12\%$ represents an intermediate translocation rate to the C horizon.

ANOVA was employed to analyze differences in the quantitative characteristics of phytoliths. Bivariate correlation and regression analysis were used to analyze the relations between soil phytolith and soil properties for *Larix gmelinii* forest. Principal component analysis (PCA) was used for characterization of soil samples according to their properties and phytolith contents. Partial redundancy analysis (Partial RDA) can distinguish the individual interpretation rate and its interactions of variables, which was employed to analyze contributions of grouped environmental variables to phytolith contents and was expressed by Venn diagram. Correlations between soil phytolith and selected soil properties were also examined by multiple regressions.

3. Results

3.1. Descriptive statistics of soil properties

Descriptive statistics of selected soil properties were summarized in Table 1. There were significant differences in SOC, TP and SWC between 0–10 cm soil layer and other layers ($p < 0.01$), and significant differences in $\text{NH}_4^+\text{-N}$, AK and pH among 0–10 cm, 10–20 cm and other soil layers ($p < 0.05$). The factors of SOC, $\text{NH}_4^+\text{-N}$, TP and SWC presented decreasing trends with soil depth, while BD and pH increased with soil depth.

Table 1
Statistical summary for soil nutrients contents

Soil depth	SOC (g kg ⁻¹)	TP (mg kg ⁻¹)	NH ₄ ⁺ -N (mg kg ⁻¹)	AP (mg kg ⁻¹)	AK (mg kg ⁻¹)	pH	SWC (%)	BD (g cm ⁻³)
0–10 cm	142.2 ± 59.5a	968.3 ± 252.1a	25.2 ± 12.3a	20.4 ± 18.9a	147.9 ± 69.4a	5.3 ± 0.4a	29.1 ± 10.2a	-
10–20 cm	31.1 ± 24.0b	607.4 ± 193.8b	19.5 ± 9.2b	16.4 ± 8.9a	97.7 ± 54.8b	5.6 ± 0.4b	13.5 ± 8.6b	1.0 ± 0.1a
20–40 cm	16.1 ± 11.3b	659.1 ± 311.5b	13.4 ± 6.8c	16.06 ± 13.1a	61.8 ± 36.1c	5.8 ± 0.3c	11.6 ± 6.3b	1.1 ± 0.1b
40–60 cm	13.4 ± 8.2b	629.4 ± 204.3b	13.4 ± 4.7c	21.4 ± 13.0a	40.3 ± 32.1c	5.8 ± 0.3bc	-	-
0–60 cm	53.4 ± 63.6	720.3 ± 287.8	17.9 ± 9.9	17.9 ± 12.8	89.1 ± 63.4	5.6 ± 0.4	18.4	1.1 ± 0.1
Note: Different lower letters indicate significant differences among different soil layers ($P < 0.05$). The same below.								

For mineral elements (Table 2), there was a significant difference in Fe between 0–10 cm and 20–40 cm soil layers ($p < 0.05$). Other mineral elements (Na, Mg, Al, K, Ca) showed significant differences between 0–10 cm soil layer and other layers ($p < 0.01$).

Table 2
Statistical summary for mineral elements (unit: g kg⁻¹)

Soil depth	Na	Mg	Al	K	Ca	Fe
0–10 cm	8.9 ± 3.0a	5.4 ± 1.8a	60.9 ± 11.1a	16.6 ± 3.3a	12.1 ± 5.7a	35.7 ± 8.4a
10–20 cm	14.1 ± 3.7b	7.8 ± 1.8b	74.1 ± 7.4b	19.9 ± 1.7b	7.9 ± 2.1b	37.1 ± 7.0ab
20–40 cm	15.6 ± 3.7b	9.0 ± 1.8bc	77.3 ± 5.8b	20.7 ± 2.5b	7.1 ± 1.4b	39.9 ± 8.4b
40–60 cm	14.8 ± 3.7b	9.6 ± 1.8c	78.9 ± 6.9b	20.7 ± 1.7b	7.9 ± 1.4b	39.9 ± 7.0ab
0–60 cm	13.4 ± 4.5	7.8 ± 2.4	73.1 ± 10.6	19.1 ± 2.5	9.3 ± 3.6	37.8 ± 7.7

3.2. Phytolith morphology

Generally, the phytolith shapes in different plant species are different, usually including one-dimensional, two-dimensional and three-dimensional directions (Wang and Lv 1993). According to relevant researches

(An 2016; Solomonova et al. 2019; Wen et al. 2018), eight types of phytoliths were recorded in *Larix gmelinii* forest soils including dendritic-elongate, papillate-elongate, board-elongate, smooth-elongate, square, rectangle, fan-reed and short point with the dominant shape of elongate phytoliths, which reflected cold climate characteristics in this area (Fig. 1).

3.3. Vertical characteristics

Phytolith contents showed a broad variation in *Larix gmelinii* forest soil (Fig. 2). The mean phytolith content was 19.1 g kg^{-1} with a variation coefficient of 71.62%. Phytolith contents in soil profiles ranked as 10–20 cm > 0–10 cm > 20–40 cm > 40–60 cm, showing a trend of increasing first and then decreasing. The variance analysis and multiple comparisons showed that the phytolith contents in layer of 10–20 cm were significantly higher than those in layers of 20–40 cm and 40–60 cm ($p < 0.05$).

The substantial differences of T_r values were observed among sampling sites in *Larix gmelinii* forest. T_r ranged mainly from 7.0–54.9% with an average of 28.8%, indicating an intermediate translocation rate of phytolith in soils. Meanwhile, T_d ranged mainly from 6.8–40.7% with a mean of 21.6%, meaning a greater translocation distance.

3.4. Impacting factors

3.4.1. Relations between soil phytolith and basic physicochemical indexes and nutrients

The PCA indicated relations between soil phytolith and basic physicochemical indexes, nutrients (Fig. 3). The first principal component (PC1) explained by SOC and BD, showed relatively high loadings (32.0%) of phytolith. The second principal component (PC2) also showed relatively high loadings (18.3%) and was mainly explained by pH, SWC and AP. The PC1 positively correlated with SOC, phytolith, TP, AP, AK, SWC, TP and $\text{NH}_4^+\text{-N}$, and negatively correlated with pH and BD. The PC2 positively correlated with phytolith, BD, TP, AP and AK, and negatively correlated with pH, $\text{NH}_4^+\text{-N}$ and SWC. According to the variables ordination in PCA diagrams, it appears that phytolith tends to associate to SOC, TP, AK, AP and $\text{NH}_4^+\text{-N}$ rather than SWC, pH and BD. It is likely that the soil samples have closer relations with pH and BD. There was a negative correlation between phytolith and pH and BD, which suggested that pH and BD increasing can result in a loss of soil phytolith. In contrast, SOC, AP, AK, TP and $\text{NH}_4^+\text{-N}$ favored the phytolith preservation in soil. At the same time, it can be seen that phytolith had a stronger correlation with phosphorus nutrients than potassium and nitrogen nutrients; and SWC is not the limiting factor of phytolith.

3.4.2. Relations between soil phytolith and mineral elements

Soil phytolith content was significantly negatively correlated with Na, Mg, Al and Fe contents ($p < 0.05$) (Fig. 4). Na and Mg showed a significant correlation with phytolith at the 0.001 level. Significant correlations between phytolith and Al, Fe was found at the 0.05 level. Whereas no significant correlation was found between soil phytolith and K, Ca.

3.4.3. Relations between soil phytolith and soil properties

Soil basic physicochemical properties, nutrients and mineral elements accounted for 75.5% of soil phytolith variations in *Larix gmelini* forest (Fig. 5). Mineral elements (c + e + f + g) had the greatest influence on phytoliths (69.6%), and soil nutrients (b + d + e + g) had the least influence on phytoliths (40.1%). The individual interpretation rate of each grouped soil factor to phytoliths was in the order of nutrients (8.4%) > basic physicochemical properties (5.9%) > mineral elements (1.2%). On the aspects of interaction effect, the interaction of the three factors (g) had the greatest impact on phytolith, which can explain 35.6% variation. The interaction between basic physicochemical properties and mineral elements (f) also showed an important effect on phytoliths with an explanation rate of 28.3%. On the aspects of common influence, the interpretation rate of basic physicochemical properties and nutrients to phytolith was the highest (74.3%); the interpretation rate of basic physicochemical properties and mineral elements to phytolith was the lowest (67.1%).

(PC—basic physicochemical properties including SWC, BD and the pH; NI—nutrient indexes including AK, AP, TP, $\text{NH}_4^+\text{-N}$ and SOC; ME—mineral elements including Na, K, Ca, Mg, Fe, Al. a, b, c indicate the individual interpretation rate of PC, NI, ME to phytoliths; d, e, f indicate the interactive interpretation rate of PC and NI, NI and ME, PC and ME to phytoliths; g indicate the interactive interpretation rate of PC, NI and ME to phytoliths.)

3.4.4. Dominant factor screening

Path coefficients were calculated through stepwise regression analysis (Fig. 6). Na, Mg and K were screened from soil indexes. The simple correlation coefficients of Na, Mg and phytolith were -0.660 and -0.577 ($p < 0.001$); the simple correlation coefficient between K and phytolith was 0.314 ($p < 0.05$), indicating these three variables played an important role on soil phytoliths in *Larix gmelinii* forest. All three factors had a negative direct effect on phytolith content followed by descending order of Na, Mg and K. Through the analysis of the indirect path coefficient, it was found that K had the greatest indirect influence on phytolith through Na, and the indirect path coefficient was 0.328 .

4. Discussion

Eight types of phytoliths were recorded in *Larix gmelinii* forest soils (Fig. 1), which similar to the SEM images of epidermal cell wall phytoliths in Klein and Geis's studies (Klein and Geis 1978). Elongate was the dominant phytolith shape in *Larix gmelinii* forest soils, while the dendritic-elongate, papillate-elongate phytoliths maybe reflect that isolated phytoliths from *Larix gmelinii* forest soils not only come from the *Larix gmelinii* trees but also affected by understory grasses and shrubs.

The carbon sequestration potential of phytoliths not only depends on the encapsulating efficiency of organic matter during the formation of phytoliths (Parr and Sullivan 2011; Parr et al. 2010), but also on the phytolith yield during plant growth (Li et al. 2013a). Accordingly, the significant positive correlations between soil phytolith contents and carbon content occluded in phytolith, phytolith carbon content in soil were also found in *Larix gmelinii* forest ($p < 0.01$, Fig. 7), indicating that the phytolith content increasing would promote the carbon sequestration capacity of phytolith. Almost all of the silica in *larix* needles is located in the epidermal and hypodermal cell walls (Sangster et al. 2001). Therefore, the *Larix* phytoliths all seem to be cell wall types and deposited on a carbohydrate matrix, which will result in potentially high in carbon. However, the specific influence mechanism on carbon sequestration of *Larix gmelinii* remains to be studied further.

The fate of phytolith in soil is important because of its effects on agronomical nutrient resources and carbon sequestration (Nguyen et al. 2019). Under different environmental conditions, phytolith accumulation is mainly controlled by the return flux of phytolith and the stability of phytolith in soil. Phytoliths are released into the soil after plant death and decay. Phytolith accumulation occurs when phytolith input exceeds its translocation, dissolution and leaching in soil profile (Zhang et al. 2016). Therefore, phytolith content in soil is largely controlled by aboveground plant yield and forest types. Generally, different forest types are characterized as different return flux of phytoliths. The stability of phytoliths is mainly controlled by its physicochemical properties and environmental conditions (Nguyen et al. 2019). Differences in soil properties, such as soil texture (Hart and Humphreys 2003) and pH (Frayse et al. 2009; Fraysse et al. 2008) may affect the retention and the loss of phytoliths in soil. Soil conditions, especially soil moisture and pH, can not only affect phytolith accumulation in soil due to their relations with the stability of soil phytolith (Chen et al. 2018), but also influence the bioavailability of silicon in soil, in turn, the silicon absorption from soil solution by plants (Li et al. 2014; Parr and Sullivan 2005; Yang et al. 2018). Previous studies have shown that soil with low pH and high organic matter can induce more absorption and accumulation of silicon by plants and more accumulation of phytolith carbon in plants (Song et al. 2012b). Our results showed that there was a significant positive correlation between phytolith content and SOC in *Larix gmelinii* forest soil (Fig. 3), indicating the effect of litter input on phytolith accumulation (Zhang et al. 2016). Meanwhile, the occluded effects of organic matter on phytolith may be another factor in phytolith preserving since its shield protection against the hydrolysis of silica (Nguyen et al. 2014; Parr and Sullivan 2005; Trinh et al. 2017). Furthermore, a significant negative correlation was found between soil phytolith and pH in *Larix gmelinii* forest soil ($p < 0.05$). Such strong pH dependency, a result of increasing pH deprotonation of Si–OH groups resulting in a H-bonded H₂O adsorption on the negatively charged Si–O[−] surface (Ehrlich et al. 2010), was also observed in other

studies (Frayssé et al. 2009; Li and Delvaux 2019; Nguyen et al. 2014). The pH is well understood as a crucial factor driving phytolith dissolution kinetics via protonation or deprotonation reactions (Frayssé et al. 2009; Nguyen et al. 2014; Trinh et al. 2017), which can either enhance surface resistance or make the surface more vulnerable from nucleophilic attacks (Dove and Crerar 1990). At higher pH, Si–O bonds are weakened and Si release is facilitated, thus phytoliths are more easily dissolved under alkaline conditions (Song et al. 2012a); In an acidic environment, lower pH value can reduce the nucleophilic attack of OH^- on $\equiv \text{Si-O-Si} \equiv$ bond (Dove and Crerar 1990), and make the phytolith stable for a long time (Frayssé et al. 2009; Frayssé et al. 2006; Nguyen et al. 2014). In addition, low pH may convert Al_{ox} and Fe_{ox} into soluble Al^{3+} , Fe^{3+} , thus preventing the dissolution of phytoliths (Bartoli and Wilding 1980; Nguyen et al. 2014; Nguyen et al. 2019; Van Bennekom et al. 1991). It has been reported that Al^{3+} is preferentially adsorbed on the deprotonated sites on the surface of soil phytoliths to slow down the electron density transfer, inherently inhibiting the desilication effect (Nguyen et al. 2019). There was also a significant correlation between soil phytolith and $\text{NH}_4^+\text{-N}$ and TP in *Larix gmelinii* forest soil. The elevated soil nutrients levels enhance the absorption of soluble silicon by plant roots and the accumulation of silicon in phytoliths (Huang et al. 2015; Zhao et al. 2016), then presenting indirect effects on promoting the formation of phytoliths in plants and the input amount of phytoliths into soils by litter. Additionally, the hydrolysis of NH_4^+ also results in soil acidification, which can increase the preservation of phytoliths in soil. In our studies, the mineral element contents of Na, Mg and K were dominant factors affecting phytolith content, which can neutralize soil acidity and increase pH, and then the phytolith dissolution were promoted. Oxides, such as Al_{ox} and Fe_{ox} , have many OH^- , OH_2 , OH_3^+ and other groups on their surface and possess strong adsorption capacity for Al^{3+} , K^+ and other cations, which weakens the depressing effect of metal cations on Si release (Nguyen, et al., 2014).

Combined with previous studies (He 2016; Lin 2015), phytolith storages in soil from different climatic zones of China were calculated (Fig. 8). An obvious latitude trend from south to north in China was found: tropical zone (15.9 t ha^{-1}) < subtropical zone (21.6 t ha^{-1}) < cold temperate zone (41.0 t ha^{-1}). Phytolith contents in soil distributed in different regions are closely related to the regional geographical conditions and vegetation (Wang and Lv 1993). Theoretically, the soil is rapidly desalinated and desiliconized in the high temperature and humidity area (Alexandre et al. 1997). Thus, the biogeochemical stability of soil phytoliths in tropical areas is lower than that in subtropical areas (Zhang et al. 2017). As a result of the strong desalination and desiliconization, phytolith storage in tropical soils is lower than in subtropical soils. In addition to the effects of species and soil environment (pH, water, nutrients, etc.), climate and human activities (Parr and Sullivan 2005; Yang et al. 2016; Zhang et al. 2016; Zhao et al. 2016; Zuo et al. 2014) can also affect the stability of soil phytoliths by affecting biogeochemical activities. Comparatively, the *Larix gmelinii* forest is distributed in the cold temperate zone with a low temperature and weak desalination and desiliconization effects, which is beneficial to the preservation of soil phytolith (Yang et al. 2016). Phytolith mainly comes from soil silicon. Sufficient available silicon in soil can provide favorable conditions for vegetation to form phytoliths (Guo et al. 2015). As tropical soils are mostly highly weathered, where silicon supply for plants is much lower than in

other ecosystem soils. Therefore, our results showed that the phytolith content in soil from *Larix gmelinii* forest was obviously higher than those in other areas.

However, some recent studies have shown that phytoliths most probably reflect only the minor part of phytogenic silica in plants and soils (Hodson 2019; Kaczorek et al. 2019; Puppe and Leue 2018) and a combination of microscopic analyses and silicon extraction techniques should be applied in the silicon cycling examinations. Puppe et al. (2017) concluded that about 84% of small-scale and/or fragile phytogenic silicon was not quantified by the used phytolith extraction method. Analyses of small-scale and fragile phytogenic silicon structures are urgently needed in future work as they are the most important drivers of silicon cycling in terrestrial biogeosystems.

5. Conclusions

In conclusion, phytolith is an important way for long-term sequestration of soil organic carbon. The phytolith storage in cold temperate zone (41.0 t ha^{-1}) is obviously higher than in tropical and subtropical zones. Soil physicochemical properties have a certain impact on soil phytolith content in *Larix gmelinii* forest, such as soil organic carbon, pH value, nutrients and mineral elements. However, the acid-base level of soil is more important for phytolith preservation. The effects of hydrothermal conditions on the yield and stability of phytoliths on a large spatial scale need to be studied in future. The phytolith structures and the effect of silicon availability on phytoliths will allow us to fully understand phytolith dynamics.

Declarations

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Figures

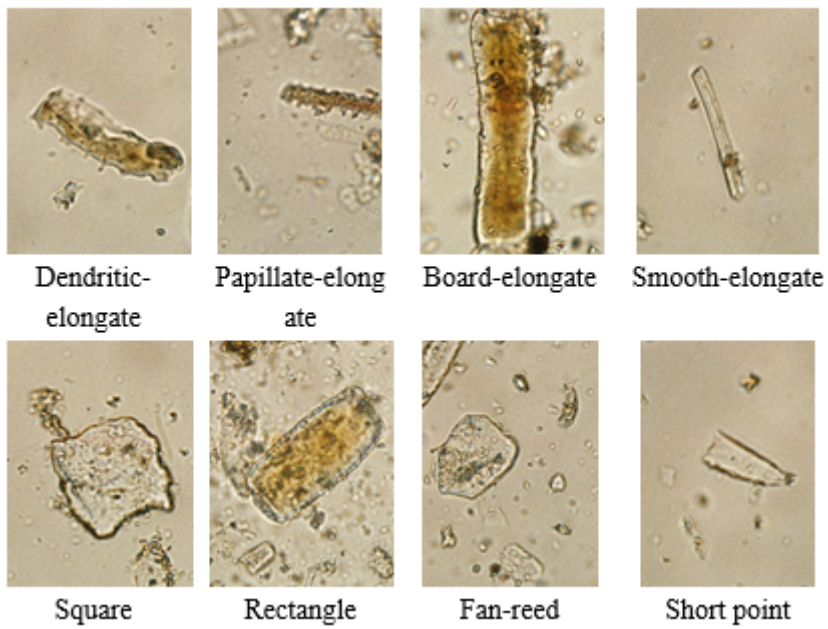


Figure 1

Optical microscope images of phytoliths extracted from *Larix gmelinii* forest soils

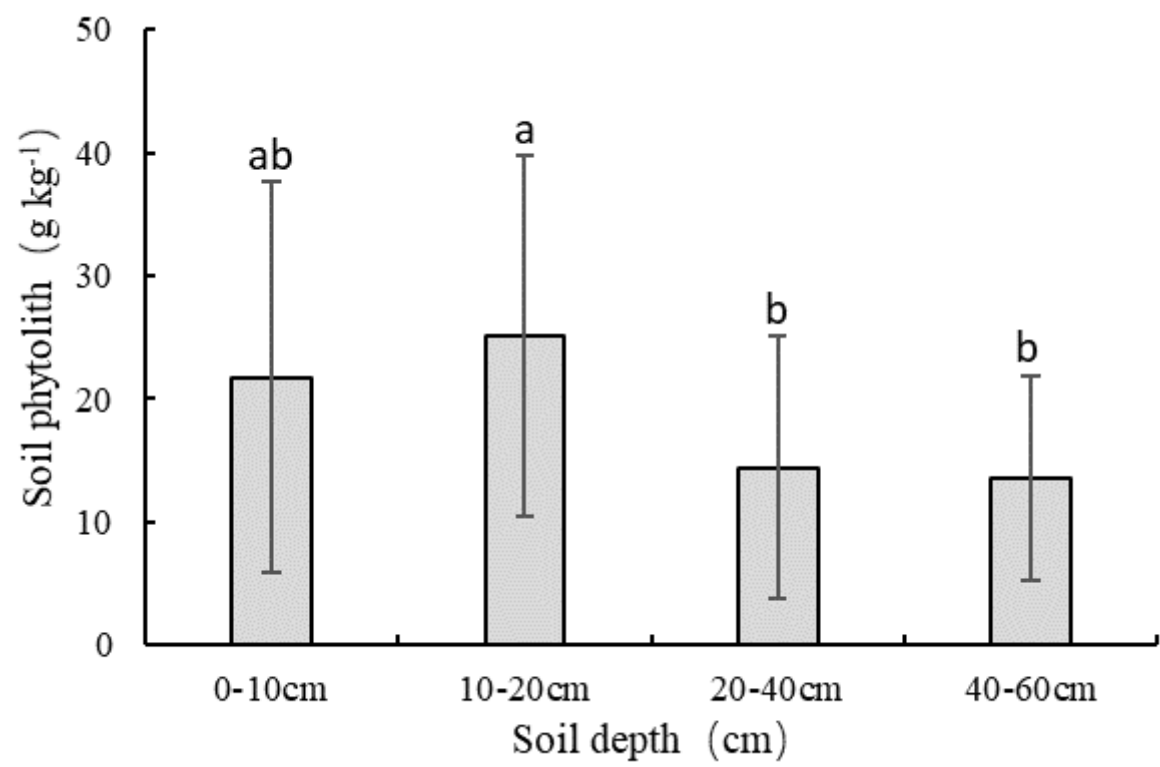


Figure 2

Phytolith contents in different soil depths (Means $\pm$ SD, n=100)

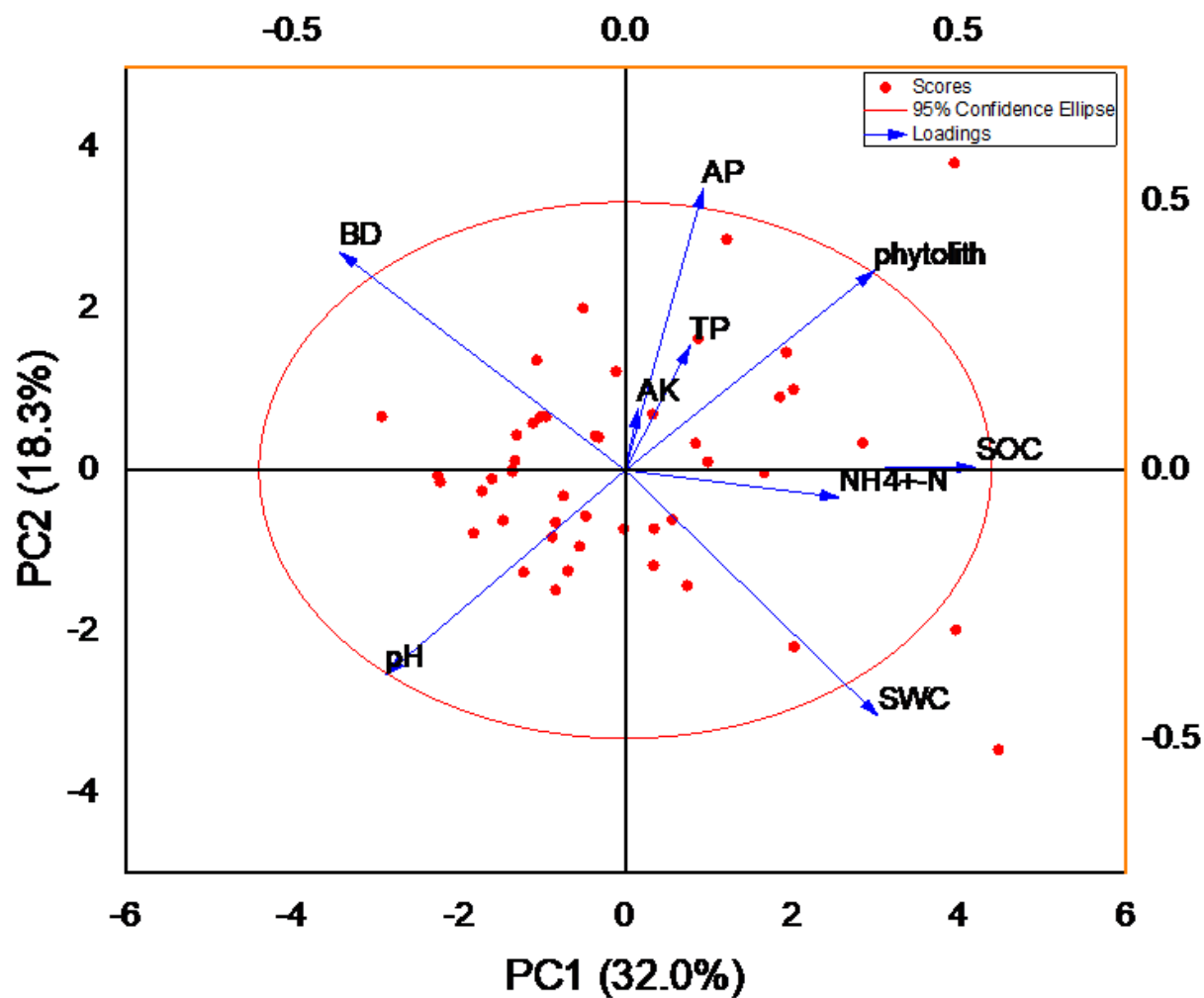


Figure 3

PCA of soil phytolith and physicochemical indexes. (SOC = soil total organic carbon; SWC = soil water content; BD = bulk density; TP = total phosphorus; NH₄⁺-N = ammonium nitrogen; AK = available potassium; AP=available phosphorus.)

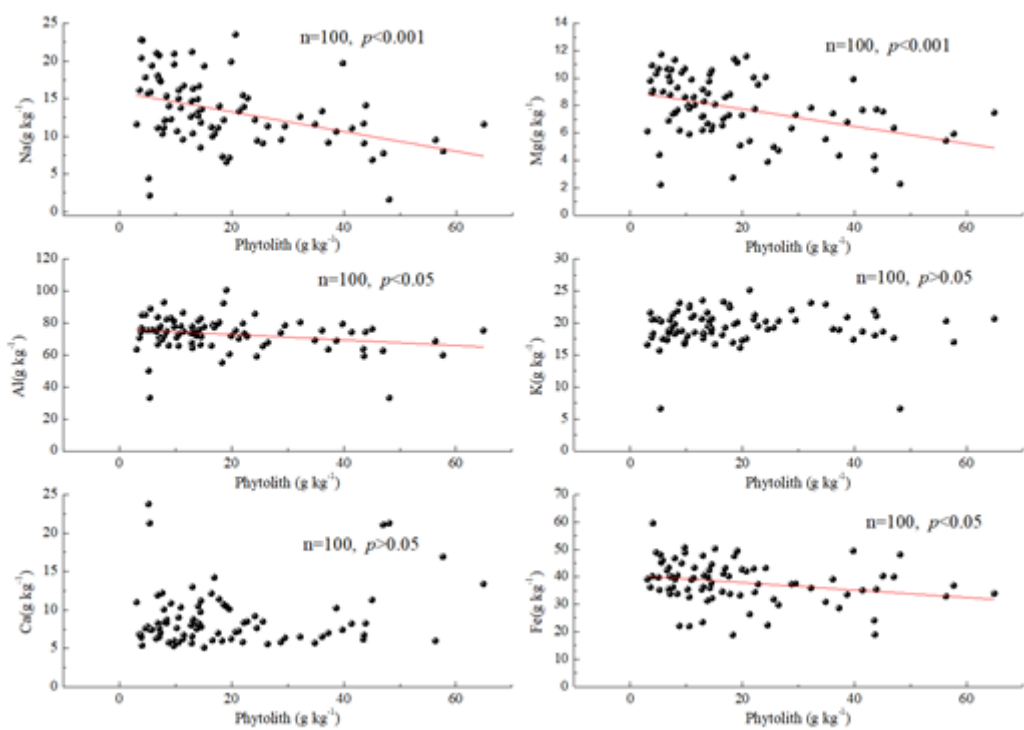


Figure 4

Scatter diagram between soil phytolith and mineral elements

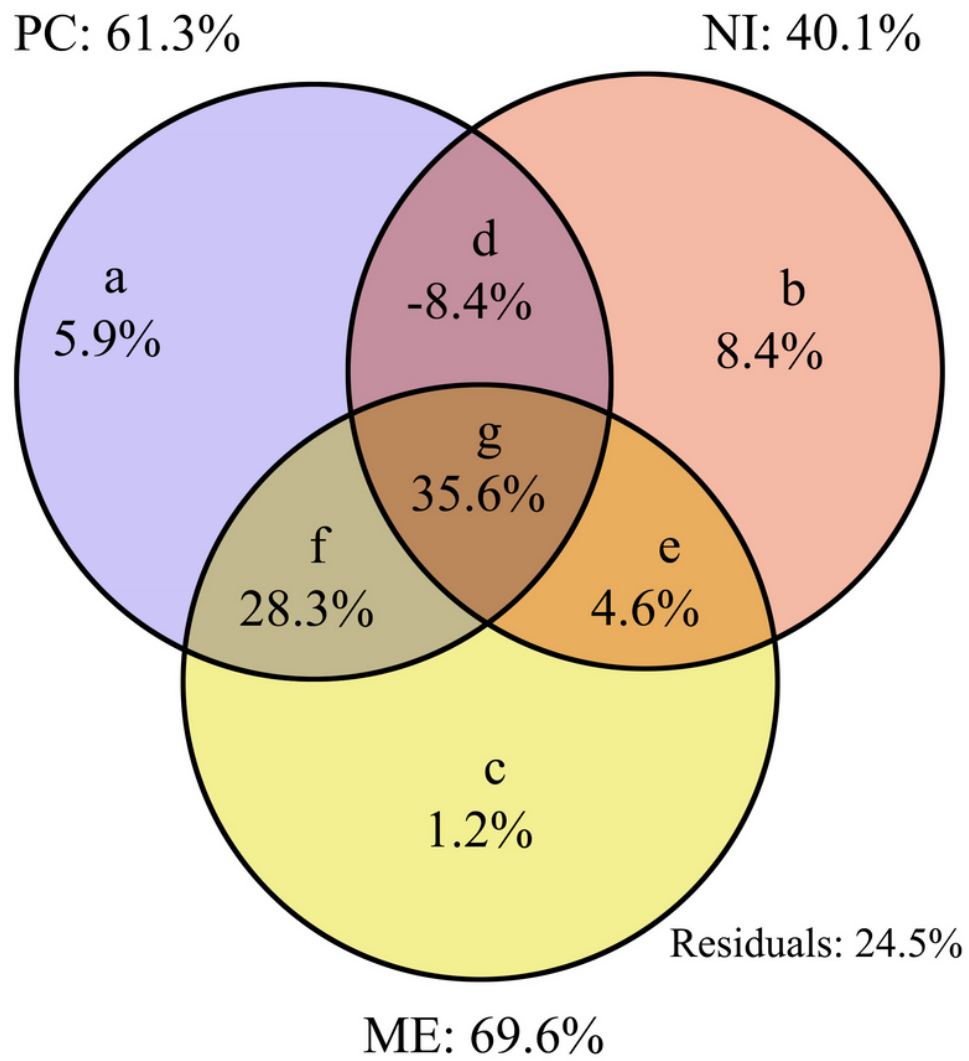


Figure 5

Venn diagram for soil phytolith and soil indexes

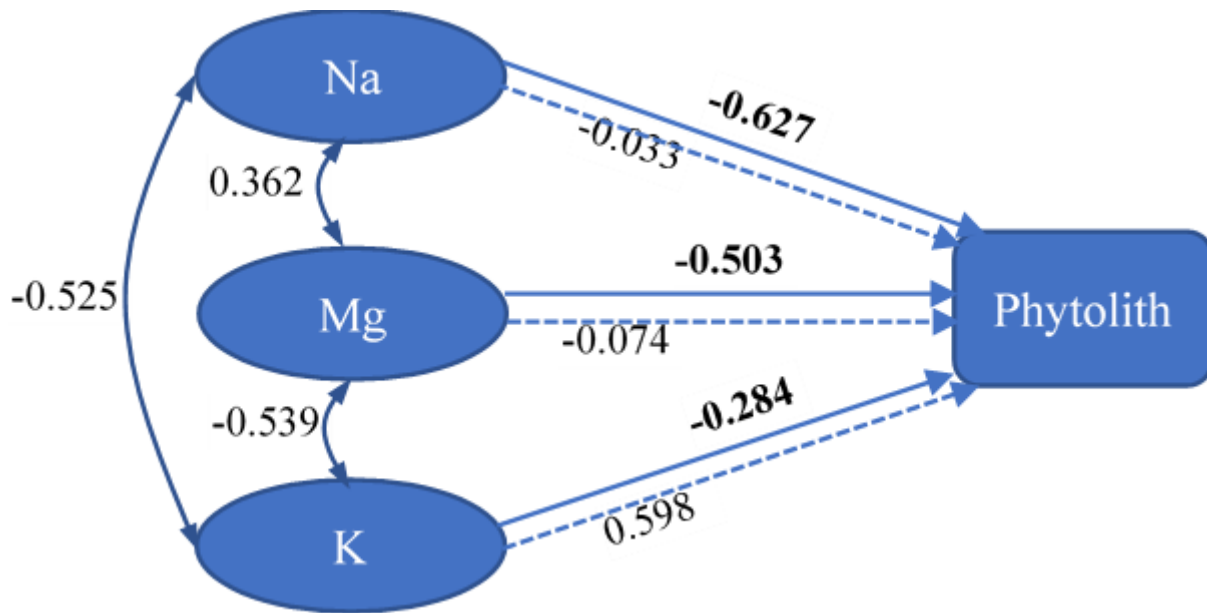


Figure 6

Path coefficients of soil phytolith in *Larix gmelinii* forest

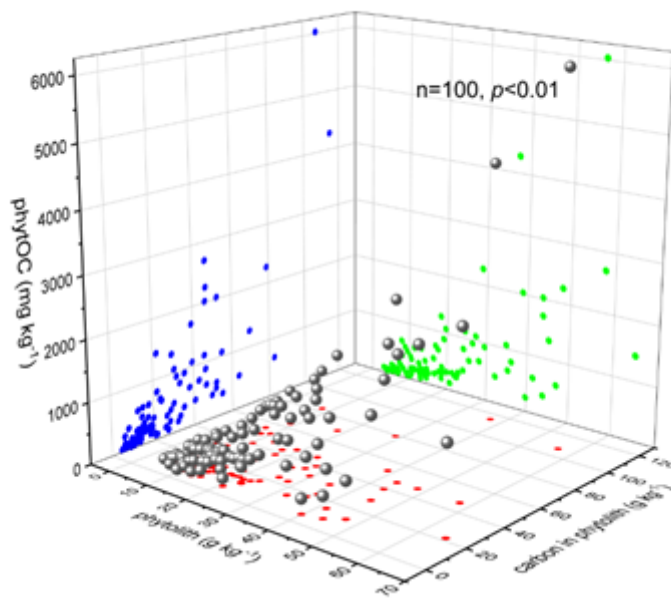


Figure 7

Correlations between soil phytolith contents and carbon contents in phytolith, soil phytolith carbon contents

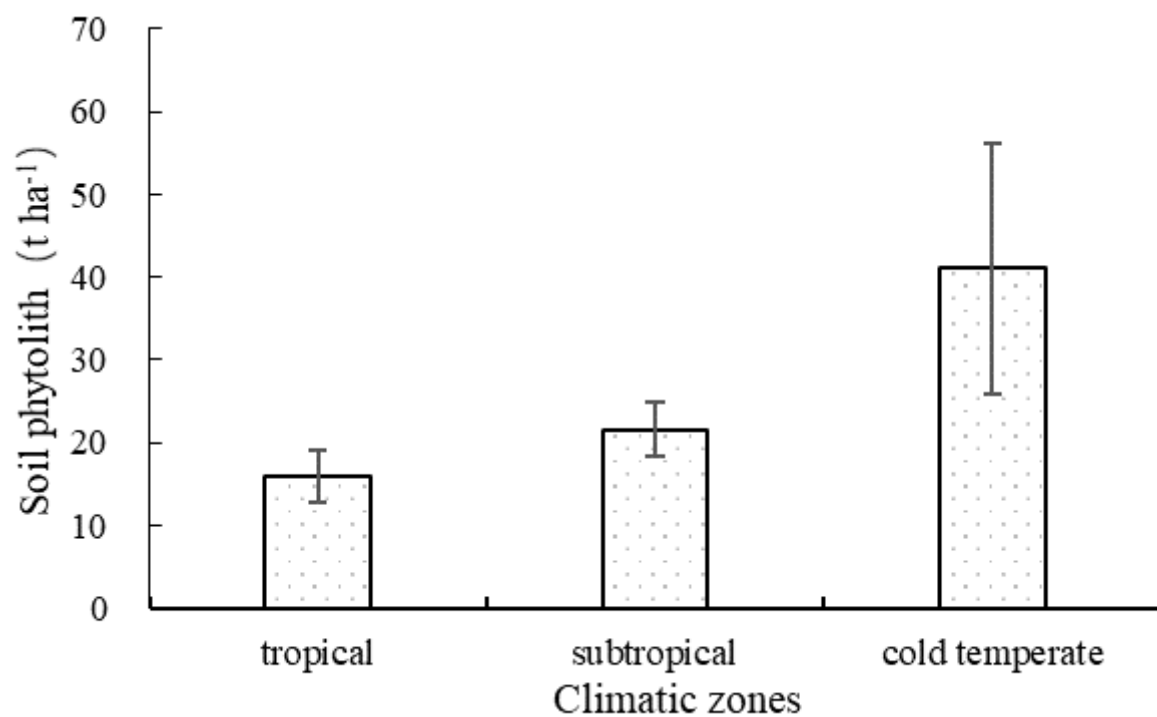


Figure 8

Phytolith storages in different climate zones (Means $\pm$ SD). (The tropical data was calculated from He's work (2016); and the subtropical data was calculated from Lin's work (2015).)