RESEARCH ARTICLE

Soil C, N and P stocks and stoichiometry under different vegetation on the surface of the Leshan Giant Buddha

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HIGHLIGHTS

- Leshan Giant Buddha is damaged seriously because of weathering and plant settlement.
- Amounts of soil organic C, N and P was accumulated in the surface of the Buddha.
- Soil organic C, N and P stocks under herbs are the most abundant.
- Soil organic C, N and P mainly stocks in the shoulder, arm and the platform.

GRAPHICAL ABSTRACT

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ABSTRACT

The accumulation of soil organic matter and nutrients is an important pathway in effectively understanding the mechanisms of plant settlement and rock weathering, while the characteristics of soil organic carbon (C), nitrogen (N) and phosphorus (P) under different vegetation remain unclear. In this study, the stocks and stoichiometry of soil organic C, N and P were determined in different positions and types of vegetation on the surface of the Leshan Giant Buddha. We found that the total stocks of soil organic C, N and P were 1689.77, 134.6 and 29.48 kg, respectively, for the Buddha. The stocks of soil organic C, N and P under vascular plants were higher than those under other vegetation, with highest values observed under herb. Higher stocks per unit area (m^2) of soil organic C, N and P were found on the left and right arms, shoulders, and two platforms. These results provide a full primary picture in understanding soil organic C, N and P accumulation and distribution on the surface of the Buddha, which could supply the fundamental data on weathering management of the Buddha and other similar open-air stone carvings.

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1 Introduction

An open-air stone carved landscape is extremely vulnerable to plant settlement and natural rock weathering. The stocks of soil organic matter and nutrients provide the basis for vegetation development on the surface of open-air stone carvings, which can speed up the weathering process and further destroy the aesthetics of landscape (Giesen et al., 2014; Wang et al., 2014; Cuadros et al., 2018; Marler and Del Moral 2018). Moreover, the vegetation in turn promotes the formation and stocks of soil carbon (C) and nutrients (Castle et al., 2016; Mitchell et al., 2018; He et al., 2019). The mutual promotion of plants and soils often exacerbates the weathering of the open-air stone, thus threatening the stone carved landscape. Nevertheless, due to the uneven distribution of stone carved landscape structures and the complexity of the micro-environment, there are significant differences in environmental conditions and resource levels in varying locations (Arellano et al., 2016; Pandita et al., 2019). Although the fact that many open-air stone carved landscapes are blessed with strong artistic value and religious meaning (Twilley 2006; Pillans and Fifield 2013; Waragai 2016; Lawonn et al., 2017; Lebedeva and Brantley 2017), far less information has been documented for the stocks of soil organic matter and nutrients based on current literature.

Soil organic matter is the material basis for the occurrence and development of plant communities, and the composition and structure of vegetation could reflect the characteristics of the habitat and determine the storage capacity of soil organic C, nitrogen (N) and phosphorus (P) (Ren et al., 2018; Lucas-Borja and Delgado-Baquerizo 2019; Dovrat et al., 2020). Generally, the first step of plant settlement is wet deposition on the surface of open-air stone carvings. The stock of subsidence materials from deposition as well as the loose rock surface, direct sunlight (Seneviratne and Indrasena, 2006), rainfall and other factors could be beneficial to the settlement of lower pioneer plants such as lichens and algae (Dettweiler-Robinson et al., 2013; Abinandan et al., 2019; Schaub et al., 2019). The growth of lichens is further weathered by the secretion of organic acids (Scarciglia et al., 2012), which promotes the decomposition of primary minerals, accelerates the formation of secondary clay minerals and induces the stocks of organic matter and nutrients (Lan et al., 2015). Afterwards, when the availability of nutrients in rock mass matrix is improved, conditions are created for the growth and development of higher plants such as herbs, and these higher plants further decompose and break minerals and further change the properties of minerals by root adhesion, interlotting and peeling (Fukami and Nakajima, 2013; Tamura et al., 2017; Tian et al., 2019). The decomposition and stock of organic matter and the synthesis of humus during the growth and diffusion of higher plants could also promote the stocks of organic matter and nutrients (Castellano et al., 2015; Kjær et al., 2018; Vilmundardóttir et al., 2018). This process is actually an evolution of the “food chain”. This invasion process is complicated, and we lack

relevant knowledge. There is few data to support targeted restoration and protection of weathering erosion problems in stone carved landscapes.

The Leshan Giant Buddha is a typical open-air stone carved landscape with uneven surface. Different positions are invaded by different types of vegetation, and the landscape is threatened to varying degrees. Based on the renovation project of the Leshan Buddha from 2018 to 2019, the soil covered by different types of vegetation on the surface of the Buddha were investigated on the spot to check the vegetation invasion characteristics on the surface of the Buddha by analyzing the spatial distribution of soil organic C, N and P. Therefore, it is hypothesized that uneven surfaces would affect soil organic matter storage and contribute to the distribution pattern of different vegetation types. The results will be expected to provide scientific evidence for management and conservation of the Leshan Giant Buddha and other similar open-air carved landscapes.

2 Materials and methods

2.1 Study site

The Leshan Giant Buddha (29°32'47"N, 103°45'48"E) is located in the south-east of the downtown area of the Leshan City, Sichuan Province, China. Built on the thick purple-red sandstone of the Triassic Jiaguan Formation, the 71-m-high Giant Buddha is the largest stone statue in the world, and was listed as a world's natural and cultural heritage in 1996. The regional climate belongs to the Warm-humid Subtropic Monsoon Zone. The total annual precipitation is approximately 1000 mm, mainly occurring from June to September. The average annual temperature ranges between 16.5°C and 18.0°C, and the average annual frost-free days are more than 300 d. Since the last restoration in 2011, rich vegetation has covered the Buddha surface in the past eight years, seriously destroying the landscape (Fig. 1) (Wu et al., 2020).

2.2 Field sampling and laboratory analyses

A comprehensive field investigation was carried out on the body surface of the Leshan Giant Buddha during the autumn in 2018. The surface of the Buddha body was divided into 7 different vegetation types (no plant, lichen, liverwort, moss, fern, herb and woody) by referring to *Flora of China* (1994). Given that the special site of the renovation project led to the limited scope of the investigation, we could not carry out a close investigation into the Buddha. The surface vegetation of the Buddha body was classified according to the area occupied by top vegetation types, while the area occupied by different vegetation types under the combination of multiple layers was not considered. In line with the spatial distribution pattern of the Buddha's body, the area was divided into 15 patches with the site characteristics considered (Fig. 1), and the length, width and height of the patches were measured. Soil samples were randomly collected at accessible locations,

Fig. 1 Sampling locations of the Leshan Giant Buddha (Photo taken on October 15, 2018). P1: head, P2: left shoulder, P3: left arm, P4: left hand, P5: left leg, P6: left foot, P7: right shoulder, P8: right arm, P9: right hand, P10: right leg, P11: right foot, P12: chest, P13: platform between two hands, P14: between the legs, P15: platform between the legs.

and a total of 21 soil samples were collected (7 vegetation types $\times$ 3 replicates).

The herb and woody native layers were deeper, so soil cores (with a volume of 100 cm^3) were used to collect the soil samples. For the remaining 5 types of vegetation with thin soil layers, a ruler was used to delineate a small plot of $10 \text{ cm} \times 10 \text{ cm}$, and then all the topsoil in the plot was scraped by a wooden stick. To protect cultural relics, the soil samples of no plant and lichen were taken under the same elevation and type of vegetation on the same side of the wall. Part of the soil samples were brought back to the laboratory and dried at 105°C to calculate the bulk density and dry weight. The other part of soil samples were air-dried in the room, and then passed through a 100-mesh sieve after being ground and packed into a plastic bag for the determination of C, N and P concentrations.

The C concentration of all soil samples was estimated using the dichromate oxidation and titration method (Lu, 2000). The N concentration was determined by sulfuric acid-mixed catalyst digestion, and the N in the digestion liquid was measured by Kjeldahl (KDY-9380, KETUO). The P concentration was determined by the sulfuric acid-perchloric acid digestion-molybdenum blue colorimetric method, and measured at 700 nm wavelength (UV-2450 UV spectrophotometer).

2.3 Data calculations and statistical analyses

The stocks of soil organic C, N and P under different vegetation types were calculated as follows:

$$S = C \times \rho \times H \times 10$$

where S is the soil organic C, N and P stocks (kg m^{-2}) under a certain vegetation type; C for the organic C, N and P concentrations (g kg^{-1}), ρ for soil bulk density (g cm^{-3}), and H is the thickness of the soil (cm).

The concentrations and stoichiometric ratios of soil organic C, N and P were expressed by mass ratio. Their variations under different vegetation types were analyzed by one-way ANOVA using the least significant difference method. Multiple comparisons were then used to test the significant differences among different vegetation types. All data were analyzed in SPSS 20.0 (IBM SPSS, Chicago, IL, USA).

3 Results

3.1 Soil organic C, N and P concentrations

Significant differences in soil organic C, N and P concentrations were observed under different vegetation types on the surface of the Leshan Buddha (Fig. 2). Soil organic C concentration ranged from 4.8 to 90.8 g kg^{-1} , N and P concentrations ranged from 0.52 to 8.83 g kg^{-1} and from 0.32 to 2.08 g kg^{-1} , respectively, among different vegetation types. The concentrations of soil organic C and N showed similar order of liverwort>fern>moss>woody>herb>lichen>no plant, while the soil P concentration showed the order of fern>moss>liverwort>woody>lichen>no plant>herb.

3.2 Soil organic C, N and P stoichiometry

Soil organic C, N and P stoichiometry varied significantly under different vegetation types on the surface of the Leshan Buddha (Fig. 3). Soil C:N ratio varied from 7.39 to 13.63, with higher ($P < 0.05$) values observed under woody and herbs and lower ($P < 0.05$) values observed under lichen. Soil C:P and N:P ratios varied from 11.99 to 75.19, and from 1.29 to 7.44, respectively among different vegetation types. Similar trends were observed for soil C:P and N:P ratios under different types of vegetation on the surface of the Buddha, with the highest values observed under liverwort and the lowest values observed in no plant plots.

3.3 Stocks and distribution of soil organic C, N and P

Soil organic C, N and P under different vegetation types on the surface of the Leshan Giant Buddha were mainly distributed on the chest, platform between hands and the right leg. Compared with other vegetation types, the stocks of soil organic C, N and P under vascular plants were higher than those under other vegetation types, with the highest values observed under herbs. The stocks of soil organic C, N and P

on the surface of the Leshan Giant Buddha were 1689.77, 134.6 and 29.48 kg, respectively. The stocks of both soil organic C and N showed similar patterns under different vegetation types: herb>woody>fern>moss>no plant>liverwort>lichen (Fig. 4A, B). The soil P stock on the surface of the Buddha's body followed the order of herb>woody>fern>no plant>moss>lichen>liverwort (Fig. 4C).

3.4 Distribution of soil organic C, N and P at different locations

The storages of soil organic C, N and P per square meter varied significantly among different locations ($P < 0.001$) on the surface of the Leshan Giant Buddha. Higher storages of soil organic C, N and P per square meter were found at the left arm, right shoulder, right arm, platform between two hands

Fig. 2 Concentrations of soil organic C, N and P under different vegetation types on the surface of the Leshan Giant Buddha. Error bars represent the standard errors. Different lowercase letters indicate significant ($P < 0.05$) differences in soil organic C, N and P concentrations among different vegetation types.

Fig. 3 Stoichiometric ratios of soil carbon (C), nitrogen (N) and phosphorus (P) under different vegetation types on the surface of the Leshan Buddha. Error bars represent the standard errors. Different lowercase letters indicate significant ($P < 0.05$) differences in soil organic C, N and P stoichiometric ratios among different vegetation types.

Fig. 4 Soil (A) organic carbon, (B) nitrogen and (C) phosphorus stocks under different vegetation types at different locations on the surface of the Leshan Giant Buddha. Error bars represent the standard errors. P1: head, P2: left shoulder, P3: left arm, P4: left hand, P5: left leg, P6: left foot, P7: right shoulder, P8: right arm, P9: right hand, P10: right leg, P11: right foot, P12: chest, P13: platform between two hands, P14: between the legs, P15: platform between the legs.

and the platform between two legs, while lower values were observed at the left feet, right feet and the head (Fig. 5).

4 Discussion

The soil organic C, N and P storage varied significantly among different locations and vegetation types on the surface of the Leshan Giant Buddha, on accordance with our hypothesis. We found that the soil organic C, N and P stocks were higher at the two arms, shoulders and the platforms between hands and legs. On the one hand, the products, sand grains and sinkers accumulate in the flat part owing to the weathering of the parent rock. On the other hand, as a tourist site, human activities may interfere with the weathering process, especially at the locations near tourist boardwalks (Cerveny et al., 2016). As a consequence, these locations had higher formation rates of soil organic matter, with more nutrient supply toward rapid plant growth and reproduction (Liu et al., 2015).

Soil organic C, N and P stocks were higher under herbs compared with other vegetation types, suggesting that herbs have a great influence on the landscape of the Leshan Giant Buddha. Moreover, the woody plants would gradually be updated, with higher stocks of soil organic C, N and P during natural succession (Wang et al., 2018; Makoto and Wilson, 2019). The space for the storage of soil organic C, N and P on the surface of the Leshan Giant Buddha became greater, and the Buddha's body would be damaged and gradually lose its landscape function. However, the stocks of soil organic C, N and P were higher on the chest and right leg of the Buddha body (Fig. 4), and the platform between the hands and the right leg of the Buddha's body were severely invaded by herbs. These results provided an effective fundamental investigation for the management and protection of stone carvings.

The stocks and spatial distribution of soil organic C and nutrients on the surface of the Leshan Giant Buddha's body are of great significance for understanding the elemental cycle and balance mechanism in this area and are also a key to predict the future of the Buddha's vegetation (Kaye et al., 2003; Yang et al., 2019). The soil organic C was significantly differed under different vegetation types (Fig. 4A), as a consequence of change in vegetation types along with the natural succession, which resulted in an increase in soil clay and abundance of soil nutrients (Sun et al., 2016; Yan et al., 2018). For example, large amounts of litter were accumulated under the deciduous Paper Mulberry (*Broussonetia papyrifera*) trees, resulting in a growing increase of soil organic C and nutrients. However, the soil organic C and N concentrations under herb and woody plants were significantly lower than those of Bryophyta and fern. A possible reason was that the soil under liverworts and plant body were difficult to be separated during sampling process, resulting in the concentrations of soil organic C and N under liverwort vegetation were higher than those under other vegetation types. Moreover, soil organic C and N were mainly affected by litter

decomposition and root litter input, so there was a large variability under different vegetation types. By contrast, the source of the soil P is relatively fixed with low variability because its concentration is mainly affected by soil parent material (Mage and Porder, 2013). Phosphorus is a sedimentary mineral with low mobility in the soil (Tian et al., 2012), so the distribution of soil P in the whole space was more uniform. Soil P between liverwort and moss, lichen and woody, weathered soil and herbs was not significantly different under different vegetation types.

Soil organic C, N, P stoichiometric ratio is the main index reflecting the soil biogeochemical cycles in soil (Ågren and Sveriges, 2008; Hättenschwiler and Jørgensen, 2010). Soil C:N ratio is a sensitive indicator of soil quality, affecting the cycling of organic C and N in soils (Dise et al., 1998). Tian et al. (2010) have documented that the average C:N ratio in Chinese soils was 11.9, similar with the average soil C:N ratio of 10.25 in our study. Previous researches have indicated that the availability of P is determined by the decomposition rate of soil organic matter and that a lower C:P ratio is an indicator of high P availability (Frost et al., 2005). The soil C:P ratios under vascular plants and moss were significantly higher than those under other plants because the vascular plants were more abundant, suggesting that the ecological measurements could control the nutrient concentration in soils. Soil N and P are the most common restrictive elements for plant growth (Cleveland and Liptzin, 2007; Reed et al., 2012; Zhou et al., 2018), but there was no significant difference between weathered soil and soil under lichen, moss and herbs, fern and woody plants. However, soil N:P ratio was greater under higher plants than those under other vegetation types, indicating that P and not N may be a nutrient limiting factor with the succession of vegetation.

5 Conclusions

In summary, the Leshan Giant Buddha is covered by rich soil organic C, N and P, which will speed up the surface weathering as well as vegetation development. We found that the higher vegetation such as herbs and woody plants can be more beneficial for soil organic matter and nutrients, implying that the development of higher plants may be the potential efficient pathway to protect the landscape of the Leshan Giant Buddha. In addition, the shoulder, arm, chest, right leg and the platform of the Buddha's body had higher stocks of soil organic C, N and P, which can be the important managing places to protect the Buddha landscape. Our results not only provided scientific evidences for the targeted management and protection of the Leshan Giant Buddha but also provided the necessity of surface renovation to the Buddha, although the actual interval time needs further investigations.

Conflict of interest

The authors declare no conflict of interest.

Fig. 5 Storages of soil (A) organic carbon, (B) nitrogen and (C) phosphorus per square meter at different locations on the surface of the Leshan Giant Buddha. Error bars represent the standard errors. P1: head, P2: left shoulder, P3: left arm, P4: left hand, P5: left leg, P6: left foot, P7: right shoulder, P8: right arm, P9: right hand, P10: right leg, P11: right foot, P12: chest, P13: platform between two hands, P14: between the legs, P15: platform between the legs.

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