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Factors controlling accumulation of soil organic carbon along vegetation succession in a typical karst region in Southwest China

Shujuan Liu [a,b,c,1], Wei Zhang [a,b,1], Kelin Wang [a,b,*], Fujing Pan [a,b,c], Shan Yang [d], Shiyan Shu [e,f]

[a] Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha 410125, China
[b] Huanjiang Observation and Research Station of Karst Ecosystem, Chinese Academy of Sciences, Huanjiang, Guangxi Zhuang Autonomous Region 547100, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] Changsha university, Changsha 410003, China
[e] Changjiang Project Supervision & Consultancy Co. Ltd, Wuhan 430010, China
[f] Changjiang Ecology (Hubei) Technology Development LLC, Wuhan 430010, China

HIGHLIGHTS

- Vegetation restoration is conducive to soil carbon sequestration in karst areas.
- The factors controlling SOC accumulation differed along vegetation succession.
- The interaction effect among significant factors became more and more prominent along succession.

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ABSTRACT

Vegetation succession enhances the accumulation of carbon in the soil. However, little is known about the mechanisms underlying soil organic carbon (SOC) accumulation in different vegetation types in the karst region of Southwest China. The goal of this study was to identify and prioritize the effects of environmental parameters, including soil physico-chemical properties, microbial biomass, enzyme activities, and litter characteristics, on SOC accumulation along a vegetation succession sere (grassland, shrubland, secondary forest, and primary forest) in the karst landscape of Southwest China. Relationships between these parameters and SOC were evaluated by redundancy analysis. The results showed that SOC accumulation was significantly different among vegetation types ($P < 0.01$) and increased with vegetation succession (from 29.10 $g \cdot kg^{-1}$ in grassland to 73.92 $g \cdot kg^{-1}$ in primary forest). Soil biochemistry and physical characteristics significantly affected the accumulation of SOC. Soil microbial biomass showed a predominant effect on SOC in each of the four vegetation types. In addition, the soil physical property (especially the silt content) was another controlling factor in the early stages (grassland), and urease activity and saccharase activity were important controlling factors in the early-middle and middle-late stages, respectively. Litter characteristics only showed mild effects on SOC accumulation. Variation partitioning analysis showed that the contribution of sole main factors to SOC variation decreased, while the interaction effect among parameters increased along the succession gradient.

1. Introduction

Soil contains more carbon than does the atmosphere and vegetation of the Earth combined (Tarnocai et al., 2009). Understanding the mechanisms controlling the accumulation of soil carbon is critical to predict patterns of global warming (Jenkinson et al., 1991; Knorr et al., 2005). Recent studies suggest that vegetation succession caused by both natural restoration and managed activity enhances the soil carbon sequestration capacity, which could thereby combat the effects of global climate change (IPCC, Intergovernmental Panel on Climate Change, 2007; Wilson et al., 2003; Deng et al., 2013; Chang et al., 2011). In addition, understanding the relationships between soil organic carbon

Abbreviations: SOC, soil organic carbon; SMBC, soil microbial biomass carbon content; SMBN, soil microbial biomass nitrogen content; litter C/N, ratio of carbon to nitrogen in the litter; SAC, saccharase activity; URE, urease activity; RDA, redundancy analysis; N, nitrogen; P, phosphorus.

* Corresponding author at: Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha 410125, China.
E-mail address: kelin@isa.ac.cn (K. Wang).

[1] Shujuan Liu and Wei Zhang are the first co-authors. These authors contribute equally to this work.

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(SOC) and soil biotic and abiotic characteristics in different vegetation types is essential for carbon management. However, soil carbon sequestration may be affected by different factors in different vegetation types (Zhu et al., 2012). Therefore, it is essential to identify the main drivers that control soil carbon sequestration to achieve effective soil carbon management at the regional or global scale. However, little is known about the factors controlling soil organic carbon in karst areas.

Karst is a distinctive topography, created by the action of acidic water on carbonate bedrock, such as limestone, dolomite, or marble. Due to its specific geologic and climate conditions, karst area is characterized by small environment capacity, weak anti-disturbance, low stability and powerless self-adjustment (Chen and Wang, 2004). In the late of the 20th century, an increasing human population and other heavy anthropogenic impacts have seriously damaged the vegetation in the karst region of Southwest China (Yao et al., 2001).

In 1999, China launched the 'Grain-for-Green' project that converted 9.26×10^6 ha of former croplands to forests or grasslands until 2010, which resulted in significant increases in soil carbon sequestration in China (Zhang et al., 2013). The karst region of Southwest China covers an area of 550,000 km^2 (Li et al., 2002), and is one of the main regions involved in the 'Grain-for-Green' project. These abandoned agricultural lands are experiencing a change from crop to forest or other secondary vegetation states, which are accompanied by changes in ecosystem structure, processes, and functions (Davidson et al., 2007; Zhang et al., 2010). Since the 1990s, government policies have forced farmers to abandon fields in parts of the karst area where erosion losses were especially high. With the enforcement of the projects, agricultural and rocky land gradually restored to grassland, shrubland, and forest, depending on the time since abandonment.

Some studies have reported an increase in SOC content along vegetation successions in many regions (Silver et al., 2000; Chang et al., 2011). In addition, many factors have been reported to affect soil carbon sequestration, such as vegetation type and biodiversity (Wardle et al., 2012), microbe type (Averill et al., 2014), litter quantity and quality (Gentile et al., 2011), and soil physical properties (Marschner et al., 2008). However, these parameters have usually been considered as single or several environmental factors that act independently on soil carbon accumulation. There has been little work done to explore the influences of composite influencing factors on SOC accumulation in different vegetation types along vegetation succession. Although soil carbon accumulation during ecosystem restoration in the karst region has been well documented (Zhu et al., 2012; Zheng et al., 2012), the specific factors that drive this accumulation are poorly known.

In this study, SOC was measured along a vegetation succession sere in a karst area in Southwest China, and other soil physicochemical properties, microbial biomass, enzyme activities, and litter characteristics were recorded. Our objectives were to (1) characterize the trend of SOC variation along vegetation succession, (2) identify the critical parameter(s) affecting SOC along vegetation succession, and (3) explain how these critical parameters affect SOC. We hypothesized that the factors controlling SOC accumulation differed along vegetation succession, and the interaction effect among the controlling factors became more and more prominent along succession.

2. Materials and methods

2.1. Study sites

This study was conducted at Guzhou catchments (24°54′–24°55′ N, 107°56′–107°57′E) and Mulun National Natural Reserve (25°06′09″–25°12′25″ N, 107°53′29″–108°05′45″ E) in Huanjiang county, Guangxi province in Southwest China. This region experiences a typical subtropical monsoon climate. Mean annual temperature is 19 °C, and mean annual precipitation is 1380 mm, mostly falling from May to September. Both sites are typical karst landscapes with a gentle valley flanked by steeper hills. The soil is lime soil and the parent rock is limestone. Soil pH ranged from 6.29 to 7.85 during the study period. Average soil depth was 50–80 cm in the depression and 10–30 cm on the hillslope.

The Guzhou catchments are located in an area of 10.2 km^2 with elevation ranging from 375 to 816 m above sea level, and contain 1.01 km^2 of farmlands, which are mainly located in the depression. Before the 1980s, the catchments were severely disturbed by deforestation and cultivation. Toward the end of 1996, some residents moved out of the area, and a part of the sloping farmlands was abandoned owing to the "Grain-for-Green" project. Three vegetation types that belong to different succession stages are widespread in the catchments, including grasslands, shrublands, and secondary forest lands. The grasslands were used as farmland but were abandoned in the 1990s, and then naturally recovered to a grass community. The dominant species in the grass community are *Miscanthus floridulus*, *Neyraudia reynaudiana*, and *Imperata cylindrica* (Table 1). Shrublands were deforested and cultivated before the 1980s, but were protected at the end of the 1980s and naturally recovered to a shrub community. The dominant species in the shrubland are *Alchornea trewioides*, *Cipadessa cinerascens*, and *Rhus chinensis* (Table 1). The secondary forests were deforested and cultivated before 1959, and were then protected and naturally recovered to secondary forest. The dominant species in the secondary forests are *Toona sinensis*, *Gleditsia sinensis*, *Radermachera sinica*, *Bauhinia brachycarpa* var. *cavaleriei*, *Sterculia euosma*, and *Rapanea kwangsiensis* (Table 1).

Mulun National Natural Reserve, about 25 km away from the Guzhou catchments and with an area of 108.6 km^2, was established in 1991 to protect a remnant of undisturbed mixed evergreen and deciduous broadleaved forests in the karst region. The primary forest at this site has not been disturbed for more than 200 years. The dominant species in the primary forest are *Cyclobalanopsis glauca*, *Miliusa chunii*, *Cryptocarya chinensis*, *Cleidion bracteosum*, and *Aidia cochinchinensis* (Table 1).

2.2. Sampling methods and collection

All samples were taken from July to August 2009. Plots were designed in 30 × 20 m quadrats, and in at least 30-m intervals from 3 sample lines of uniform vegetation in the whole slope under all four nonadjacent vegetation types. Soil samples were extracted from each plot. Before soil sampling, each plot was divided into four subplots (15 × 10 m). Eight sets (20 × 20 cm) of leaf litter and soil cores (15 cm depth) per subplot in 3-m intervals were taken and thoroughly mixed into one composite sample, respectively. A total of 51 plots included 12 grassland plots, 12 shrubland plots, and 11 secondary forest plots in Guzhou and 16 primary forest plots in Mulun National Natural Reserve. A total of 204 subplots were investigated, and 204 litter samples and 200 topsoil samples (2 shrubland subplots and 2 secondary forest subplots did not cover soil) were collected. The composite samples were placed in polyethylene bags and carried to the laboratory within no more than 10 h. For each subplot, canopy cover, slope, soil depth, rock exposure, and dominant species (determined according to Zhang, 2005) were recorded. In addition, we recorded the plot corner latitude, longitude, and altitude using a geographic positioning system (E640 + MobileMapper), and drew the map by ArcGIS 9.2. Litter samples were oven-dried at 70 °C to constant weight and ground for further analysis. Soil samples were air-dried and sieved with 2-mm mesh for soil physico-chemical analysis.

2.3. Laboratory analysis

Soil chemical and physical properties, including SOC, soil pH, and soil texture, were measured according to Liu et al. (1996). SOC was determined by a KCr_2O_7–H_2SO_4 oil bath. Soil pH value was measured in a 1:2.5 (w/v) soil to distilled water suspension. Soil texture analysis was determined by a pipette and sieve analysis. According to the USDA classification system, soil particle can be divided into 3 particle fractions: