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Tea plantation age effects on soil aggregate-associated carbon and nitrogen in the hilly region of western Sichuan, China

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ABSTRACT

Research on the variations of organic carbon (C) and total nitrogen (N) in soil aggregate fractions is important for better understanding C and N dynamics in agricultural soils. However, the effect of continuous planting of tea (*Camellia sinensis* L.) after the conversion of abandoned land to tea plantation on C and N dynamics has not been studied in detail. This study aimed to investigate the shifts in C and N concentrations in soil aggregate fractions after the conversion of abandoned land into tea plantation that were grown for varying periods of time (16, 23, 31, and 53 years) near Zhongfeng in the Mingshan district in the hilly region of western Sichuan, China. Soil samples were collected from the 0–20 and 20–40 cm depth intervals. Six aggregate fractions (> 5, 5–2, 2–1, 1–0.5, 0.5–0.25, and < 0.25 mm) were obtained by shaking and wet-sieving. In all studied tea plantations, the soil aggregates were dominated by the > 5 and < 0.25 mm fractions, which were the main pools of C and N. The mean weight diameter (MWD) of soil aggregates in the 23-year-old tea plantation was the greatest, indicating that aggregates in the 23-year-old tea plantation were more stable than in the other plantations. Aggregate stability was more strongly correlated with labile C than with organic C concentrations. Soil aggregates with different particle sizes had considerable variations in their organic C and total N concentrations in all tea plantations. The fractions that were most important to the retention of organic C and total N were the coarse aggregate fractions (> 2 mm). The greater C/N ratio of the coarse aggregate fractions implied that their organic C was younger and more labile than that in the fine aggregate fractions (< 0.5 mm). Long-term tea cultivation was favorable to the sequestration of soil C and N, especially in the < 0.25 mm fraction. However, the rates of C and N sequestration in the whole soil decreased with tea plantation age. It can be concluded that the development and implementation of a suitable management protocol is critically important to the maintenance of soil C and N sinks after 53 years of tea cultivation.

1. Introduction

Maintenance of soil organic carbon (C) is important for the sustainable use of soil resources due to organic carbon's multiple effects on soil nutrient status and structural stability (Nieto et al., 2010). In addition, the global concern surrounding climate change has increased interest in promoting C sequestration in soils to mitigate the increasing CO_2 level in the atmosphere (Chang et al., 2012). Because most agricultural soils have experienced some degree of organic C depletion, increasing the agricultural soil C pool has been suggested as an important method to sequester CO_2 from the atmosphere (Sackett et al., 2015).

Soil can act as a source or sink of atmospheric CO_2, largely depending on the balance between soil organic C formation and decomposition (Noponen et al., 2013). Aggregates have been considered as the basic unit of the soil in mediating mineral-organic interactions of a number of soil biophysical and biochemical processes at the microscale, which are linked to decomposition and transformation of organic C through binding to various agents (Raei et al., 2015). Hence, C sequestration in soils involves storage and stabilization of organic C among various aggregate fractions with regard to the turnover behavior of organic C. Furthermore, the variations in organic C in aggregate fractions may be a crucial issue for better understanding the effects of soil management practices on C dynamics and sequestration in agricultural soils (Wiesmeier et al., 2012).

Heterogeneous distribution of organic C associated with aggregates has been widely reported. Several studies established that organic C concentrations were greater in micro-aggregates (< 0.25 mm) than in macro-aggregates (> 0.25 mm) (Li et al., 2007; Mao et al., 2014). However, in other studies, greater concentrations of organic C were present in macro-aggregates (Mikha and Rice, 2004; Kong et al., 2005). These quantitative differences in organic C concentrations among

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different sizes of soil aggregates were thought to be related to soil clay particles that vary in different aggregate fractions (Christensen and Sorensen, 1985). Generally, the distribution of aggregate-associated C is mainly determined by aggregate size. However, aggregate distribution and stability are controlled by both biotic and abiotic factors (Abiven et al., 2009), where one of the most important is land-use conversion (Li and Pang, 2010).

During the last century, improper land-use practices, such as over-cultivation, over-pasturing and deforestation, have accelerated the fragmentation and degradation of ecological environments in the hilly region of western Sichuan, China due to increasing human population pressure. This resulted in destruction of natural ecosystems and reduction of the current or future soil productivity capacity. These negative impacts could be attributed to water and wind erosion, decline in fertility, changes in aeration and moisture levels, or shifts in soil flora or fauna. To prevent further deterioration of natural ecosystems, the Chinese government has launched a series of nationwide conservation projects focusing on the rehabilitation and recovery of these damaged ecosystems (Li and Pang, 2010). One of the important tasks aimed at achieving sustainable agricultural development in the hilly region of western Sichuan was the conversion of land use from abandoned land to tea (*Camellia sinensis* L.) plantation (Li et al., 2014).

Tea is a major cash crop in many developing countries, including China, India, and Sri Lanka. China is the largest tea-producing country in the world. By 2013, the tea plantation area in China had reached 2.58 million ha and continues to increase (International Tea Committee, 2014). In a previous study, it was reported that land-use change from abandoned land to tea plantation increased organic C and total nitrogen (N) levels in soil aggregate fractions mainly due to the augmented input of organic matter into soils via leaf and root residues and the formation of stable aggregates that protected organic matter (Li et al., 2014). The establishment of tea plantations could markedly improve organic C and total N concentrations in aggregate fractions in the hilly region of western Sichuan, China and potentially reduce erosion risks. However, the effects of different chronosequence phases on aggregate-associated C and N concentrations in tea plantations have not been studied in detail. Therefore, the present work was aimed to assess and quantify the short- and long-term effects of the conversion of abandoned land to tea plantation on the (i) distribution and stability of aggregates, (ii) concentrations of aggregate-associated C and N, and (iii) contents of C and N in various aggregate fractions.

It was hypothesized that (i) the rates of C and N sequestration in the whole soil differed with the stage of tea cultivation and (ii) the changes of aggregate-associated C and N contents differed with aggregate size in the process of tea cultivation. The results could provide a soil-focused theoretical basis for the sustainable development of tea plantations.

2. Materials and methods

2.1. Experimental site

Research began in January 2011 at the Zhongfeng long-term agricultural research site of Sichuan Agricultural University in Ya'an, Sichuan, China (Fig. 1). The prevailing climate surrounding the study site is a subtropical monsoon climate. Mean annual temperature is 15.4 °C, with the lowest and largest mean daily temperatures of 4.3 and 35.2 °C, respectively (Wang et al., 2016). Average annual precipitation is 1500 mm with 72.6% of the precipitation occurring during July to September. The exposed layer is sedimentary rock mainly formed after the Mesozoic age and the soil is classified as Luvisols (FAO, 1990).

The cultivation density of tea (broad row was 150 ± 15 cm wide, narrow row was 35 ± 15 cm wide, and the distance between two plants was 16 ± 4 cm) was set at about 8×10^4 plants per hectare. Swine manure (15 Mg ha^{-1}) and complex fertilizer ($N:P_2O_5:K_2O$ = 20:8:8, m/m/m, 0.75 Mg ha^{-1}) were spread yearly in mid-October as the base fertilizer along vertical edges beneath the tree canopy. A top dressing of the tea plantations was added three times per year. The following year in mid-February, 1.5 Mg ha^{-1} of complex fertilizer and 0.6 Mg ha^{-1} of urea were applied; in late-May and July, 0.75 Mg ha^{-1} of complex fertilizer and 0.3 Mg ha^{-1} of urea were added to the soil surface, where the position of top dressing was the same as the basal fertilizer application.

2.2. Experimental design

The method of space-for-time substitution, an effective way to study changes over time (Sparling et al., 2003), was used to monitor soil changes occurring along a tea plantation chronosequence that has developed with similar soils and climatic conditions. Establishment of tea plantations at different times offers an ideal opportunity to understand the tea cultivation process because soil conditions before tea cultivation are largely driven by geomorphologic processes.

In this study, soil samples from four tea plantations with different ages (16, 23, 31, and 53 years) were collected in September 2011 (Table 1). All studied tea plantations were located on similar geomorphologic units with similar soil parent material, slope direction and gradient, and fertilization practices. The soil aggregate distribution and stability of the abandoned land converted to tea plantation were described in detail by Zheng et al. (2011). The experiment was a completely randomized design with five replications for each tea plantation, resulting in a total of 20 plots (15 m × 15 m).

2.3. Soil sampling

In each plot, five undisturbed samples were collected from the 0–20 and 20–40 cm soil depth intervals and the five undisturbed samples from each soil depth interval were mixed to form a composite sample. A total of 40 composite samples were stored in plastic containers and transferred to the laboratory. Then, each composite sample was gently broken along natural planes of weakness into natural aggregates and passed through a 10-mm sieve to remove large roots, stones, and macrofauna. The aggregates were air-dried at room temperature for one week.

2.4. Aggregate separation

The distribution of aggregates was estimated by the wet-sieving technique (Kemper and Chepil et al., 1965). In this procedure, a 250-g composite sample was placed on the topmost sieve of a nest of sieves of diameters 5, 2, 1, 0.5, and 0.25 mm. The sample was pre-soaked in distilled water for 10 min before oscillating vertically in water 20 times (along 4 cm amplitude) at the rate of 1 oscillation s^{-1}. The resultant aggregates on each sieve were oven-dried at 105 °C for 24 h, weighed, and analyses were conducted to determine their organic C and total N concentrations. The mass of the < 0.25 mm fraction was obtained by difference between the initial sample weight and the sum of sample weights collected on the 5, 2, 1, 0.5, and 0.25 mm sieves.

2.5. Soil chemical analyses

Soil pH was determined using a glass electrode with a l:2.5 soil mass : water volume ratio (Lu, 2000). Soil organic C was determined by acid dichromate wet oxidation (Nelson and Sommers, 1996). Total N was determined by the micro-Kjeldahl method (Bremner, 1996). Labile C was determined by oxidation with 333 mmol L^{-1} $KMnO_4$ (Blair et al., 1995).

2.6. Calculations and statistical analyses

Mean weight diameter (MWD, mm) was used to estimate the stability of aggregates (Fattet et al., 2011) and was calculated using the formula in Kemper and Rosenau (1986):