Agriculture, Ecosystems and Environment 258 (2018) 1–13

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Changes in soil organic and inorganic carbon stocks in deep profiles following cropland abandonment along a precipitation gradient across the Loess Plateau of China

Xiaoyang Han[a,b], Guangyao Gao[a,b,*], Ruiying Chang[c], Zongshan Li[a], Ying Ma[d], Shuai Wang[e], Cong Wang[a], Yihe Lü[a,b], Bojie Fu[a,e]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] Joint Center for Global Change Studies, Beijing 100875, China
[c] Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan, 610041, China
[d] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[e] State Key Laboratory of Earth Surface Processes and Resources Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Keywords:
SOC and SIC
Shallow and deep layers
Precipitation gradient
Vegetation restoration
Loess Plateau

ABSTRACT

Determining changes in soil organic carbon (SOC) and inorganic carbon (SIC) stocks following ecological restoration is important for estimating the regional carbon budget and evaluating ecological effects. However, there is limited understanding on the interacting effects of vegetation restoration and climate gradients on SOC and SIC stocks in shallow and deep soil layers over large scales. This study selected seven sites along a climate transect from the east to the west of the Chinese Loess Plateau, and the SOC and SIC stocks were measured to a depth of 300 cm in sites covered by cropland and three vegetation restoration types (grassland, shrubland and woodland). The spatial variations and controlling factors of the SOC and SIC stocks at different depths following vegetation restoration along the precipitation gradient were investigated in detail. The results indicated that the SOC and SIC stocks in the 100–300 cm layers accounted for more than 50% of the total values in the 0–300 cm profile. The total SOC stock in the 0–300 cm profiles significantly increased along precipitation gradient ($p < 0.01$) in all vegetation types except woodland. The total SIC stock decreased, but the change was not significant, which caused little variation in the total carbon stocks along the precipitation gradient ($p > 0.05$). Shrubland and woodland plantation following cropland abandonment resulted in soil carbon accumulation, whereas grassland represented carbon loss in sites with mean annual precipitation (MAP) greater than 470 mm. The changes in the SOC stock (ΔSOC) in the surface layer (0–20 cm) and those in the SIC stock (ΔSIC) in the deep layers (100–300) following revegetation significantly decreased along precipitation gradient ($p < 0.05$). The interactions between ΔSOC and ΔSIC stocks were evident, especially in the upper soil layers. An accumulation of 1 kg SOC was accompanied by 0.73 kg loss of SIC in the 0–40 cm layer and 1.26 kg increase of SIC in the 40–300 cm layer per square meter following revegetation. MAP and mean annual temperature (MAT) mainly affected the spatial patterns of SOC and SIC in the upper layers, while land use and soil texture mainly affected soil carbon in the deep layers. This study indicates that vegetation restoration does not always result in soil carbon sequestration at every depth after cropland abandonment, which depends on climatic conditions and varies among different vegetation types.

1. Introduction

Soil plays an important role in sequestering atmospheric CO_2 and emitting greenhouse gas. As the largest carbon pool in the terrestrial ecosystem, the carbon stock in soil is at least three times the amount of carbon in the atmospheric and biotic pools (Post et al., 1990; Batjes, 1996; Davidson et al., 2000). Soil carbon stocks depend on the balance of carbon input and output, which is affected by land use types, soil properties, microbial activities, and natural disturbances, and are especially correlated with climatic variables (Post et al., 1982;

* Corresponding author at: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.
E-mail address: gygao@rcees.ac.cn (G. Gao).

https://doi.org/10.1016/j.agee.2018.02.006
Received 2 November 2017; Received in revised form 2 February 2018; Accepted 3 February 2018

Halvorson et al., 2002; Arevalo et al., 2009). Moreover, the changes in soil carbon pool could impact atmospheric CO_2 concentrations and global climate conditions (Lal, 2004; Díaz-Hernández, 2010; Jeong et al., 2013). Understanding the patterns, magnitude and driving forces of the terrestrial carbon cycle, and their subsequent climate feedbacks caused by land use change, is still a major challenge for earth system science studies (Liu et al., 2017). Thus, studies on soil carbon stocks in different land use types along climate gradients are essential for predicting and evaluating the consequences of regional and global climate change.

The global soil organic carbon (SOC) and soil inorganic carbon (SIC) stocks in the top 1 m are approximately 1200–1600 and 940 Pg (1 Pg = 10^{15} g), respectively (Post et al., 1982; Eswaran et al., 1999). SOC mainly comes from the decomposition of biotic residues, and it is the most active part of the soil carbon pool and exhibits rapid turnover in response to the environment. The dynamics of SOC contents are of great importance to soil quality evolution and the global carbon cycle (Lal, 2004; Selim et al., 2016). SIC mainly accumulates as calcium carbonate ($CaCO_3$) and dolomite ($MgCO_3$), and it is relatively stable and mainly stored in arid and semiarid areas (Mi et al., 2008; Hirmas et al., 2010). SIC has also been suggested to play a significant role in carbon sequestration (Lal, 2008). SIC can be classified into lithogenic inorganic carbon (LIC) and pedogenic inorganic carbon (PIC), and the formation of PIC can be expressed through the following equations (Wu et al., 2009; Tan et al., 2014):

$$CaCO_3+H_2O+CO_{2\downarrow} \leftrightarrow Ca^{2+}+2HCO_3^- \leftrightarrow CaCO_3+H_2O+CO_{2\uparrow} \quad (1)$$

$$CaSiO_3+3H_2O+2CO_{2\downarrow} \leftrightarrow Ca^{2+}+2HCO_3^-+H_4SiO_4 \quad (2)$$

For every mole CO_2 released during the precipitation of pedogenic carbonate, it consumes 2 mol of atmospheric CO_2, leading to the sequestration of atmospheric CO_2 in soil (Schlesinger, 1982). SOC and SIC are essential parts of the soil carbon pool, and both should be considered when estimating the soil carbon stocks in terrestrial ecosystems. Many studies usually focused on the amount or distribution of SOC and SIC stocks in the profile in certain region or sites (Díaz-Hernández, 2010; Wang et al., 2010; Chang et al., 2012; Liu et al., 2016; Raheb et al., 2017). The quantitative relationship between the changes of SOC and SIC stocks in deep profiles following vegetation restoration need further exploration.

Detecting the spatial-temporal variations of soil carbon is important for terrestrial carbon stock estimations. A considerable number of studies have been carried out on the spatial distribution of soil carbon at specific site (Arevalo et al., 2009; Wei et al., 2010; Chang et al., 2014; Selim et al., 2016), regional (Hirmas et al., 2010; Liu et al., 2014; Willaarts et al., 2016), continental (Li et al., 2007; Piao et al., 2009; Wertebach et al., 2017), and global (Van Minnen et al., 2009; Wei et al., 2014; Deng and Shangguan, 2017) scales. Most of them have focused on soil carbon in the shallow layers (0–100 cm), which resulted in the underestimation of soil carbon stock, as the shallow depths do not fully reflect the impacts of treatments (i.e., land use management, tillage and fertilization) on soil carbon variations (Harrison et al., 2011). The sampling depth is critical for soil carbon estimations, and it is essential to sample soil profiles as deeply as possible. Jobbágy and Jackson (2000) reported that the global SOC stock estimates increased by 33% and 56% if the depth of the SOC data increased from 100 cm to 200 cm and 300 cm, respectively. The study by Harper and Tibbett (2013) in southwestern Australia showed that the mean SOC mass densities to a depth of 500 cm were 2 to 5 times greater than those within the depth of 50 cm. In contrast to SOC, little attention has been paid to SIC variations in deep soil profiles at regional scales (Mi et al., 2008; Wu et al., 2009; Wang et al., 2010).

The factors that influence the distributions and dynamics of SOC and SIC are different between shallow and deep soil layers (Liu et al., 2011b; Wang et al., 2016b; Jia et al., 2017). Climate variables, such as precipitation and temperature, can affect the distribution and growth of vegetation, which have dominant control over the spatial distribution of SOC and SIC (Davidson and Janssens, 2006; Kirschbaum et al., 2008; Jia et al., 2017). Land use management practices, such as land use change (Sainju et al., 2008; Qiu et al., 2012; Tan et al., 2014), afforestation (Arevalo et al., 2011; Berthrong et al., 2012; Feng et al., 2013) and drainage system installation (Liu et al., 2011a), may have considerable impacts on deep soil carbon stocks. Different land use management practices can result in differences in vegetation productivity (Wu et al., 2016), microbial community properties (Mabuhay et al., 2006) and soil physicochemical properties (Wang et al., 2016b), which are closely related to changes in deep soil carbon stocks. Furthermore, the dissolution and leaching of SIC in the soil profile are also affected by soil water content and fine root biomass (Chang et al., 2012). Therefore, the interaction effects of land use change and climate gradients on SOC and SIC changes in shallow and deep layers need further study, especially in arid and semiarid regions, such as the Loess Plateau in China.

A large-scale ecological rehabilitation project was launched in 1999 to restore the degraded ecosystem of the Loess Plateau, which is known as the “Grain for Green” programme. More than 4.90 million ha of sloping cropland and abandoned land have been converted to grassland and forestland through this programme (Lü et al., 2012). The vegetation restoration inevitably led to extensive land use changes, which substantially affected the recycling process of soil carbon and other nutrients in this region, and their effects were highly variable among different soil layers and different climatic conditions (Wang et al., 2011; Raheb et al., 2017). It is important to evaluate the soil carbon changes following vegetation restoration after cropland abandonment in the Loess Plateau (Zheng et al., 2005). Most of the previous studies have investigated only SOC or SIC stocks under different land use types in relation to vegetation restoration and climate factors at certain sites or in specific watersheds. For example, Wang et al. (2016b) and Gao et al. (2017) investigated the SOC stocks to depths of 500 cm and 1800 cm under different land use types in a watershed, respectively. Jia et al. (2017) detected the spatial variability of SOC at depths of 0–500 cm along a south-north transect of the Loess Plateau, whereas the variations in the SIC stocks were not considered in their study. Chang et al. (2012) and Liu et al. (2016) studied both SOC and SIC stocks at a specific site, but the depth they considered was only 100 cm, and they considered only the effects of afforestation and grassland restoration, respectively. To the best of our knowledge, little research has focused on the distribution and stocks of both SOC and SIC in deep soil layers along a climate gradient. Moreover, the comparisons among the effects of various vegetation restoration types on the changes in SOC and SIC stocks over a large spatial scale need further research. These knowledge gaps are the motivation for the work presented in this paper.

This study selected seven sampling sites along a climate transect from east to west of the Loess Plateau and compared SOC and SIC stocks at 0–300 cm depth among cropland, grassland, shrubland and woodland stands. The objectives of this study were to (1) investigate the variations in SOC and SIC stocks to a depth of 300 cm in cropland and three vegetation restoration types along a precipitation gradient, (2) detect the changes in the SOC and SIC stocks and their interactions at different depths following vegetation restoration, and (3) identify the factors controlling the SOC and SIC stocks in both shallow and deep soil layers.

2. Materials and methods

2.1. Study area and transect description

This study was conducted in the Loess Plateau of China (Fig. 1). The Loess Plateau has an area of about 6.4×10^5 km^2, and it is dominated by a temperate, arid, and semiarid continental monsoon climate. The mean annual precipitation (MAP) ranges from 200 to 650 mm, and the mean annual temperature (MAT) ranges from 8 to 14 °C (Fig. 1). More than 65% of the precipitation falls between June and September.