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Changes of soil carbon in five land use stages following 10 years of vegetation succession on the Loess Plateau, China

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ABSTRACT

Changes in land use caused by natural vegetation succession can enhance the soil organic carbon (SOC) and carbon (C) stock of terrestrial ecosystems, as reported in many studies throughout the world. However, the dynamics of SOC and soil C stocks and their changes in each succession stage are not clearly following restoration age. Additionally, whether litter and fine roots have positive effects on SOC and soil C sequestration is unclear. We simultaneously studied litter and fine root production and SOC and C stocks along a natural vegetation succession – abandoned farmland, grassland, shrubland, pioneer woodland to natural climax forest – in 2005 and 2015 on the Loess Plateau of China. This allowed a better understanding of the variations of SOC and soil C stock in different land use stages in relation to soil layers and effects of litter and fine roots following vegetation restoration. The land use stages and soil layers significantly affected the rates of SOC and soil C sequestration change. The SOC and soil C stocks in the 0–60 cm soil profile rapidly increased over the course of the long-term natural vegetation succession. During 2005 to 2015, the topsoils (0–20 and 20–40 cm) had higher rates of SOC change (from 0.06 to 0.55 and from 0.23 to 0.51 g kg^{-1} yr^{-1}, respectively) and soil C sequestration rates (from 0.37 to 1.09 and from 0.40 to 1.16 Mg ha^{-1} yr^{-1}, respectively) than subsoils (40–60 cm, from 0.04 to 0.36 and from 0.05 to 1.16 Mg ha^{-1} yr^{-1}). The litter and fine root production increased with age of the natural vegetation succession, and had significant positive effects on changes in SOC and soil C sequestration. Therefore, long-term natural vegetation restoration improved the SOC accumulation, and increased litter and fine root inputs were probably the main factors contributing to soil C sequestration.

1. Introduction

Soil organic carbon (SOC) as a key component of the global carbon (C) cycle and its potential as a sink for atmosphere carbon dioxide (CO_2) on a global scale has been widely discussed in the scientific literature (DeGryze et al. 2004; IPCC, 2007; Stockmann et al. 2013; Deng and Shangguan 2017). It has long been recognized that land use/cover change and management can alter the amount of organic C stored in the soil (Van der Werf et al. 2009; Laganière et al. 2010; Deng et al. 2017; Kalinina et al., 2015a, b) and this in turn affects both soil fertility and atmospheric CO_2 concentration (Powers et al. 2011; Deng et al. 2017). Many studies around the world have reported that the SOC content declines by 20%–43% after natural forest or perennial grassland is converted to agricultural land (Guo and Gifford 2002; Don et al. 2011). In contrast, vegetation restoration through conversion of farmland into grassland or forest has been shown to increase SOC by increasing C derived from new vegetation (Laganière et al. 2010; Deng et al. 2016). Therefore, vegetation restoration (e.g. afforestation, natural restoration and grass planting) have been proposed as effective methods for reducing atmospheric CO_2 due to C sequestration in soils (UNFCCC, 2009; IPCC, 2007; Deng et al. 2017).

Many recent studies have examined the dynamics of SOC and soil C stocks following vegetation restoration (Laganière et al. 2010; Aryal et al. 2014; Wang et al. 2016; Karelin et al. 2017), but have obtained varied results. For example, Sean et al. (2012) illustrated that changes in SOC with afforestation were positively correlated with plantation age and Nave et al. (2012) demonstrated that afforestation had significant positive effects on SOC sequestration in the USA, although these effects require decades to manifest and primarily occur in the uppermost (and perhaps most vulnerable) portion of the mineral soil profile. However, Smal and Olszewska (2008) documented that soil C stock significantly decreased in Scots pine (*Pinus silvestris* L.) forests in sandy post-arable

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soils. In addition, many studies reported that soil C stock initially declined and then increased following farmland conversion into forestland (Kalinina et al. 2009, 2013). The soil C dynamic pattern remains unclear because different land-use conversion types and soil depths have been combined, with large differences in depths and land-use conversion types in temporal C stock changes (Deng et al. 2016). Thus, our understanding of soil C dynamics for different soil depths and land-use conversion types remains incomplete.

The Loess Plateau in China is well known for the most severe soil erosion in the world (Fu 1989). Vegetation degradation and exponential population growth have caused massive amounts of soil and water to be lost (Liu et al. 2007). To control soil erosion and restore ecosystems, China has launched the "Grain for Green" Program, aimed at restoring degraded farmland to forest and grassland (Deng et al. 2017). In the study area, farmland had already been abandoned, and processes of natural and artificial restoration were underway (Deng et al. 2013, 2016; Cheng et al. 2015). Previous studies reported that natural vegetation restoration can recover the properties of degraded soil and maintain soil fertility (Feldpausch et al. 2004). For this reason, understanding natural vegetation restoration processes on the Loess Plateau is becoming increasingly important. Deng et al. (2013) studied SOC and soil C stock dynamics along with the natural vegetation succession from abandoned farmland to natural climax forest in the Ziwuling Forest Region of the Loess Plateau, and found that SOC and soil C stocks in the 0–60 cm soil profile rapidly increased in long-term (~150 years) natural vegetation succession. However, dynamics of SOC and soil C stock and their change rates in every land use stage were not clear following restoration age. In addition, although we know that land use and vegetation development stages affects SOC and C stock, the difference in the dynamics of SOC and C stocks in each of these stages are not clear. It also remains unclear whether changes in input from litter and fine roots have a positive effect on SOC and soil C sequestration.

Therefore, this study used two times of a field survey on five land use stages: abandoned farmland (AF), grassland (GL), shrubland (SL), pioneer woodland (WL) and natural climax forest (NF) in 2005 and 2015 in the Ziwuling Forest Region of the Loess Plateau. The objectives were to: (i) explore the variations of SOC and soil C stock for different land use stages and soil layers; (ii) quantify the contributions of relevant factors (land use stage, soil layer and age) to variations in SOC and soil C stock; and (iii) examine the effects of litter and fine roots on SOC and soil C sequestration.

2. Materials and methods

2.1. Study area

The study was conducted at Lianjiabian Forest Farm in Heshui County of Gansu Province (33°50′–36°50 N′, 107°30′–109°40′E and 1100–1756 m a.s.l.), in the Ziwuling Mountain region in the central south of the Loess Plateau (Fig. 1). The Ziwuling Mountain region covers an area of 23,000 km^2, with a warm-temperate and sub-humid continental monsoon climate. The annual mean temperature is 10 °C and the mean annual rainfall is 587 mm (1960–2010). The soil humid is about 12%–14%. The study area has landforms typical of loess hilly topography with altitude range of 1300–1700 m. Loessial soil (*Calcic Cambisols*) is the main soil type, developed from primary or secondary loess parent materials, which are evenly distributed 50–130 m deep and present on top of a red earth consisting of calcareous cinnamon soil. The area has a warm temperate deciduous broad-leaved forest biome. The natural vegetation is deciduous broadleaf forest of which the climax vegetation is *Quercus liaotungensis* Koidz forest. In the region, *Populus davidiana* Dode communities dominate pioneer forests, *Hippophae rhamnoides* (Linn.) is the main shrub species, and *Bothriochloa ischaemun* (Linn.) Keng and *Lespedeza davurica* (Laxm.) Schindl. are the main herbaceous species. Previous research in the study area showed that secondary forests naturally regenerated on AF from GL, SL and WL to NF (*Q. liaotungensis*) over the past 150–160 years (Deng et al. 2013; Wang et al. 2016). AF has usually been abandoned for about 5 years in the study area.

2.2. Experiment design and sampling

The first field survey was undertaken between 15 July and 15 August 2005, and the second survey between 15 July and 15 August 2015 using the same sampling sites as 2005. The sampling areas of the communities involved were determined according to their sizes. There were five 20 m × 20 m plots chosen in WL and NF communities, five 5 m × 5 m plots in SL communities, and five 2 m × 2 m plots in the herbaceous communities (i.e. AF and GL). The plots were not > 5 km apart and their largest relative elevation difference was < 120 m. Most plots had a slope gradient below 20° and faced north. All surveyed soils developed from the same parent materials and had vegetation for differing numbers of years. To minimize the effects of site conditions on experimental results, all selected sites had a similar slope aspect, slope gradient, elevation, soil type and land use history. The basic information of the sites is shown in Table 1.

Soil samples were taken at five points lying at the four corners and center of the soil sampling sites described above. Soil drilling samplers were used to sample soil in three soil layers: 0–20, 20–40 and 40–60 cm. In each plot, ground litter and fine roots were removed and then soils were sampled at the five points and mixed according to soil layers to form one soil sample. All soil samples were air-dried and sieved through a 2 mm screen, and prepared for SOC analysis. Bulk density (BD) of the soil at sampling sites was measured in the different soil layers using a soil bulk sampler of 5 cm diameter and 5 cm high stainless-steel cutting ring (three replicates) at points adjacent to the soil sampling quadrats by measuring the original volume of each soil core and the dry mass after oven-drying at 105 °C. In addition, before sampling soil, five 1 m × 1 m quadrats were set in the five soil sampling points of SL, WL and NF sites, and five 0.5 m × 0.5 m quadrats set in the five soil sampling points of AF and GL sites. We collected all ground litter in quadrats to measure litter biomass in the five land use stages.

To measure fine root biomass, root sampling was performed with three replicates in three soil layers of 0–20, 20–40 and 40–60 cm in each quadrat using a 9 cm diameter root auger. The majority of the roots found in the soil samples thus obtained were then isolated using a 2 mm sieve. The remaining fine roots taken from the soil samples were isolated by spreading the samples in shallow trays, overfilling the trays with water and allowing the outflow from the trays to pass through a 0.5 mm sieve. No attempts were made to distinguish between living and dead roots. All roots thus isolated were oven-dried at 65 °C and weighed to within 0.01 g.

2.3. Laboratory assays

Soil BD was calculated depending on the inner diameter of the core sampler, sampling depth and oven-dried weight of the composite soil samples (Deng et al. 2013; Fig. 2). SOC was assayed using dichromate oxidation (Kalembasa and Jenkinson 1973).

2.4. Soil C stock calculation

In our sample soils, there was no coarse fraction (i.e. > 2 mm) and so we did not need to insert "1 – coarse fragment (%)" in formulae. The following equation was used to calculate SOC stock (Guo and Gifford 2002):

$$Cs = \frac{BD \times SOC \times D}{10} \quad (1)$$

in which, Cs is SOC stock in Mg ha^{-1}, BD is in g cm^{-3}, SOC is in g kg^{-1} and D is soil thickness in cm.

Changes in SOC and C sequestrations were estimated based on