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Temporal and spatial variations in soil organic carbon sequestration following revegetation in the hilly Loess Plateau, China

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ABSTRACT

Land use change is one of the major factors that affect soil organic carbon (SOC) variation and global carbon balance. Since the late 1970s, a significant area of the hilly Loess Plateau has undergone major land use changes during several revegetation programs, especially in the Grain for Green Project. However, so far there has not been a comprehensive study to determine temporal and spatial variations in SOC due to revegetation in this region, which hampers accurate predictions of the SOC sequestration potential and the land use change impacts. In this study, slope cropland and five typical revegetation types in the hilly Loess Plateau were selected, and then classified into 36 groups according to different revegetation years and landforms to investigate temporal and spatial variations of SOC and the impacts of relevant factors following revegetation. The results showed that the SOC concentration in the top soil horizon (0–5 cm) increased most significantly with revegetation and that increases in SOC slowed with increasing soil depth, but coefficient of variations in different soil horizons indicated that revegetation could cause SOC concentration differences at up to a 30 cm depth. Temporal variation in SOC occurred in two main phases in replanted cropland: in the first 10 or 15 yr, the profile mass of SOC (SOC density, SOCD) increased slightly; after this phase, SOCD increased significantly, with sequestration rates of 0.69, 0.55 and 0.24 $t \cdot ha^{-1} \cdot yr^{-1}$ (revegetation 10 to 35 yr) for planted woodland, planted shrubland and abandoned cropland, respectively. The SOC sequestration rate in wild grassland was 0.23 $t \cdot ha^{-1} \cdot yr^{-1}$ (revegetation 10 to 35 yr), which was similar to that in abandoned cropland. In contrast, the SOCD in wild shrubland increased rapidly in the first 10 yr, with a rate of 0.93 $t \cdot ha^{-1} \cdot yr^{-1}$, and then by 0.56 $t \cdot ha^{-1} \cdot yr^{-1}$ over the next 25 years. SOCD spatial differences in different landforms had reached several times the annual SOCD increment and followed a new trend after revegetation: SOC sequestration in shady slope areas was significantly higher than in sunny slope areas, but no significant difference was found between gentle slopes and steep slopes after revegetation. A general linear model was used to identify the factors that were most relevant to SOC variation. Revegetation years accounted for nearly half of the total contribution to SOC variation (42%), and land use type was responsible for 33% of SOC variation. SOCD distribution in a watershed confirmed that variables of land use and years after revegetation dominated SOC variation. Landforms had a small influence on SOC variation at the regional scale, but the influence of the slope aspect was still large. The SOC sequestration rate was about 0.21 to 0.64 $t \cdot ha^{-1} \cdot yr^{-1}$ with revegetation in the hilly Loess Plateau, which was highest in wild shrubland, followed by planted woodland, planted shrubland, abandoned cropland and wild grassland. Considering the large area of revegetation and relatively high SOC sequestration rate, SOC sequestration in this region should contribute significantly to decreasing the carbon concentration in atmosphere.

1. Introduction

Global climate change, especially global warming, is profoundly influenced by the sequestration dynamics of soil organic carbon (SOC). The global SOC stock is approximately 1395–2200 Pg (IPCC, 2000; Jobbagy and Jackson, 2000) which is 4.5 times the amount in the terrestrial biotic pool and 3.3 times greater than the global atmosphere carbon pool (IPCC, 2000; Jobbagy and Jackson, 2000; Lal, 2008). The terrestrial biosphere sequestered around 3.5 Pg C each year, which accounted about 41% of annual C emission by anthropogenic sources (IPCC, 2007; Lal, 2008). Meanwhile, the global SOC sequestration potential was 0.4–1.2 $Pg \cdot yr^{-1}$ (Lal, 2004, 2008). Land use change is widely considered

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a major factor that affects SOC sequestration (Chen et al., 2007; Garten, 2002; IPCC, 2000; Lal, 2008). Some studies have indicated that up to 50% of SOC may be lost after 30–50 years of cultivation (Garcia-Oliva and Masera, 2004; Post and Kwon, 2000; Upadhyay et al., 2005). In contrast, increasing forested land through revegetation will increase SOC sequestration. The global average SOC sequestration rate was 33.2 to 33.8 $g \cdot m^{-2} \cdot yr^{-1}$ due to revegetation on cultivated lands (Post and Kwon, 2000), and therefore large areas of land conversion could have a significant effect on the global C budget. The potential SOC sequestration through afforestation was estimated at 3 $Tg \cdot yr^{-1}$ (1 Tg $= 10^{12}$ g) in Norway, 6 $Tg \cdot yr^{-1}$ in New Zealand, 9 $Tg \cdot yr^{-1}$ in Sweden, 107 $Tg \cdot yr^{-1}$ in Russia and 117 $Tg \cdot yr^{-1}$ in the USA (IPCC, 2000; Lal, 2008). Because some ecosystem models did not take these land use changes into account, the simulated carbon sink was consistently 25% or 42% less than estimates derived from the satellite inventory method or the atmospheric inversion sink (Piao et al., 2009).

Since the late 1970s, several revegetation programs have been conducted in the hilly Loess Plateau with the aim to control soil erosion and combat land degradation. During the last 10 years, the Chinese government has invested more than 430 billion RMB (63 billion US$) in the Grain for Green Project (GGP) (Li, 2001; Zhang et al., 2011), which called for 14.67 million hectares (Mha) of slope croplands and 17.33 Mha of barren land to be replanted from 1999 to 2010 (see also the Forest Resources Management Department of China Forestry Administration, 2007. Annual Reports on the Development of Chinese Forestry (1999–2007). Chinese Forestry Press, Beijing.). The hilly Loess Plateau contained a large area of degraded barren land and slope cropland that was restored or replanted in this project; some studies showed the replanted cropland with a slope gradient over 15° would account for about 14% of the total area in GGP (Chen et al., 2007; Xu et al., 2004). So the land use in this region has changed significantly since then. A large decrease in cropland and a large increase of abandoned cropland, wild grassland, shrubland and planted woodland have been observed, and planted shrubland and woodland have become the main land use types in this region (Liu, 1999). This change will have profound influences on SOC sequestration and variation, and it is therefore very important to measure the SOC sequestration and predict the sequestration potential due to the revegetation in this region.

It is estimated that afforestation in China could increase SOC sequestration at an rate of 42.05 $g \cdot m^{-2} \cdot yr^{-1}$ at soil depths from 0 to 20 cm (Shi and Cui, 2010), and SOC sequestration following the GGP achieved a national average rate of 36.67 $g \cdot m^{-2} \cdot yr^{-1}$ in the top 20 cm soil (Zhang et al., 2011), but these rates varied widely. As many studies have demonstrated, the extent of SOC change is affected by many biotic and abiotic factors, such as vegetation type, litter, previous land use, climate, soil texture, site management, landforms and conversion timing (Banning et al., 2008; Fantappi et al., 2011; Niu and Duiker, 2006; Paul et al., 2002; Post and Kwon, 2000). Thus, following revegetation, changes in the temporal and spatial distribution of SOC sequestration inevitably occur (Paul et al., 2002). This is particularly true to the hilly Loess Plateau, which is characterized by mountainous and extremely complex topography (Li et al., 2008), and the ecosystem and landscape of which were dramatically changed during revegetation (Chen et al., 2007). Although some studies of SOC sequestration in the Loess Plateau have been published (Chen et al., 2007; Fu et al., 2011; Wang et al., 2011), the lack of complete inventory data and the inherent variability of SOC means that the temporal and spatial variations in SOC sequestration following revegetation are unclear. This uncertainty hampers the accurate estimate of SOC sequestration potential and large-scale estimates of SOC sequestration.

The objectives of this study were (1) to characterize the temporal and spatial variation of SOC sequestration following revegetation, (2) to clarify the contributions of relevant factors to SOC variation, such as land use, landforms, revegetation timing and growing conditions and (3) to estimate the contribution of revegetation to SOC sequestration in the hilly Loess Plateau of China.

2. Materials and methods

2.1. The study area

The study area is located mainly in the Zhifanggou catchment area (36°46′42″–36°46′28″N, 109°13′46″–109°16′03″E). Two nearby catchments, the Xiannangou and Dunshan catchments, were selected as complementary sampling sites. These three catchments are all located in the central region of the hilly Loess Plateau, Ansai county, China (36°30′45″–37°19′31″N, 108°51′44″–109°26′18″E). This region has a semi-arid continental climate. Annual precipitation varies greatly, with only about 300 mm in dry years and more than 700 mm in wet years. The average annual precipitation is 505 mm, with 60–80% of the rain falling during the monsoon season (June to September). Annual evaporation is greater than 1463 mm. Mean monthly temperatures range from 22.5 °C in July to 7 °C in January. The ≥0 °C accumulated temperature averages 3733.5 °C, while the ≥10 °C accumulated temperature averages 3160.2 °C. On average, there are about 157 frost-free days and 2415 h of total yearly sunshine, and the total yearly flux is 493 $kJ \cdot cm^{-2}$. The soil in this region is classified as a Calciustepts soil and is developed from wind-accumulated loess parent material, with an average thickness of 50–80 m and a uniform silt loam texture (Gong et al., 1999). This soil is highly erodible, with an erosion modulus of 10,000–12,000 $Mg \cdot km^{-2} \cdot yr^{-1}$ before the restoration efforts began in this region (Liu, 1999).

2.2. Plots selection and investigation

The major agricultural land use type in the hilly Loess Plateau is slope cropland. Agricultural management in this region, including the major crop types grown, has not changed significantly since the 1970s (Chen et al., 2003; Li et al., 2004; Zhao et al., 1995a, 1995b), so the SOC concentrations in slope cropland soil are considered to be essentially unchanged as well (Chen et al., 2007; Dai et al., 2008a; Jiao et al., 2005; Wen et al., 2007). Therefore, in this study, the SOC content of slope cropland (in the same landforms) was used as the initial SOC value (0 yr) in the revegetation chronosequence of planted croplands. Beginning in the late 1970s, slope cropland was replanted by shrubs and woods, mainly *Robinia pseudoacacia* L. and *Caragana Korshinskii* Kom, to control soil erosion. Abandoned cropland was also generated during this period due to the extremely low productivity of the land and its long distance from farmers' residences (Chen et al., 2003; Li et al., 2004; Zhao et al., 1995a, 1995b). These areas exhibit a fairly long revegetation chronosequence of the replanted cropland, therefore, the SOCD variation along this chronosequence could reveal SOCD changes in different revegetation years and predict the future SOCD variation produced by revegetation.

Wild grassland and shrubland were usually found on steep slopes and/or at sites where the soil is shallow or contains many small rocks; these areas were not suitable for cultivation and have been abandoned. However, these sites were often used for pasture and/or cut for firewood, so the wild vegetation was of limited coverage or even barren for long periods. Some wild grasslands and shrublands were closed to pasture and wood gathering in the late 1970s due to concerns about soil conservation and lower demand for pasture or firewood. In 1999, all of these lands were closed for vegetation restoration in this region under the GGP.

In May 2009, based on this land use history, 79 sites in the Zhifanggou catchment and 50 complementary sampled sites in another two nearby catchments (Xiannangou and Dunshan catchments) were selected according to different land uses, revegetation years and landforms. In total, 129 study sites were selected and classified into 36 types. A portable GPS receiver was used to locate the