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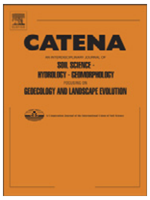

The effects of afforestation on soil organic and inorganic carbon: A case study of the Loess Plateau of China

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ABSTRACT

The determination of the changes in soil organic carbon (SOC) and inorganic carbon (SIC) in the subsoil following afforestation is meaningful and necessary for assessing carbon sequestration, but such knowledge is limited. In this case study, a paired-site approach was used to determine the differences in the SOC and SIC stock in the topsoil and subsoil, respectively, between a black locust (*Robinia pseudoacacia* L.) forest site (converted from cropland 30 years ago) and a cropland site in the middle of the Loess Plateau of China. Compared with the cropland, the SOC stock was significantly greater under the forest in both the top 20 cm and the subsoil (30–60 cm layer). The annual litter input under the forest was more than twice that of the cropland, and the fine root biomass was significantly higher in the forest. We conclude that the higher litter input and fine root biomass may partly contribute to the greater SOC in the forest. In addition, the soil nitrogen (N) content changed in synchronicity with SOC during afforestation, which indicates that SOC accumulation in the top/subsoil may be determined by the increase in soil N in these layers. In contrast, the SIC stock in the top 20 cm of the forest was significantly lower than that of the cropland. However, this decrease in the SIC level in the topsoil of the forest was offset by an increase in SIC in the subsoil (60–100 cm). The change in SIC along the soil profile following afforestation could be explained by the dissolution and leaching of SIC from the topsoil and subsequent precipitation in the subsoil. The dissolution and leaching of SIC in the forest topsoil were due to the high biological activity associated with the high aboveground litter input, fine root biomass and SOC stock as well as the high soil water content, whereas the precipitation of the leached SIC in the subsoil was a result of the dramatic decrease in the soil water content and fine root biomass in the subsoil. These findings suggest that soil can accumulate organic carbon in the topsoil and subsoil following black locust plantation establishment on cropland (as in the Loess Plateau study area) and that this type of cropland to forest plantation conversion in this area can redistribute SIC along the soil profile without affecting the net SIC accumulation.

1. Introduction

The cultivation of forest ecosystems can result in significant losses of soil organic carbon (SOC) (Davidson and Ackerman, 1993; Johnson, 1992; Mann, 1986; Murty et al., 2002; Ogle et al., 2005). On the other hand, the afforestation of previously cultivated land is generally considered to have the potential to sequester carbon into the soil (Guo and Gifford, 2002; Laganière et al., 2010; Paul et al., 2002; Post and Kwon, 2000). However, the effect of afforestation on the SOC content in the subsoil has not been well studied and is less understood than the effect that afforestation has on the topsoil SOC.

Many studies have only considered SOC changes in the topsoil (e.g., 0–20 cm) due to historical practices and the ease of sampling (Harrison et al., 2011) and have assumed little to no change in the SOC in deeper soil layers (e.g., Ogle et al., 2005). However, the subsoil has a large SOC storage capacity (Jobbágy and Jackson, 2000), and there is increasing evidence that the SOC contents in the subsoil are also sensitive to changes in land use and management (Carter and Gregorich, 2010; Hooker and Compton, 2003; Kaye et al., 2000; Khan et al., 2007; Knops and Kate, 2009; Liu et al., 2003). For example, Fontaine et al. (2007) detect that the decomposition of old organic carbon in the subsoil (60–80 cm) is stimulated by new plant-derived carbon inputs to these layers. Therefore, more studies including the subsoil SOC are needed in order to accurately estimate the changes in the soil carbon pools following afforestation. It has been suggested that the soil should be considered to at least a depth of 1 m or the top of the C horizon (Hamburg, 2000).

Soil inorganic carbon (SIC), which comprises approximately 950 Pg C in the top 1 m globally, is one of the largest carbon pools (Eswaran et al., 2000). SIC is also suggested to play a significant role in carbon sequestration (Lal, 2008). Carbon exchange between the SIC and the atmosphere has been estimated to occur at a rate of

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1.0–5.0 g C m^{-2} yr^{-1} (Schlesinger, 1997), with estimates as high as 62–622 g C m^{-2} yr^{-1} (Xie et al., 2009). The SIC pool exists largely as calcium carbonate ($CaCO_3$) and dolomite ($MgCO_3$), and SIC can be classified into lithogenic inorganic carbon (LIC) and pedogenic inorganic carbon (PIC) (Batjes, 1996). LIC is inherited from parent material with no chemical change, whereas PIC is formed during the precipitation of Ca^{2+} or Mg^{2+} and bicarbonate (HCO_3^-), as described by the following process (1).

$$2HCO_3^- + Ca^{2+} \leftrightarrow CaCO_3\downarrow + H_2O + CO_2\uparrow \quad (1)$$

Bicarbonate is formed during the dissolution of CO_2 derived from autotrophic and heterotrophic respiration into soil water as follows:

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad (2)$$

Ca^{2+} or Mg^{2+} originates from the weathering of carbonate (process 3) or Ca/Mg-silicates (process 4), as well as from other external sources of Ca^{2+} or Mg^{2+}, such as rain and dust (Monger and Martinez-Rios, 2001).

$$CaCO_3 + H_2O + CO_2 \leftrightarrow 2HCO_3^- + Ca^{2+} \quad (3)$$

$$2CO_2 + 3H_2O + CaAl_2Si_2O_8 \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^- \quad (4)$$

The source of Ca^{2+} or Mg^{2+} determines whether the precipitation of carbonates results in a net increase in SIC (Monger and Martinez-Rios, 2001). For example, if the Ca^{2+} or Mg^{2+} originates from the dissolution of carbonate (old Ca^{2+} or Mg^{2+}) via processes (3) and (1), no net CO_2 is sequestered during this pedogenic carbonate formation; thus, there is no net increase in SIC. However, if the Ca^{2+} or Mg^{2+} results from the weathering of Ca/Mg-silicates (process 4, new Ca^{2+} or Mg^{2+}), one more mole of CO_2 is consumed per mole of carbonate precipitated, and the new carbonate is formed according to processes (4) and (1). The precipitation of external Ca^{2+} or Mg^{2+} originating from rain and dust can also result in a net increase in SIC.

The higher CO_2 partial pressures associated with respiration are derived from the higher carbon input from aboveground and belowground litter and fertilization and, together with a high soil water content, favor carbonate dissolution. On the other hand, a lower carbon input in the subsoil combined with a low soil water content favors the precipitation of carbonate (Lal, 2008; Mikhailova and Christopher, 2006; Monger and Martinez-Rios, 2001; Reeder et al., 2004). The amount of SIC and its distribution along the soil profile may be influenced by land use changes and management practices that are associated with changes in the soil water content and CO_2 partial pressures. However, the effects of land use changes and management practices on the SIC have been largely neglected and therefore are not clear.

The Loess Plateau is located in western China and has an annual precipitation rate that decreases from about 650 mm in the southern Loess Plateau to about 200 mm in the northern Loess Plateau. The Loess Plateau is one of the areas with the highest SIC contents in China (Wu et al., 2009), and is known as an area that is suffering from some of the most serious erosion problems in the world because of its high soil erodibility and intensive human activity in the past. A series of ecological programs have been launched in the last few decades to control the soil erosion on the Loess Plateau. The effects that the afforestation of marginal arable land has on SOC sequestration have been investigated at some local sites (Chen et al., 2007; Fu et al., 2000; Gong et al., 2006; Wei et al., 2009) and at a regional scale (Chang et al., 2011). However, many of these studies were only conducted on the topsoil (e.g., 0–20 cm), and the response of subsoil-localized SOC to afforestation is not well understood. Moreover, changes in the SIC following afforestation have not been detected in these previous studies. Thus, the main objectives of this study were (1) to examine SOC sequestration in both the topsoil and subsoil during plantation forest establishment on marginal arable land and (2) to detect changes in the SIC pool and its distribution along the soil profile following the afforestation of cropland on the Loess Plateau.

2. Materials and methods

2.1. Study area

The study area is located in the Ziwuling area of Fuxian County in the Shaanxi province, which is in the center of the Loess Plateau. The region has a semi-arid continental climate, with a mean annual temperature of 9 °C and average annual precipitation of 577 mm, over 60% of which occurs from June to September (Tang et al., 1993). The landform is a typical loess, hilly landscape with elevations from 1200 m to 1360 m. The soil layer is about 50 m thick, and the soil is a calcareous loamy soil that is classified as an Entisol (USA soil taxonomy) (Li et al., 2005). In the mid-19th century, many people emigrated from the study area due to national conflict. Therefore, a wide area of cropland was abandoned to natural succession until the 1940s (Li et al., 2005). Secondary forest (dominated by *Quercus liaotungens, Pinus tabulaeformis* and *Populus davidiana*) became widespread in this area during this period (Zou et al., 2002). In the 1940s to the 1960s, however, large areas of forest were converted into cropland as a result of population growth. In more recent decades, especially the 2000s, most of the slope croplands in this area were again abandoned and converted into forest and shrubland. The black locust (*Robinia pseudoacacia* L.) was widely chosen as a plantation species during this period.

2.2. Site selection and description

In early July 2009, one paired black locust plantation forest and an adjacent cropland site (N 36.067°, E 109.201°) were selected. The following reasons made it hard to find additional paired sites for our study. First, only a small amount of slope croplands existed in the study area as most of them had been converted into other land uses since 1999–2000. Second, although the black locust was widely chosen as a plantation species in this region, the area of black locust forests over 15 years old was small. Third, it is difficult to find the paired site with similar slope gradient and aspect because of the hilly landscape. Nevertheless, the soil characteristics and management practices are largely uniform in this region, and the site conditions (e.g. soil type) and management measures at our selected paired sites were typical.

The areas of the forest and cropland sites were about 1 ha and 0.5 ha, respectively. Both have elevations of about 1289 m. The slope gradient (about 8°) and aspect (about 90°) are similar between the two sites. The soil at both sites is a calcareous loamy soil and is well drained. The cropland was cultivated for over 80 years before the sample year. Up to the present, the primary crop planted in the cropland was wheat, with soybean or millet being planted every 3–4 years. The average annual grain yield is about 4000 kg ha^{-1}. Before the late 1990s, farm manure was the only fertilizer used, with an average annual input of 1500 kg ha^{-1}. Urea ($CO(NH_2)_2$) has primarily been used since then, with an average annual use of 300–500 kg ha^{-1}. The forest site was also used as arable land until 1981, and the history and management strategy of the forest site were the same as that for the cropland site before forest plantation. Therefore, it is assumed that there were no differences in the soil physicochemical properties between the forest and cropland sites before 1981, because of the long-term cultivation of arable soils in both the forest and cropland sites prior to this date. After the forest conversion to a tree plantation, there was little human activity except for occasional livestock grazing prior to 1996, but grazing has since ceased