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Dynamics of aggregate-associated organic carbon following conversion of forest to cropland

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ABSTRACT

The conversion of natural forest to cropland generally results in the loss of soil organic carbon (OC) and an increase in CO_2 flux to the atmosphere. The dynamics of aggregate-associated OC after conversion to cropland are still not well understood. Such an understanding is essential for accurately estimating C flux between soil and the atmosphere. To learn more about OC dynamics after cultivation of natural forest land, we measured total soil and aggregate-associated OC in paired forest and cropland plots in Shaanxi Province, China. The cropland had been converted from adjacent forest 4, 50, and 100 yrs previously. As expected, the conversion to cropland resulted in significant declines in total soil OC concentrations and stocks. The largest decreases occurred during the early stages of cultivation. A century of cultivation decreased total soil OC stocks in the 0–20 cm depth by 0.77 kg m^{-2}. Macroaggregate-associated OC stocks decreased, but microaggregate-associated OC stocks increased following the conversion of forest to cropland. Silt + clay-associated OC stocks were not affected. The reduction in macroaggregate-associated OC stocks was caused by declines in both the amount of soil in the macroaggregate fraction and by decreases in the concentration of macroaggregate-associated OC. The results of this study indicate the conversion of forest to cropland not only reduced total soil OC stocks, but also caused a percentage shift in the distribution of total soil OC among aggregate size classes and among soil depths. These shifts would delay the loss of OC, so the loss of OC in forest soil due to cultivation might thus be lower than expected.

1. Introduction

Soil organic carbon (OC) is a large reservoir of C that can act as either a source or a sink of atmospheric CO_2 (Post et al., 1982; Batjes, 1996). The conversion of forest or grassland to cropland generally reduces soil OC and increases CO_2 flux to the atmosphere (IPCC, 2007). The conversion of natural forest to cropland typically reduces soil OC by 25–42%, depending on climate, the chemical composition of the OC, soil type, soil depth, and soil management (Guo and Gifford, 2002; FAO, 2010; Don et al., 2011). Soil OC generally decreases rapidly after forest is converted to cropland and then stabilizes at a new equilibrium (Houghton et al., 1991; Davidson and Ackerman, 1993). Understanding soil OC loss due to the conversion of forest to cropland is important for assessing C cycling in terrestrial ecosystems.

Soil aggregates are structural units within soil that control the dynamics of soil organic matter and nutrient cycling (Oades and Waters, 1991; Six et al., 2004). Conceptually, aggregates are generally classified into macroaggregates (>0.25 mm) and microaggregates (0.053–0.25 mm). The conversion of forest to cropland often results in the destruction of soil structure (Islam and Weil, 2000; Golchin and Asgari, 2008). This increases OC mineralization because organic matter within the aggregates is no longer physically protected from microbial decomposition (Islam and Weil, 2000; Golchin and Asgari, 2008). The break-up of macroaggregates also increases the proportion of microaggregate- and silt + clay-sized particles in the soil. The dynamics of OC in aggregate fractions after tillage begins is still not well understood, hindering both the accurate prediction of soil OC dynamics in disturbed ecosystems and the estimation of C flux between soil and the atmosphere. This information would be helpful for understanding the decline in OC stocks when forests or grasslands are converted to cropland.

In most temperate soils, macroaggregates are more enriched in OC than microaggregates (Oades and Waters, 1991; Six et al., 2004; von Lützow et al., 2007). Macroaggregate-associated OC is also

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more sensitive to tillage than microaggregate- or silt + clay-associated OC (Christensen, 1992; Cambardella and Elliott, 1993; Solomon et al., 2002). We hypothesized that the decrease in total soil OC stocks after the conversion of forest to cropland is primarily due to the loss of macroaggregate-associated OC. However, we were unsure whether the changes in macroaggregate-associated OC were primarily due to changes in the amount of soil within the macroaggregate fraction or to changes in the OC concentration of the fraction. The objective of this study was to answer this question by determining total soil and aggregate-associated OC stocks in paired forest and cropland sites in central Shaanxi Province, China. The cropland soils had been converted from forest 4, 50, and 100 yrs previously.

2. Materials and methods

2.1. Study sites

The study sites were in the Huanglongshan Forest, which is located in central Shaanxi Province, China (35°28′49″–36°02′01″N, 109°38′49″–110°12′47″E). The area is classified as a semi-humid, temperate forest zone. The average annual temperature is 8.6 °C. Monthly mean temperatures range from −22.5 °C in January to 36.7 °C in July. The average annual precipitation is 612 mm. The major soil in the area is cinnamon, which is a cambisol according to the FAO classification system.

2.2. Field investigation and sampling

The study consisted of three paired forest and cropland sites. The sites were at least three km apart. The cropland had been converted from the adjacent forest 4, 50, and 100 yrs previously. The forests contained primarily Liaodong oak (*Quercus liaotungensis Koidz*) and birch (*Betula platyphlla*). The stand age was >200 yrs. The dominant plants of the forest floor were bunge needlegrass (*Stipa bungeana Trin.*) and Dahurian bush clover (*Lespedeza daurica (Laxm.) Schindl.*). The cropland was primarily used for maize (*Zea mays* L.) and potato (*Solanum tuberosum*) production. All sites had the same soil type and similar topography.

We assumed the physical and chemical properties of the soil were the same in the cultivated and forested sites at the time of conversion. We also assumed that no significant changes in the OC concentration of the forest soil occurred over time (i.e. the current OC concentration of the forest soil was the same as when the forest was converted to cropland 4, 50, or 100 yrs ago). We made this assumption because soil OC concentrations in old-growth forests are generally at steady state (Odum, 1969). This assumption has been widely applied in previous studies concerning forest cultivation using a space-for-time substitution method because soil OC concentrations 50 or 100 yrs ago cannot be directly quantified (Walker et al., 2010). In some cases, researchers have observed continued increases over time in the soil OC concentration of mature forests (Luyssaert et al., 2008; Wei et al., 2012). If this occurred in our study, then our calculations would overestimate the actual decreases in OC concentrations and stocks after conversion to cropland.

Three subplots were established within each forest and cropland site in August 2009 (forest subplots, 20 × 20 m; cropland subplots, 5 × 5 m). Each subplot was at least 40 m from the boundary to reduce the possibility of tree litter being added to cropland plots. Maize (*Z. mays* L.) was growing on the cropland when the samples were collected.

Soil bulk density was measured at the 0–10 and 10–20 cm depths of each subplot using a stainless steel cutting ring 5.0 cm high by 5.0 cm in diameter. The soil cores were dried at 105 °C for 24 h. Three representative soil samples were randomly collected from each subplot for measurement of aggregate size distribution and soil OC. The samples were collected from the 0–10 and 10–20 cm depths with a soil auger (5.0 cm diam.). Visible pieces of organic material were removed, and then the moist soil samples were brought into the laboratory and air dried.

Aggregate size classes were separated by wet sieving through 0.25 and 0.053 mm sieves following the procedures described by Cambardella and Elliott (1993). The macroaggregate (>0.25 mm), microaggregate (0.25–0.053 mm) and silt + clay (<0.053 mm) fractions were dried in an oven at 50 °C for 24 h and then weighed.

A sub-sample of air-dried, undisturbed soil from each subplot was ground to pass through a 0.25 mm sieve to measure total soil OC concentration. The OC concentrations of both the total soil and aggregate fractions were analyzed using a VARIO EL III CHON analyzer (Elementar, Germany) at the Testing and Analysis Center of Northwest University, China.

2.3. Data analysis

Soil OC stocks (kg m^{-2}) were calculated as follows:

$$\text{Soil OC stocks} = \frac{D \times \text{BD} \times \text{OC}}{100} \tag{1}$$

where D is the thickness (cm) of the soil layer, BD is the bulk density (g cm^{-3}) and OC is the OC concentration (g kg^{-1}) of the 0–10 or 10–20 cm soil depths.

Stocks of OC (g m^{-2}) in each size fraction of the 0–10 and 10–20 cm depths were calculated as follows:

$$\text{Stocks of OC}_i = M_i \times \text{OC}_i \tag{2}$$

$$M_i = \frac{D \times \text{BD} \times w_i}{10} \tag{3}$$

where M_i is the amount of soil in the ith size fraction (kg m^{-2}) and OC_i is the OC concentration of the ith size fraction (g kg^{-1} aggregate), and w_i is the proportion of the total soil in the ith size fraction (%).

Changes in total soil OC concentration, total soil OC stocks, and aggregate-associated OC concentrations after conversion to cropland were modeled with the following equation (Six and Jastrow, 2002):

$$C = C_e \times \left[1 - \left(\frac{C_e - C_0}{C_e}\right) \times e^{-kt}\right] \tag{4}$$

which is equivalent to

$$C = C_e - (C_e - C_0) \times e^{-kt} \tag{5}$$

where t is the time since conversion (yr), C_e is the OC concentration (g kg^{-1}) or stock (g m^{-2}) at equilibrium, C_0 is the initial OC concentration (g kg^{-1}) or stock (g m^{-2}) before conversion ($t = 0$) and k is the rate constant (yr^{-1}).

The loss potential (L) of OC was calculated as:

$$L = C_0 - C_e \tag{6}$$

The mean residence time (MRT) was calculated as:

$$\text{MRT} = \frac{1}{k} \tag{7}$$

The half-life ($T_{1/2}$) of the original forest C was calculated as:

$$T_{1/2} = \ln 2 \times \text{MRT} \tag{8}$$