Soil Biology & Biochemistry 57 (2013) 876–883

Contents lists available at SciVerse ScienceDirect

Soil Biology & Biochemistry

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

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

Xiaorong Wei [a,*], Mingan Shao [a], William J. Gale [b], Xingchang Zhang [a], Linhai Li [c]

[a] State Key Laboratory of Soil Erosion and Dryland Farming in the Loess Plateau, Northwest A&F University, Yangling 712100, China
[b] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China
[c] Beijing Museum of Natural History, Beijing 100050, China

ARTICLE INFO

Article history:
Received 5 June 2012
Received in revised form
10 October 2012
Accepted 16 October 2012
Available online 15 November 2012

Keywords:
Aggregates size fraction
Cultivation
Dynamics
Natural forest
Organic carbon

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

* Corresponding author. Present address: Xinong Road, #26, Yangling, Shaanxi Province 712100, China. Tel.: +86 29 87011190; fax: +86 29 87012210.
E-mail address: xrwei78@163.com (X. Wei).

0038-0717/$ – see front matter
http://dx.doi.org/10.1016/j.soilbio.2012.10.020

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:

$$\text{Soil OC stocks} = \frac{D \times \text{BD} \times \text{OC}}{100} \quad (1)$$

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:

$$\text{Stocks of OC}_i = M_i \times \text{OC}_i \quad (2)$$

$$M_i = \frac{D \times \text{BD} \times w_i}{10} \quad (3)$$

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):

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

which is equivalent to

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

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:

$$L = C_0 - C_e \quad (6)$$

The mean residence time (MRT) was calculated as:

$$\text{MRT} = \frac{1}{k} \quad (7)$$

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

$$T_{1/2} = \ln 2 \times \text{MRT} \quad (8)$$

We used the procedure suggested by Qiu et al. (2012) to assess the relative contribution of changes in aggregate amount and aggregate-associated OC concentrations to the total changes in OC stocks within each aggregate fraction. We assumed that changes in OC stock within any particular aggregate fraction were caused both by changes in OC concentration of the fraction (F_1) and by changes in the mass of the aggregate fraction (F_2). We also assumed that (1) the mass that was lost from the macroaggregate fraction had the same OC concentration as the rest of the fraction before the conversion of forest to cropland and (2) the mass that was gained by the microaggregate fraction following conversion to cropland was the same as the macroaggregate OC concentration before conversion. We therefore calculated the contribution of F_1 and F_2 to the total change in OC stock within an aggregate fraction as follows:

$$F_1 = M \times \Delta C \quad (9)$$

$$F_2 = \Delta M \times C \quad (10)$$

where F_1 is the change in OC stock (g m^{-2}) within an aggregate fraction due to changes in aggregate-associated OC concentrations, F_2 is the change in the OC stock (g m^{-2}) within an aggregate fraction due to changes in the mass of the aggregate fraction, ΔM is the change in the mass of a particular fraction (kg m^{-2}), M is the initial mass of the aggregate fraction (kg m^{-2}) before land-use change, C is the final OC concentration of the aggregate fraction (g kg^{-1}) after land-use change and ΔC is the change in the OC concentration of the aggregate fraction (g kg^{-1}) due to land-use change.

A two-way analysis of variance (ANOVA) was conducted using SAS version 8 to test the effects of forest cultivation and soil depth on (i) aggregate-size distribution, (ii) total soil OC concentrations and stocks, and (iii) OC concentrations and stocks associated with each aggregate fraction.

3. Results

3.1. Aggregate-size distribution

Macroaggregates accounted for 51% of the dry soil weight at both soil depths in the natural forest (Fig. 1). The conversion to cropland significantly decreased the amount of soil in the macroaggregate fraction but increased the amount of soil in the microaggregate and silt + clay fractions (Table 1, Fig. 1a and b). The largest changes came within the first 4 yrs after land conversion. The distribution of soil among the three aggregate size fractions was relatively stable between 50 and 100 yrs of cultivation. Comparison between the two soil depths indicated that the amount of soil in the macroaggregate fraction decreased more in the 0–10 cm depth than in the 10–20 cm depth.

3.2. Total soil OC concentrations and stocks

Total soil OC concentrations decreased significantly after conversion of forest to cropland (Table 1, Fig. 2a). The decreases followed similar patterns at both depths and were most rapid during the first 4 yrs of cultivation. Specifically, total soil OC concentrations in the 0–10 cm depth decreased by 1.42 g kg^{-1} during the first 4 yrs of cultivation and by 6.51 g kg^{-1} during the first 50 yrs of cultivation. Total soil OC concentrations in the 10–20 cm depth decreased by 0.98 g kg^{-1} during the first 4 yrs of cultivation and by 3.61 g kg^{-1} during the first 50 yrs of cultivation. Total soil OC concentrations did not change significantly after 50 yrs of cultivation.

Total soil OC stocks also decreased significantly after the conversion of forest to cropland (Table 1, Fig. 2b). Total soil OC stocks in the 0–10 cm depth decreased by 0.06 kg m^{-2} during the first 4 yrs of cultivation and by 0.50 kg m^{-2} during the first 50 yrs of cultivation. In the 10–20 cm depth, total soil OC stocks decreased by 0.06 kg m^{-2} during the first 4 yrs of cultivation and by 0.35 kg m^{-2} in the 10–20 cm depth. Total soil OC stocks did not change significantly after 50 yrs of cultivation.

We used Eq. (4) to calculate the maximum declines in total soil OC concentration and stock due to conversion of forest to cropland. The predicted values were similar to the observed declines described above (Table 2 and Fig. 2). Specifically, total soil OC concentrations were predicted to decline by 48% in the 0–10 cm depth and by 42% in the 10–20 cm depth. Total soil OC stocks were predicted to decline by 37% in the 0–10 cm depth and by 38% in the 10–20 cm depth. The k values for OC concentration and stock were greater in the 0–10 cm depth than 10–20 cm depth. The mean residence times (MRT) for OC concentration and stock were shorter in the 0–10 cm depth than in the 10–20 cm depth (Table 2).

3.3. Aggregate-associated OC concentrations and stocks

Soil OC concentrations were significantly higher in the macroaggregate fraction than in the microaggregate and silt + clay fractions. The OC concentrations in each aggregate fraction decreased significantly after conversion to cropland, with the largest decreases occurring during the first 4 yrs of cultivation (Fig. 3a and b). The

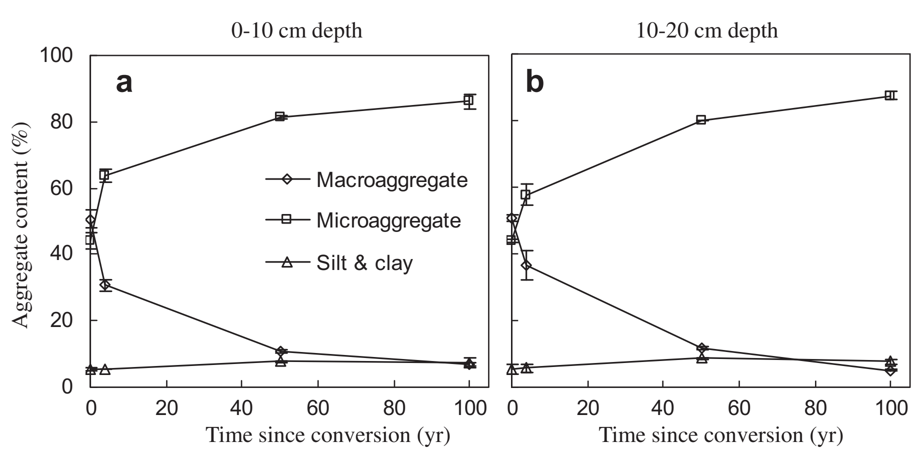

Fig. 1. Effect of converting forest to cropland on aggregate-size distribution. Macroaggregate, >0.25 mm; microaggregate, 0.25–0.053 mm; silt + clay, <0.053 mm. Error bars are the standard error of the mean.

Table 1
Analysis of variance results for all the variables.

	Forest cultivation		Soil depth		Interaction	
	F	*P*	*F*	*P*	*F*	*P*
Macroaggregate	88.7	<0.0001	4.24	0.0735	1.66	0.2509
Microaggregate	184.85	<0.0001	5.15	0.0530	0.84	0.5099
Silt + clay	3.55	0.0674	1.12	0.3206	0.01	0.9984
Total soil OC concentration	11.14	0.0031	22.49	0.0015	1.25	0.3548
Total soil OC stock	5.40	0.0251	12.07	0.0084	0.26	0.8510
Macroaggregate-associated OC concentration	55.08	<0.0001	92.24	<0.0001	9.37	0.0054
Microaggregate-associated OC concentration	39.21	<0.0001	87.88	<0.0001	15.71	0.0010
Silt + clay-associated OC concentration	3.59	0.0659	3.33	0.1054	1.04	0.4244
Macroaggregate-associated OC stock	92.02	<0.0001	6.41	0.0351	1.87	0.2135
Microaggregate-associated OC stock	17.55	0.0007	45.12	0.0001	8.63	0.0069
Silt + clay-associated OC stock	0.36	0.7808	0.09	0.7723	0.45	0.7174

decreases in macroaggregate-associated OC concentration were greater than the decreases in microaggregate- or silt + clay-associated OC concentrations. For example, during the first 4 yrs of cultivation, macroaggregate-associated OC concentrations decreased by 2.0 g kg^{-1} in the 0–10 cm depth and by 1.9 g kg^{-1} in the 10–20 cm depth. Microaggregate-associated OC concentrations decreased by 1.5 g kg^{-1} in the 0–10 cm depth and by 1.3 g kg^{-1} in the 10–20 cm depth. Silt + clay-associated OC concentrations decreased by 1.0 g kg^{-1} in the 0–10 cm depth, but were unchanged in the 10–20 cm depth.

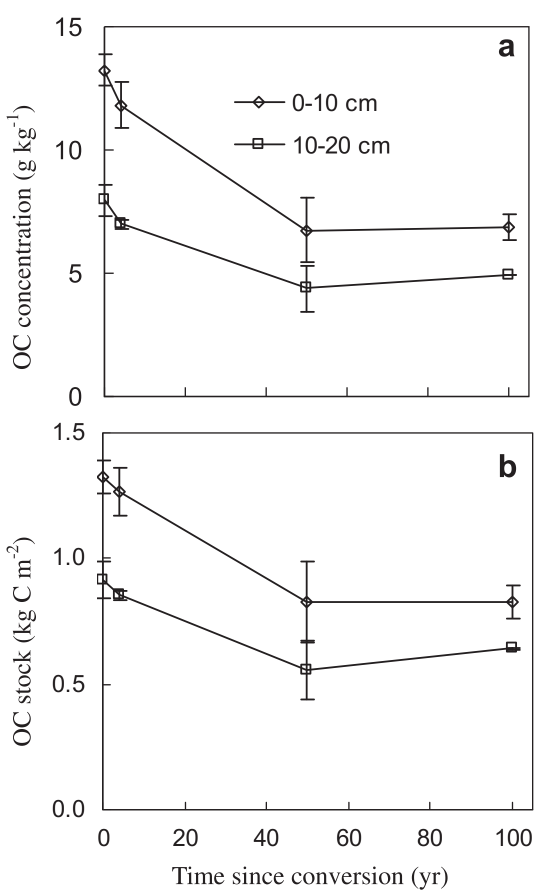

Fig. 2. Effects of conversion from forest to cropland on total soil organic C (OC) concentrations and stocks at the 0–10 and 10–20 cm depths. Error bars are the standard error of the mean.

The dynamics of OC concentration varied greatly among aggregate fractions and soil depths (Table 2). The OC concentrations at equilibrium were generally higher in the macroaggregate fraction than in the microaggregate or silt + clay fractions. The OC concentrations at equilibrium were also higher in the 0–10 cm depth than in the 10–20 cm depth. The potential drops in OC concentrations and *k* values in each aggregate fraction shared similar patterns with the equilibrium OC concentrations. However, MRT and $T_{1/2}$ increased in the order macroaggregate < microaggregate < silt + clay, indicating faster turnover of OC in the macroaggregate fraction than in the microaggregate or silt + clay fractions. Similarly, MRT and $T_{1/2}$ were greater in the 10–20 cm depth than in the 0–10 cm depth, indicating faster turnover in the 0–10 cm depth than in the 10–20 cm depth.

The response of aggregate-associated OC stocks to cultivation varied with aggregate size. In natural forest soils, macroaggregate-associated OC stocks accounted for 56% of the total soil OC stocks in the 0–10 cm depth and 58% of the total soil OC stocks in the 10–20 cm depth. Microaggregate-associated OC accounted for 40% of the total soil OC stocks in the 0–10 cm depth and 38% of the total soil OC stocks in the 10–20 cm depth. Conversion of forest to cropland decreased macroaggregate-associated OC stocks but increased microaggregate-associated OC stocks at both soil depths (Fig. 3c and d). The decrease in macroaggregate-associated OC stock was greater in the 0–10 cm depth than in the 10–20 cm depth. In contrast, the greatest increase in microaggregate-associated OC stocks was in the 10–20 cm depth.

Macroaggregate-associated OC stocks decreased rapidly after conversion of forest to cropland and then leveled off. Between 30 and 40% of the macroaggregate-associated OC stocks was lost during the first 4 yrs of cultivation (Fig. 3c and d). Macroaggregate-associated OC stocks remained relatively stable between 50 and 100 yrs of cultivation. In contrast, microaggregate-associated OC stocks increased by 23–42% within the first 4 yrs after cultivation (Fig. 3c and d). Although cultivation resulted in a decrease in macroaggregate-associated OC stocks and an increase in microaggregate-OC stocks, the decrease in macroaggregate-associated OC stock was much larger than the increase in microaggregate-associated OC stock. Overall, the conversion of forest to cropland resulted in a net decrease in total OC stocks.

4. Discussion

In our study, soil OC concentrations decreased by 47% and OC stocks decreased by 34% within 100 yrs of converting forest to cropland. In comparison, Guo and Gifford (2002) and Don et al. (2011) reported that worldwide, conversion of forest to cropland reduced soil OC stocks by 25–42%. The declines in OC stock in our study were similar to the report that conversion of forest to cropland reduced soil OC stocks by 36% in Russia (Rodionov et al., 2001). In contrast, conversion of forest to cropland reduced OC stocks by 50% in Brazil and Spain (Leite et al., 2003; Martinez-Mena et al., 2008) and by 78% in the Philippines (Yoneyama et al., 2004). Differences among these studies might be attributed to differences in mean annual temperature or precipitation, both of which can significantly influence OC mineralization (Leirós et al., 1999; Davidson and Janssens, 2006). A review of reports about changes in soil OC concentration during the first 5 yrs after conversion of forest to cropland indicated a significant positive correlation between mean annual temperature and the percent decrease in OC concentration in the 0–20 cm depth (Table 3, $R^2 = 0.388$, $P = 0.013$, $n = 15$). These results indicate the importance of considering

Table 2
Parameters describing total soil and aggregate-associated organic C (OC) dynamics.

Soil depth	Total soil				OC concentration					
	OC concentration		OC stock		Macroaggregate		Microaggregate		Silt + clay	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
OC at equilibrium[a]	6.73	4.37	0.83	0.55	11.52	9.67	9.76	8.59	7.6	7.19
Potential loss[a]	6.24	3.19	0.49	0.34	11.18	4.47	8.72	1.93	8.38	2.84
k (yr^{-1})	0.040	0.017	0.033	0.013	0.057	0.046	0.041	0.037	0.034	0.019
Mean residence time (MRT) (yr)	25.3	57.3	30.6	74.6	17.6	21.9	24.5	27.0	29.7	52.1
Half-life ($T_{1/2}$) of forest OC (yr)	17.5	39.7	21.2	51.7	12.2	15.2	17.0	18.7	20.6	36.1

[a] The units are g kg^{-1} for OC concentration and kg m^{-2} for OC stock.

climatic conditions when predicting OC losses due to the conversion of forest to cropland.

Total soil OC concentrations, total soil OC stocks, and aggregate-associated OC concentrations decreased rapidly during the first 4 yrs after the conversion of forest to cropland. This agrees with many previous studies (Houghton et al., 1991; Davidson and Ackerman, 1993). The k value for the total soil OC concentration was lower than the k value for macroaggregate-associated OC concentration, similar to the k value for microaggregate-associated OC concentration, and higher than the k value for silt + clay-associated OC concentration (Table 2). This indicates that macroaggregate-associated OC was more susceptible to loss than microaggregate- or silt + clay-associated OC following the conversion of forest to cropland. This agrees with the previous report that microaggregate-associated OC was more stable than macroaggregate-associated OC in grassland and cropland (Six and Jastrow, 2002).

The k values for total soil- and aggregate-associated OC concentration were higher in the 0–10 cm depth than in the 10–20 cm depth (Table 2), indicating that OC in the 0–10 cm depth was more susceptible to loss than OC in the 10–20 cm depth. The MRTs of total soil and aggregate-associated OC were shorter in the 0–10 cm depth than in the 10–20 cm depth. These results, which are consistent with observations by Six and Jastrow (2002), indicated that OC was more stable in the 10–20 cm depth than in the 0–10 cm depth after the conversion to cropland.

Organic C in the sand-sized fraction is generally more sensitive to cultivation than OC in the silt- or clay-sized fractions (Christensen, 1992; Cambardella and Elliott, 1993; Solomon et al., 2002). Macroaggregates can physically protect original and recently added organic matter from microbial attack and mineralization (Oorts et al., 2006; Razafimbelo et al., 2008). Tillage and cultivation can disrupt macroaggregates, decreasing the physical protection of OC and creating a more oxidative soil environment.

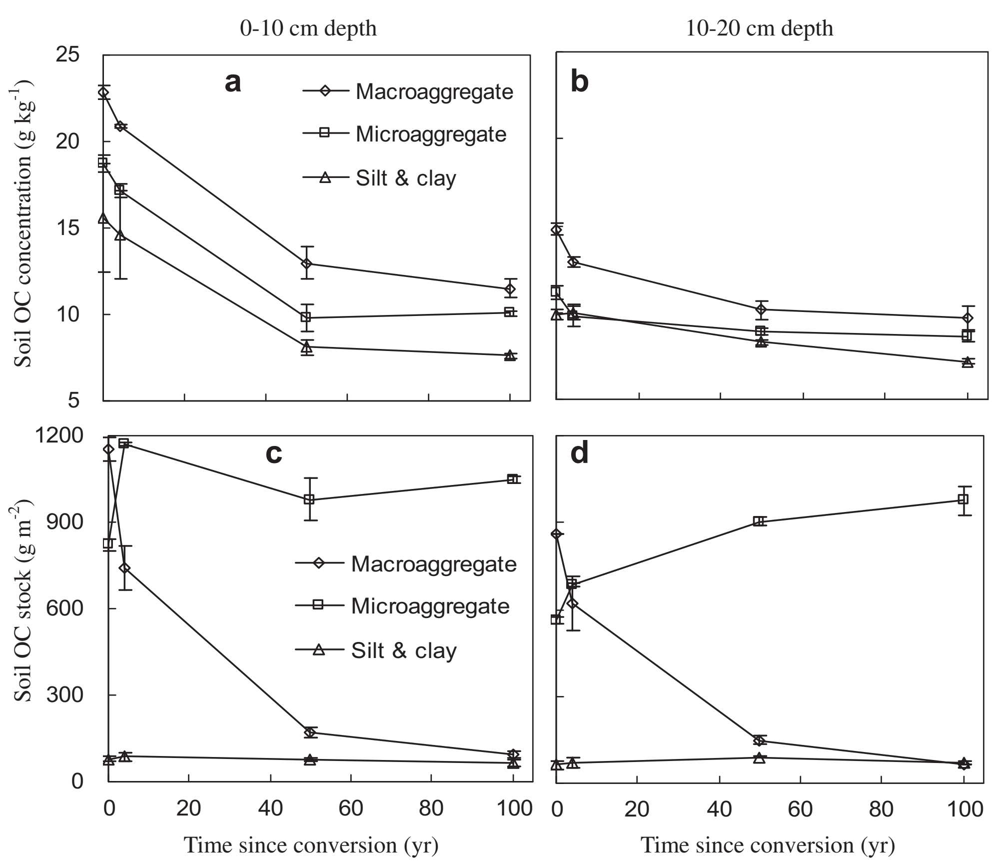

Fig. 3. Effects of conversion from forest to cropland on aggregate-associated organic C (OC) concentrations and aggregate-associated OC stocks. Macroaggregate, >0.25 mm; microaggregate, 0.25–0.053 mm; silt + clay, <0.053 mm. Error bars are the standard error of the mean.

Table 3
Reported decreases in whole soil organic C (OC) concentrations 5 yrs after the conversion of forest to cropland.

Location	MAP (mm)[a]	MAT (°C)[b]	Soil depth	OC decrease (%)	Refs
Australia	580	20.3	0–10 cm	36.9	Dalal and Mayer, 1987
Australia	670	18.5	0–10 cm	2.5	Dalal and Mayer, 1987
Brazil	790	30	0–20 cm	38.7	Xavier et al., 2009
Ethiopia	700	24.3	0–20 cm	71.7	Spaccini et al., 2001
Ethiopia	1400	19.8	0–20 cm	57.3	Spaccini et al., 2001
India	1750	27.4	0–15 cm	49.0	Saikh et al., 1998
Kenya	2091	19	0–20 cm	43.0	Kimetu et al., 2009
Nigeria	1560	29	0–20 cm	56.7	Spaccini et al., 2001
Nigeria	1600	27.2	0–20 cm	43.3	Spaccini et al., 2001
Nigeria	543	26.8	0–15 cm	58.6	Aina, 1979
Philippines	2533	27	0–30 cm	71.6	Yoneyama et al., 2004
Senegal	500	26	0–5 cm	41.9	Elberling et al., 2003
Sierra Leone	2723	27.3	0–18 cm	51.0	Brams, 1971
South Africa	812	16.5	0–10 cm	10.7	Dominy et al., 2002
South Africa	932	19.7	0–10 cm	28.1	Dominy et al., 2002

[a] Mean annual precipitation.
[b] Mean annual temperature.

These changes stimulate the mineralization of organic matter and the loss of macroaggregate-associated OC (De Gryze et al., 2006; Raiesi, 2006; Golchin and Asgari, 2008). Cultivation can thus cause a higher turnover rate (higher k and shorter MRT) of OC in macroaggregates than in total soil (Table 2). In natural forest soil, OC was mainly distributed in the macroaggregate fraction (56% in the 0–10 cm depth and 58% in the 10–20 cm depth), indicating that the dynamics of total soil OC was dominated by changes in the macroaggregate fraction after cultivation. Microaggregate-associated OC was more stable than macroaggregate-associated OC (Table 2). Silt + clay-associated OC had the lowest k and the longest MRT. This indicated that silt + clay-associated OC was the most recalcitrant of all fractions and therefore would contribute least to OC dynamics in the total soil after cultivation. This observation is consistent with the findings of Christensen (1992) and Solomon et al. (2002).

The conversion of forest to cropland reduced total soil OC stocks by 0.50 kg m^{-2} in the 0–10 cm depth and by 0.28 kg m^{-2} in the 10–20 cm depth (Fig. 2b). Macroaggregate-associated OC stocks declined by 1.06 kg m^{-2} in the 0–10 depth and by 0.80 kg m^{-2} in the 10–20 cm depth (Fig. 3c and d). The OC stocks in the microaggregate and silt + clay fractions, however, increased under cultivation at both depths, indicating a shift of OC from the macroaggregate fraction to the microaggregate and silt + clay fractions. These changes support the idea that tillage results in the disruption of macroaggregates and the release of microaggregates and silt + clay-sized particles. The redistribution of OC from sand-sized fractions to silt- and clay-sized fractions was previously observed after conversion of native forest to cropland (Tiessen and Stewart, 1983;

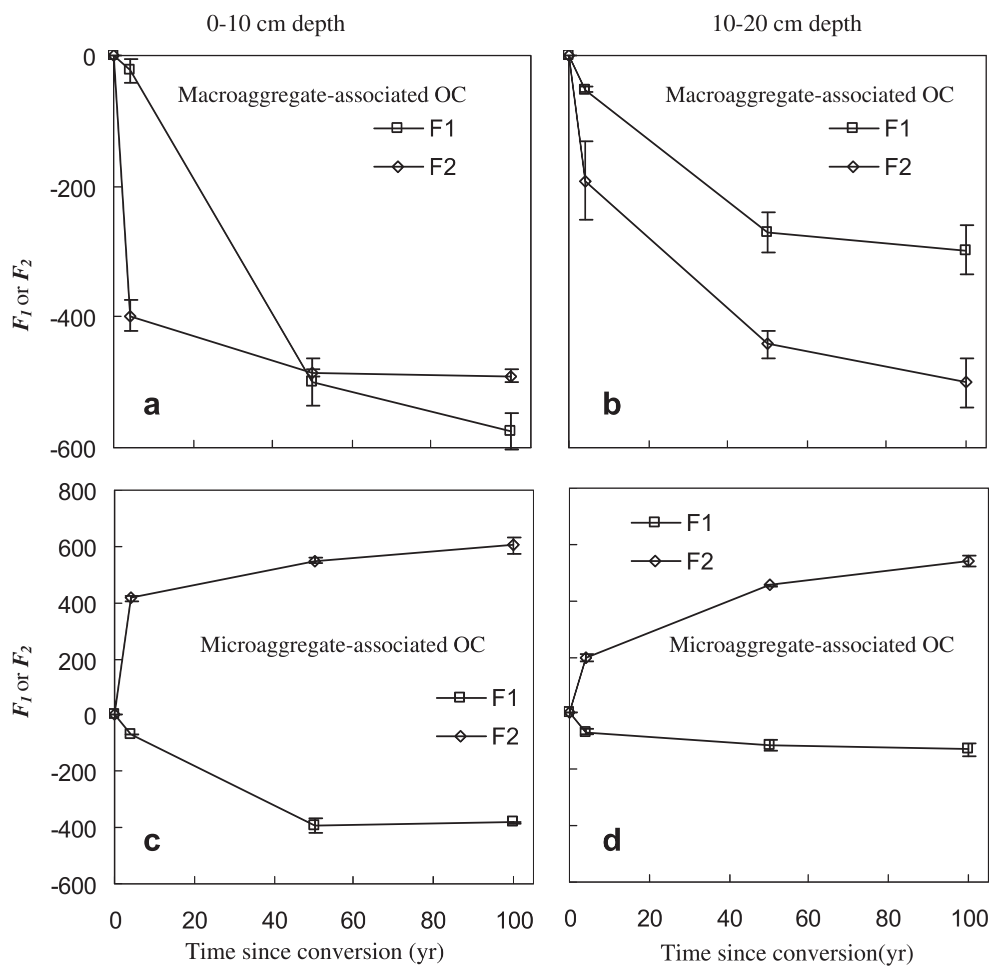

Fig. 4. Changes in aggregate-associated OC stocks after the conversion of forest to cropland. F1, the change in OC stock attributable to changes in the aggregate-associated OC concentration of the fraction after conversion. F2, the change in OC stock attributable to changes in the mass of the aggregate fraction after conversion. Macroaggregate, >0.25 mm; microaggregate, 0.25–0.053 mm; silt + clay, <0.053 mm. Error bars are the standard error of the mean.

Beheshti et al., 2012). The redistribution of OC among aggregate fractions may delay the loss of OC due to cultivation.

On a percentage basis, there was a shift in the distribution of soil OC stocks among soil depths after conversion of forest to cropland. Specifically, macroaggregate-associated OC stocks made up a smaller proportion of total soil OC stocks after cultivation, whereas microaggregate-associated OC stocks made up a larger proportion of total soil OC stocks (Fig. 3c and d). We also observed that the 10–20 cm depth contained a greater proportion of total soil OC stocks than the 0–10 cm depth did. One explanation is that aggregate-disrupting force of tillage was greater in the 0–10 cm depth. Alternatively, macroaggregates in the 0–10 cm depth may be more susceptible to environmental factors such as raindrop impact. This indicates that labile OC in the 10–20 cm depth was less susceptible to mineralization after land conversion than OC in the 0–10 cm depth was.

Calculations indicated that the declines in macroaggregate-associated OC stocks were due to decreases in the amount of soil in the aggregate fraction as well as to decreases in the OC concentration of the fraction (Fig. 4a and b). In contrast, the increases in microaggregate OC stocks were primarily due to increases in the amount of soil in the microaggregate fraction (Fig. 4c and d). These results agree with the previous report that the decreases in macroaggregate-associated OC stocks were due to declines in both macroaggregation and macroaggregate-associated OC concentrations after conversion of grassland to cropland (Qiu et al., 2012). We suggest that both factors contribute to declines in macroaggregate-associated OC stocks after conversion from natural vegetation to cropland in other parts of the world. However, the contribution of each factor to the net loss of macroaggregate-associated OC might vary with the stage of cultivation. The disruption of macroaggregates generally occurs within the first year of cultivation (Grandy and Robertson, 2006). We therefore assume that decreases in macroaggregate amounts contribute more to OC losses during the first years after cultivation, whereas decreases in macroaggregate-associated OC concentrations contribute more during later years.

5. Conclusion

Soil OC concentrations and stocks in the 0–20 cm depth decreased rapidly following the conversion of forest to cropland and then reached a new equilibrium. Total OC stocks in the 0–20 cm depth declined by 0.77 kg m^{-2}. The decline in OC stocks was mainly due to decreases in macroaggregate-associated OC, which was affected both by the amount of soil in the macroaggregate fraction and by the concentration of macroaggregate-associated OC. The decrease in the amount of soil in the macroaggregate fraction contributed most to the decline in OC stocks during the first years after cultivation, whereas the decrease in macroaggregate-associated OC concentration contributed more in later years. The distribution of OC in the soil changed after conversion to cropland, with greater proportions of total soil OC being observed in the microaggregate fraction and in the 10–20 cm depth.

Acknowledgment

We thank Zizhuang Liu, Ji Chen, Yanjun Hu, Le Wang and Shuai Yuan for their help with the field and laboratory experiments. We also thank the reviewers for their comments that improved the quality of this paper. This study was supported by the National Natural Science Foundation of China (40901145, 41271315, 40801111), The Foundations from Chinese Academy of Sciences (KZCX2-XB3-13-02), Science and Technology Development Research Program in Shaanxi Province (2011kjxx25), the Program for Youthful Talents in Northwest A&F University, and the Program from the Institute of Soil and Water Conservation, CAS & MWR.

References

Aina, P.O., 1979. Soil changes resulting from long-term management-practices in Western Nigeria. Soil Science Society of America Journal 43, 173–177.

Batjes, N.H., 1996. Total carbon and nitrogen in soils of the world. European Journal of Soil Science 47, 151–163.

Beheshti, A., Raiesi, F., Golchin, A., 2012. Soil properties, C fractions and their dynamics in land use conversion from native forests to croplands in northern Iran. Agriculture, Ecosystems and Environment 148, 121–133.

Brams, E.A., 1971. Continuous cultivation of West African soils: organic matter diminution and effects of applied lime and phosphorus. Plant and Soil 35, 401–414.

Cambardella, C.A., Elliott, E.T., 1993. Carbon and nitrogen distributions in aggregates from cultivated and grassland soils. Soil Science Society of America Journal 57, 1071–1076.

Christensen, B.T., 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. Advances in Agronomy 20, 1–90.

Dalal, R.C., Mayer, R.J., 1987. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. Australian Journal of Soil Research 25, 83–93.

Davidson, E.A., Ackerman, I.L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20, 161–193.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 400, 165–173.

De Gryze, S., Six, J., Merckx, S., 2006. Quantifying water-stable soil aggregate turnover and its implication for soil organic matter dynamics in a model study. European Journal of Soil Science 57, 693–707.

Dominy, C.S., Haynes, R.J., van Antwerpen, R., 2002. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. Biology and Fertility of Soils 36, 350–356.

Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. Global Change Biology 17, 1658–1670.

Elberling, B., Touré, A., Rasmussen, K., 2003. Changes in soil organic matter following groundnut-millet cropping at three locations in semi-arid Senegal, West Africa. Agriculture, Ecosystems and Environment 96, 37–47.

FAO, 2010. Global Forest Resources Assessment 2010 Main Report. Rome.

Golchin, A., Asgari, H., 2008. Land use effects on soil quality indicators in north-eastern Iran. Australian Journal of Soil Research 46, 27–36.

Grandy, A.S., Robertson, G.P., 2006. Aggregation and organic matter protection following tillage of a previously uncultivated soil. Soil Science Society of America Journal 70, 1398–1406.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345–360.

Houghton, R.A., Skole, D.L., Lefkowitz, D.S., 1991. Changes in the landscape of Latin America between 1850 and 1985 II. Net release of CO_2 to the atmosphere. Forest Ecology and Management 38, 173–199.

IPCC, 2007. Climate Change 2007: the Physical Science Basis. Cambridge University Press, Cambridge, U.K.

Islam, K.R., Weil, R.R., 2000. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agriculture, Ecosystems and Environment 79, 9–16.

Kimetu, J.M., Lehmann, J., Kinyangi, J.M., Cheng, C.H., Thies, J., Mugendi, D.N., Pell, A., 2009. Soil organic C stabilization and thresholds in C saturation. Soil Biology and Biochemistry 41, 2100–2104.

Leirós, M.C., Trasar-Cepeda, C., Seoane, S., Gil-Sotres, F., 1999. Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biology and Biochemistry 31, 327–335.

Leite, L.F.C., Mendonc, E.S., Machado, P.L.O.A., Matos, E.S., 2003. Total C and N storage and organic C pools of a red-yellow podzolic under conventional and no tillage at the Atlantic Forest Zone, Southeastern Brazil. Australian Journal of Soil Research 41, 717–730.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Laws, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215.

Martinez-Mena, M., Lopez, J., Almagro, M., Boix-Fayos, C., Albaladejo, J., 2008. Effect of water erosion and cultivation on the soil carbon stock in a semiarid area of South-East Spain. Soil & Tillage Research 99, 119–129.

Oades, J.M., Waters, A.G., 1991. Aggregate hierarchy in soils. Australian Journal of Soil Research 29, 815–828.

Odum, E.P., 1969. The strategy of ecosystem development. Science 164, 262–270.

Oorts, K., Nicolardot, B., Merckx, R., Richard, G., Boizard, H., 2006. C and N mineralization of undisrupted and disrupted soil from different structure zones of conventional tillage and no-tillage systems in north France. Soil Biology and Biochemistry 38, 2576–2586.

Post, W.M., Emannuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298, 156–159.

Qiu, L.P., Wei, X.R., Zhang, X.C., Cheng, J.M., Gale, W., Guo, C., Long, T., 2012. Soil organic carbon losses due to land use change in a semiarid grassland. Plant and Soil 355, 299–309.

Raiesi, F., 2006. Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in Central Iran. Agriculture, Ecosystems and Environment 112, 13–20.

Razafimbelo, T.M., Albrecht, A., Oliver, R., Chevallier, T., Chapuis-Lardy, L., Feller, C., 2008. Aggregate associated-C and physical protection in a tropical clayey soil under Malagasy conventional and no-tillage systems. Soil & Tillage Research 98, 140–149.

Rodionov, A., Amelung, W., Urusevskaja, I., Zech, W., 2001. Origin of the enriched labile fraction (ELF) in Russian chernozems with different site history. Geoderma 102, 299–315.

Saikh, H., Varadachari, C., Ghosh, K., 1998. Changes in carbon, nitrogen and phosphorus levels due to deforestation and cultivation: a case study in Simlipal National Park, India. Plant and Soil 198, 137–145.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil & Tillage Research 79, 7–31.

Six, J., Jastrow, J.D., 2002. Soil organic matter turnover. In: Lal, R. (Ed.), Encyclopedia of Soil Science. USA Marcel Dekker., New York, NY, pp. 936–942.

Solomon, D., Fritzsche, F., Lehmann, J., Tekalign, M., Zech, W., 2002. Soil organic matter dynamics in the subhumid agroecosystems of the Ethiopian Highlands: evidence from natural ^{13}C abundance and particle-size fractionation. Soil Science Society of America Journal 66, 969–978.

Spaccini, R., Zena, A., Igwe, C.A., Mbagwu, J.S.C., Piccolo, A., 2001. Carbohydrates in water-stable aggregates and particle size fractions of forested and cultivated soils in two contrasting tropical ecosystems. Biogeochemistry 53, 1–22.

Tiessen, H., Stewart, J.W.B., 1983. Particle-size fractions and their use in studies of soil organic matter. II. Cultivation effects on organic matter composition in size fractions. Soil Science Society of America Journal 47, 509–514.

von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., 2007. SOM fractionation methods: relevance to functional pools and to stabilization mechanisms. Soil Biology and Biochemistry 39, 2183–2207.

Walker, L.R., Wardle, D.A., Bardgett, R.D., Clarkson, B.D., 2010. The use of chronosequences in studies of ecological succession and soil development. Journal of Ecology 98, 725–736.

Wei, X., Qiu, L., Shao, M., Zhang, X., Gale, W., 2012. The accumulation of organic carbon in mineral soils by afforestation of abandoned farmland. PLoS ONE 7 (3), e32054. http://dx.doi.org/10.1371/journal.pone.0032054.

Xavier, F.A.D., Maia, S.M.F., de Oliveira, T.S., Mendonca, E.D., 2009. Soil organic carbon and nitrogen stocks under tropical organic and conventional cropping systems in northeastern Brazil. Communications in Soil Science and Plant Analysis 40, 2975–2994.

Yoneyama, T., Dacanay, E.V., Castelo, O., Kasajima, I., Park, Y.H., 2004. Estimation of soil organic carbon turnover using natural ^{13}C abundance in Asian tropics: a case study in the Philippines. Soil Science and Plant Nutrition 50, 599–602.