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The dynamics of soil OC and N after conversion of forest to cropland

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ABSTRACT

In this study, we investigated the dynamics of soil organic carbon (OC) and nitrogen (N) following the conversion of forest to cropland. The cropland had been converted from adjacent forest areas 4, 50, or 100 years previously. Our specific objectives were 1) to determine the dynamics of OC and N in density fractions and of OC and N derived from forest and cropland and 2) to examine the contributions of these changes to changes in total OC and N. Conversion to cropland led to rapid losses of soil OC and N. The decreases in total soil OC and N in the 0–10 cm depth were mainly due to decreases in light-fraction OC and N. In the 10–20 cm depth, the decreases in total soil OC and N were determined by the loss of OC and N from both the light- and heavy-fractions. The losses in forest-derived OC and N were larger than the gains in crop-derived OC and N. The predicted losses of forest-derived OC and N in both depths were almost 2 times the losses of total soil OC and N. The mean residence times of forest-derived OC and N were shorter than those of total soil OC and N. Our findings indicated that the dynamics of soil OC and N after the conversion of forest to cropland were dominated by the losses of forest-derived and light-fraction OC and N.

1. Introduction

The conversion of natural forest to agricultural land can lead not only to losses of soil organic carbon (OC) and nitrogen (N) but also to increases in CO_2 flux to the atmosphere (Don et al., 2011; Harris et al., 2012). Reports from around the world indicate that soil OC declined by 20–43% after conversion of natural forest to agricultural land (Don et al., 2011; Guo and Gifford, 2002; Murty et al., 2002; Wei et al., 2014). These losses could increase C emissions to the atmosphere by 12–23 Gt.

Density fractions of soil organic matter are sensitive indicators of changes in soil quality. Analysis of these density fractions can provide important insight about how soil OC and N respond to changes in land use (Boone, 1994; John et al., 2005; Six et al., 2002). The light-fraction of soil organic matter is mainly composed of plant residues, roots, and fungal hyphae at different stages of decomposition. The heavy-fraction is a more stable and dense organomineral fraction with lower concentrations of OC and N (Boone, 1994; Six et al., 2002; Bu et al., 2012; Schrumpf et al., 2013). The distribution of soil OC and N among different density fractions varies depending on the ecosystem. Soil OC and N concentrations in light-fraction organic matter are generally higher in forest soil than in cropland or grassland soil (Spycher et al., 1983; John et al., 2005; Yamashita et al., 2006; Bu et al., 2012). John et al. (2005) reported that 86–91% of soil OC was associated with heavy-fraction organic matter in grassland and cropland soils, whereas Spycher et al. (1983) observed that 53% of the OC and 45% of the N were associated with light-fraction organic matter in a forest soil. Conversion from forest to cropland leads to significant changes in OC and N in density fractions.

The isotopic signature of soil organic matter after land-use change can be a powerful tool for understanding the biogeochemistry of OC and nutrients in different ecosystems (Dawson et al., 2002; West et al., 2006). Changes in soil $\delta^{13}C$ have been successfully used to partition original and newly added OC in soil after conversion from natural vegetation to crops (Blagodatskaya et al., 2011; Osher et al., 2003; Vågen et al., 2006). The application of $\delta^{15}N$ to partition original and newly added N in soil following land-use change has not been well examined, however. After the cultivation of previously forested land, soil organic matter decomposition accelerates due to tillage and fertilization (Fließbach and Mäder, 2000; Roscoe and Buurman, 2003), resulting in the enrichment of soil $\delta^{15}N$ (Wright and Inglett, 2009) and a decline in total soil

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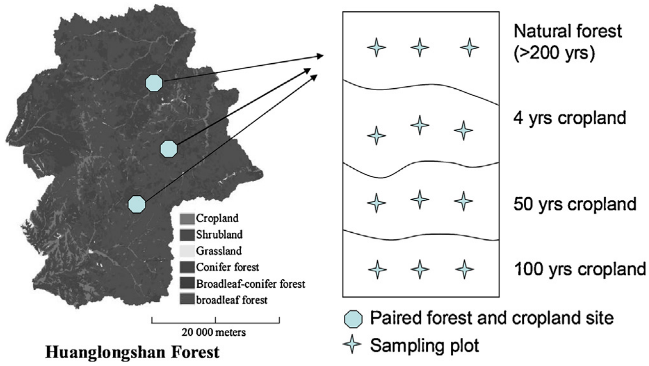

Fig. 1. Sampling scheme of this study.

N. The application of N fertilizer to cropland can also change soil δ^{15}N (Bateman and Kelly, 2007; Choi et al., 2003). The changes in soil δ^{15}N after the conversion of forest to cropland can be used to partition forest- and crop-derived N.

In this study, we investigated the dynamics of OC and N following the conversion of forest to cropland. The cropland had been converted from adjacent forest 4, 50, or 100 years previously. The organic matter was separated by into light and heavy-fractions. δ^{13}C and δ^{15}N techniques were used to distinguish between forest- and crop-derived OC and N. The objectives of this study were 1) to determine the dynamics of OC and N in density fractions and of OC and N derived from forest and cropland and 2) to examine the contributions of these changes to changes in total soil OC and N.

2. Materials and methods

2.1. Study sites

We conducted this study in the Huanglongshan Forest, Shaanxi Province, China (35°28′49″–36°02′01″ N, 109°38′49″–110°12′47″ E). The region is characterized by a semi-humid, temperate climate with a mean annual temperature of 8.6 °C (ranging from −22.5 °C in January to 36.7 °C in July) and a mean annual precipitation of 612 mm. The soil in the region is a Cambisol according to the FAO classification system.

2.2. Field investigation and sampling

Soil samples were collected from three areas in the study region (Fig. 1). The areas, which were approximately 3 km from each other, had the same soil type and similar topography. Each area included a forest site and three cropped sites. The cropped sites had been established from the adjacent forest 4, 50, or 100 years ago (Fig. 1). The forest was composed of Liaodong oak (*Quercus liaotungensis* Koidz) and birch (*Betula platyphylla* Sukaczev) and had a stand age of more than 200 years. The forest floor was covered with bunge needlegrass (*Stipa bungeana* Trinius). The cropped sites had been primarily planted to millet (*Setaria italica* (Linnaeus) P. Beauvois), maize (*Zea mays* Linnaeus), and potato (*Solanum tuberosum* Linnaeus). Millet and maize are C4 species. The aboveground biomass of the crops was harvested and removed each year. Chemical fertilizers have been applied to the cropped sites, but the rate of application varied from year to year. Maize was growing on the cropland when the samples were collected.

Three plots were established at each forest and cropland site in August 2009 (forest plots, 20 m × 20 m; cropland plots, 5 m × 5 m). Each plot was at least 40 m from the site boundaries to reduce the possibility of tree litter falling on the cropland plots. One sample was collected from each plot using a stainless steel cutting ring (5 cm in height × 5 cm in diameter). This sample was used to determine the bulk density of the 0–10 and 10–20 cm depths. Three additional samples were collected from the 0–10 and 10–20 cm depths of each plot to combine a composite sample for measurement of OC and N concentrations in both total soils and density fractions. We only collected samples from the top 20 cm of the soil profile because cultivation mainly affects soil OC and N mainly at these depths. Litter was removed from the surface of the forest plots before sampling. Visible pieces of organic material were removed from all soil samples. The moist soil samples were transported to the laboratory and air dried.

Each area also had one cropland site that had been cultivated for more than 200 years. These sites were used as a reference for calculating the proportion of OC (f_{OC}) or N (f_N) derived from the cropland. Soil samples were collected from both the 0–10 and 10–20 cm depths of these sites. The soil type and topography in the reference cropland were similar to those in the 4, 50, and 100 cropland sites. We cannot absolutely verify that the reference cropland had the same history as the converted cropland. However, the Huanglongshan Forest Bureau has confirmed that the reference cropland has always been planted with millet, maize, and potato (C3/C4 rotation), similar to the converted cropland (Zhang, 1986; Yang and Hou, 2005). The tillage practices were similar on both the reference and converted croplands. Chemical fertilizers were first used in the region in 1933 (Peng, 1995). Manure had not been applied to either the reference or the converted cropland because the selected sites were far from the village. We thus believe that the reference cropland and the converted soils had a similar history in regard to crop rotation, tillage and fertilization.

2.3. Laboratory analyses

The light and heavy-fractions were separated by a modified density-fractionation procedure developed by Gregorich and Ellert (1993). The free and occluded light-fractions were combined in the modified procedure. Ten grams of each soil sample were placed in a 100 mL centrifuge tube and dispersed ultrasonically in 70 mL of a NaI solution (1.8 g cm^{-3}) for 3 min at an energy input of 400 J mL^{-1}. The centrifuge tube was packed in ice to minimize temperature increases. The solution was centrifuged (15 min, 4000 rpm), and the supernatant was aspirated with a vacuum pump and filtered through a Whatman membrane filter (0.45 μm) in a Millipore vacuum unit. The fraction recovered on the filter (i.e., light-fraction) was washed with 100 mL of 0.01 M $CaCl_2$ followed by 200 mL of distilled water. The light-fraction was dried at 60 °C, weighed and ground. The pellet in the tube (i.e., heavy-fraction) was washed five times with 0.01 M $CaCl_2$ and then washed again with distilled water until the clay fraction remained in suspension after 24 h. The samples were dried at 60 °C, weighed, and then ground for analysis.

The OC and N concentrations in the total soil (air-dry) and density fractions were analyzed with a VARIO EL III CHON analyzer (Elementar, Germany) at the Testing and Analysis Center of Northwest University, China. Soil samples were treated with HCl before analysis to remove the carbonates.

The natural abundances of δ^{13}C and δ^{15}N in the soil organic matter were analyzed with a MAT253 Stable Isotope Ratio Mass Spectrometer (Thermo Fisher Scientific, USA) at the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering at Hohai University, China. Variations in the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios are reported relative to the Vienna PDB standard and to atmospheric N_2, respectively, and are expressed as:

$$\delta(‰) = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000 \quad (1)$$

where R is the ratio of ^{13}C to ^{12}C or of ^{15}N to ^{14}N.

2.4. Data analyses

Our analysis of soil OC and N dynamics was based on two assumptions: 1) soil properties in the cropland and forest sites were the same when the forest was converted to cropland and 2) the levels of OC and N in the forest have not changed over time. The latter assumption is based on the fact that soil OC and N are generally in a steady state in mature forests (Odum, 1969). In order to determine the origin of organic matter in the converted cropland, we made two additional assumptions: 1) the $\delta^{13}C$ and $\delta^{15}N$ signals were stable over time (i.e. old and new soil organic matter originating from the same vegetation type had the same isotopic signal) and 2) the spatial variability of isotopic signals in the cropland and forest sites was low. These assumptions have been made in previous studies (Walker et al., 2010; Wei et al., 2013) and are necessary because neither the amount of OC and N in the soil nor the isotopic signal of soil organic matter 50 years ago cannot be directly quantified. If OC and N contents in the forest soil increased with time, then our assumptions could result in overestimation of the declines in soil OC and N after the conversion of forest to cropland (Wei et al., 2012, 2013).

The stocks of OC and N in total soils (SOC or SN, kg m^{-2}) were calculated as:

$$\text{SOC} = \frac{D \times \text{BD} \times \text{OC}}{100} \tag{2}$$

$$\text{SN} = \frac{D \times \text{BD} \times \text{N}}{100} \tag{3}$$

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

The stocks of OC and N in each density fraction (SOC_i and SN_i, kg m^{-2}) were calculated as:

$$\text{SOC}_i = \frac{D \times \text{BD} \times \text{OC}_i \times M_i}{100} \tag{4}$$

$$\text{SN}_i = \frac{D \times \text{BD} \times \text{N}_i \times M_i}{100} \tag{5}$$

where M_i is the mass in the ith density fraction (g kg^{-1}) and OC_i and N_i are the concentrations of OC and N in the ith density fraction (g kg^{-1}) of the 0–10 or 10–20 cm soil depths.

For the cropland soils, the proportion of OC (f_{OC}) or N (f_{N}) derived from the cropland at each soil depth was calculated by solving the following equations (Osher et al., 2003):

$$\delta^{13}\text{C} = (1 - f_{\text{OC}}) \times \delta^{13}\text{C}_{\text{F}} + f_{\text{OC}} \times \delta^{13}\text{C}_{\text{C}} \tag{6}$$

$$\delta^{15}\text{N} = (1 - f_{\text{N}}) \times \delta^{15}\text{N}_{\text{F}} + f_{\text{N}} \times \delta^{15}\text{N}_{\text{C}} \tag{7}$$

where $\delta^{13}\text{C}_{\text{F}}$ or $\delta^{13}\text{N}_{\text{F}}$ is the value of soil δ^{13}C or δ^{13}N in the forest, δ^{13}C or δ^{13}N is the value of soil δ^{13}C or δ^{13}N in the cropland, and $\delta^{13}\text{C}_{\text{C}}$ or $\delta^{13}\text{N}_{\text{C}}$ is the value of soil δ^{13}C or δ^{13}N in the reference cropland. The $\delta^{13}\text{C}_{\text{C}}$ was −19.83‰ in the 0–10 cm depth of the reference cropland and −20.35‰ in the 10–20 cm depth. The $\delta^{13}\text{N}_{\text{C}}$ was 3.68‰ in the 0–10 cm depth of the reference cropland and 3.37‰ in the 10–20 cm depth.

The forest- and crop-derived OC and N stocks (kg m^{-2}) were calculated as:

$$\text{SOC}_F = \text{SOC} \times (1 - f_{\text{OC}}) \tag{8}$$

$$\text{SOC}_{\text{C}} = \text{SOC} \times f_{\text{OC}} \tag{9}$$

$$\text{SN}_{\text{F}} = \text{SN} \times (1 - f_{\text{N}}) \tag{10}$$

$$\text{SN}_{\text{C}} = \text{SN} \times f_{\text{N}} \tag{11}$$

where SOC_{F} and SOC_{C} are the stocks of forest- and crop-derived OC, respectively, and SN_{F} and SN_{C} are the stocks of forest- and crop-derived N, respectively.

We used the following equation to model (1) the dynamics of the OC and N stocks in the total soils and density fractions and (2) the dynamics of the forest- and crop-derived OC and N stocks after the conversion of forest to cropland (Six and Jastrow, 2002):

$$C = C_e \times \left[1 - \left(\frac{C_e - C_0}{C_e}\right) \times e^{-kt}\right] \tag{12}$$

which is equivalent to

$$C = C_e - (C_e - C_0) \times e^{-kt} \tag{13}$$

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

The potential losses or gains (L) of OC or N stocks (kg m^{-2}) were calculated as:

$$L = C_0 - C_e \tag{14}$$

The mean residence time (MRT) (yr) was calculated as:

$$\text{MRT} = \frac{1}{k} \tag{15}$$

The parameters of the first-order model were obtained by fitting the model for each replication. The mean value and standard error of each parameter were calculated. The parameters were used to predict the variables. The root mean square error (RMSE) and the modeling efficiency (EF) were calculated to evaluate the overall fit of the model. A perfect fit of the model predictions would have an RMSE of 0 and an EF of 1. Our results showed that the predictions were close to the observations (scattered around the 1:1 line) (Fig. 2). The RMSE and EF were 0.104 kg m^{-2} and 0.916 for OC and 0.026 kg m^{-2} and 0.821 for N, respectively.

The propagation of error associated with variables such as f_{OC} and f_{N} as well as the forest- and crop-derived OC and N stocks were evaluated using standard deviation (Goñi and Eglinton, 1996; Goñi et al., 2005; Gordon et al., 2001; Taylor, 1997). For example, if q is any function of several variables $x, \cdots, z$, then the standard deviation associated with $q(\sigma q)$ can be assessed as:

$$\sigma q = \sqrt{\left(\frac{\partial q}{\partial x} \times \sigma x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z} \times \sigma z\right)^2} \tag{16}$$

The variability associated with other variables was evaluated using standard errors. A two-way analysis of variance (ANOVA) was conducted using JMP version 10 software to test the effects of cultivation and soil depth on OC and N stocks both in total soils and in density fractions. The stocks of forest- and crop-derived OC and N were also determined.

3. Results

3.1. Rapid decreases in OC and N in total soils

The conversion of forest to cropland significantly decreased the stocks of OC and N in total soils (Fig. 3a and b, Table 1). The decreases were larger in the 0–10 cm depth than in the 10–20 cm depth. Soil OC and N stocks in the 0–10 cm depth decreased by 19% and 21%, respectively, within the first 4 years of conversion and by 33% and 31%, respectively, within 50 years of conversion. Soil OC and N stocks in the 10–20 cm depth decreased by 3% and 1%, respectively, within the first 4 years of conversion and by 16% and 15%, respectively, within 50 years of conversion. Soil OC and N stocks did not decrease significantly in either depth beyond 50 and 100 years after conversion.

Our calculations predicted that soil OC and N stocks would decline by 37 ± 5% and 36 ± 8%, respectively, in the 0–10 cm depth and by 38 ± 5% and 29 ± 6%, respectively, in the 10–20 cm depth,

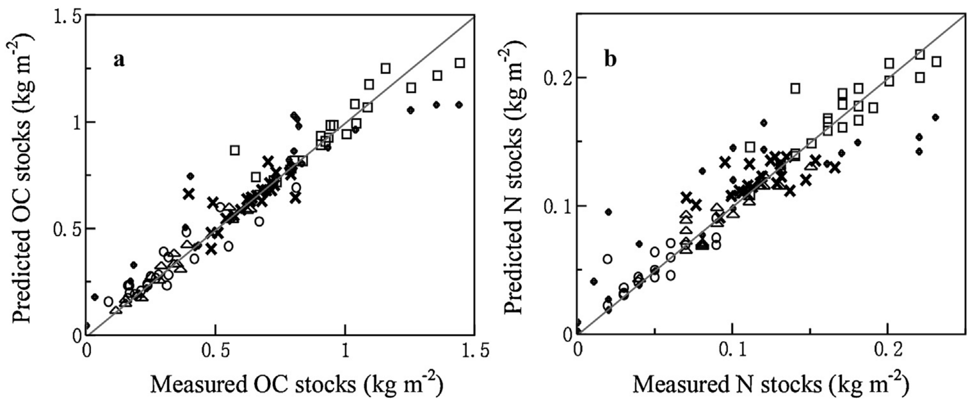

Fig. 2. Comparison between the measurements and predictions of the first-order model on OC stocks (a) and N stocks (b). Squares: OC or N in total soils; diamonds: forest-derived OC or N; triangles: crop-derived OC or N; circles: OC or N in the light-fraction; crosses: OC or N in the heavy-fraction. The solid line is the 1:1 line. The root mean standard errors for OC and N were 0.104 kg m^{-2} and 0.026 kg m^{-2}, respectively, and the modeling efficiencies for OC and N were 0.916 and 0.821, respectively.

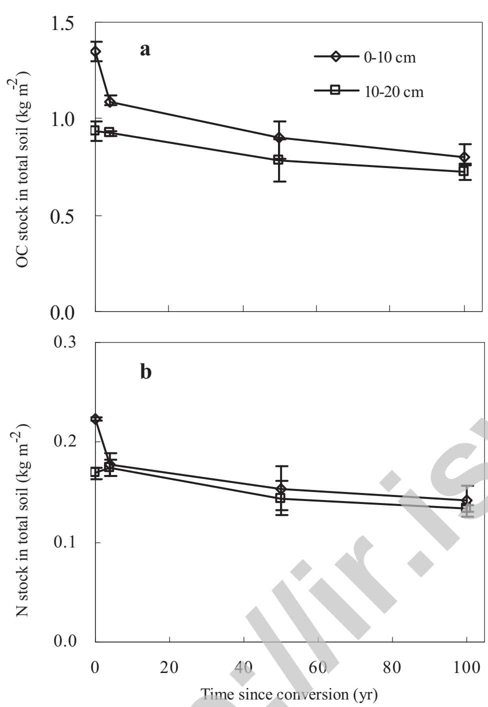

Fig. 3. Changes in OC and N stocks in total soils at the 0–10 and 10–20 cm depths after conversion of forest to cropland. Error bars are the standard error of the mean.

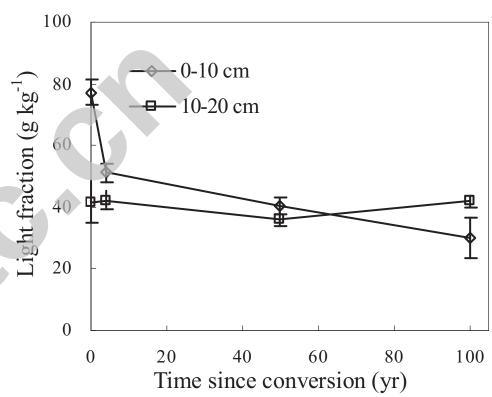

Fig. 4. Changes in the mass of soil light-fraction at the 0–10 and 10–20 cm depths after conversion of forest to cropland. Error bars are the standard error of the mean.

at equilibrium state. The *k* values of soil OC and N stocks were larger in the 0–10 cm depth than in the 10–20 cm depth, whereas the MRTs were shorter in the 0–10 cm depth than in the 10–20 cm depth (Table 2). The largest decreases in total OC and N in both depths were predicted to occur during the first 30 and 80 years of conversion, respectively.

3.2. Decreases in soil OC and N in the density fractions

The conversion of forest to cropland significantly decreased the mass of the soil light-fraction (Fig. 4, Table 1). The mass of the light-fraction in the 0–10 cm depth decreased most within the first

Table 1
Analysis of variance results for all the variables ($n = 3$).

	Cultivation time		Soil depth		Interaction	
	F	*P*	*F*	*P*	*F*	*P*
Soil δ^{13}C	71.4	0.0000	0.9	0.3664	1.4	0.2538
Soil δ^{15}N	61.6	0.0000	0.0	0.9151	0.2	0.6531
OC stock in total soils	24.1	<0.0001	12.1	0.0024	2.9	0.1046
N stock in total soils	15.9	0.0007	3.1	0.0931	0.8	0.3733
Mass of light-fraction	21.1	0.0002	7.4	0.0132	18.4	0.0004
OC stock in light-fraction	23.1	0.0001	7.9	0.0108	7.1	0.0149
OC stock in heavy-fraction	2.04	0.1684	2.7	0.1134	0.4	0.5567
N stock in light-fraction	22.5	0.0001	5.0	0.0371	5.6	0.0281
N stock in heavy-fraction	2.7	0.1155	0.4	0.5269	0.2	0.6876
Cropland derived OC stock	59.2	<0.0001	1.5	0.2366	0.0	0.9994
Forest derived OC stock	65.7	<0.0001	2.6	0.1208	1.4	0.2592
Cropland derived N stock	37.4	<0.0001	0.0	0.9237	0.13	0.7215
Forest derived N stock	47.5	<0.0001	1.1	0.3075	0.70	0.4137

Table 2
Parameters (mean ± standard error) describing the dynamics of soil OC and N after the conversion from forest to cropland.

	Total soil		Forest derived		Crop derived		Light-fraction		Heavy-fraction	
	OC	N	OC	N	OC	N	OC	N	OC	N
0–10 cm										
C_e (kg m^{-2})	0.83 ± 0.08	0.14 ± 0.02	0.05 ± 0.02	0.02 ± 0.01	0.82 ± 0.00	0.17 ± 0.00	0.21 ± 0.04	0.03 ± 0.01	0.59 ± 0.05	0.13 ± 0.01
L (kg m^{-2})	0.49 ± 0.05	0.08 ± 0.02	1.09 ± 0.09	0.15 ± 0.00	-0.70 ± 0.04	-0.14 ± 0.00	0.47 ± 0.04	0.06 ± 0.00	0.09 ± 0.01	0.02 ± 0.01
k (yr^{-1})	0.033 ± 0.006	0.029 ± 0.005	0.048 ± 0.001	0.061 ± 0.005	0.012 ± 0.002	0.017 ± 0.001	0.226 ± 0.011	0.197 ± 0.032	0.007 ± 0.002	0.009 ± 0.002
MRT (yr)	30.3 ± 4.5	34.4 ± 5.6	20.8 ± 1.9	16.3 ± 1.4	87.0 ± 18.3	58.5 ± 17.8	4.4 ± 0.7	5.1 ± 0.9	137.7 ± 18.2	116.3 ± 14.6
10–20 cm										
C_e (kg m^{-2})	0.55 ± 0.04	0.12 ± 0.01	0.04 ± 0.01	0.02 ± 0.00	0.84 ± 0.01	0.13 ± 0.00	0.16 ± 0.01	0.03 ± 0.0/	0.54 ± 0.04	0.10 ± 0.01
L (kg m^{-2})	0.34 ± 0.06	0.05 ± 0.01	1.24 ± 0.16	0.13 ± 0.01	-0.79 ± 0.01	-0.12 ± 0.01	0.14 ± 0.04	0.03 ± 0.01	0.10 ± 0.01	0.02 ± 0.01
k (yr^{-1})	0.013 ± 0.003	0.012 ± 0.003	0.028 ± 0.008	0.027 ± 0.007	0.009 ± 0.003	0.014 ± 0.002	0.020 ± 0.003	0.015 ± 0.002	0.004 ± 0.001	0.003 ± 0.001
MRT (yr)	76.9 ± 9.3	83.3 ± 10.4	35.6 ± 6.4	37.2 ± 8.3	108.7 ± 8.2	70.4 ± 18.7	49.5 ± 8.9	65.5 ± 12.8	244.5 ± 28.2	310.1 ± 6.8

C_e: The stocks of OC or N at equilibrium; L: Potential loss or gains of OC and N stocks; MRT: Mean residence time of OC and N stocks. The negative values of L indicate gains of soil OC and/or N stocks.

4 years after conversion (34%) but did not change significantly between 50 and 100 years after conversion. Conversion did not affect the mass of the light-fraction in the 10–20 cm depth.

The stocks of light-fraction OC and N decreased significantly after conversion (Fig. 5a and c, Table 1). The decreases varied both with time since conversion and with soil depth. The rapid decreases in light-fraction OC and N in both depths occurred within the first 4 years after conversion. The heavy-fraction OC and N, however, decreased slowly (Fig. 5b and d). The decreases in light-fraction OC and N were generally larger in the 0–10 cm depth than in the 10–20 cm depth. In contrast, the decreases in heavy-fraction OC and N were generally smaller in the 0–10 cm depth than in the 10–20 cm depth. For example, light-fraction OC and N decreased by 40–76% and 36–67%, respectively, in the 0–10 cm depth but only by 13–41% and 25–39%, respectively, in the 10–20 cm depth. The heavy-fraction OC and N decreased by 1–5% and 10–15%, respectively, in the 0–10 cm depth and by 5–17% and 15–23%, respectively, in the 10–20 cm depth. Additionally, the decreasing rates of total OC and light-fraction OC were significantly correlated with light-fraction N, with correlation coefficients of 0.827 and 0.803, respectively ($P < 0.0001$). However, the decreasing rate of heavy-fraction OC was not correlated with light-fraction N.

The contribution of the decreases in the density fractions to the total decreases in OC and N varied with soil depth. Decreases in light-fraction OC and N after conversion accounted for 92–95% and 72–78%, respectively, of the total decrease in OC and N in the 0–10 cm depth. In contrast, in the 10–20 cm depth, declines in light- and heavy-fraction contributed similarly to the total declines in OC and N. Specifically, declines in light-fraction OC and N accounted for 51–57% and 40–47%, respectively, of the total decline in OC and N. Declines in heavy-fraction OC and N accounted for 43–49% and 53–60%, respectively, of the total decline.

The predicted losses of OC and N at equilibrium state were higher in the light-fraction than in the heavy-fraction (Table 2). Light-fraction OC and N were predicted to decline by 69 ± 10% and 61 ± 16%, respectively, in the 0–10 cm depth and by 45 ± 9% and 51 ± 8%, respectively, in the 10–20 cm depth. Heavy-fraction OC and N were predicted to decline by 13 ± 3% and 13 ± 4%, respectively, in the 0–10 cm depth and by 16 ± 4% and 15 ± 5%, respectively, in the 10–20 cm depth. The predicted losses of OC and N in the light-fraction accounted for 84 ± 9% and 75 ± 10%, respectively, of predicted total losses in the 0–10 cm depth and 59 ± 7% and 62 ± 5%, respectively, of predicted total losses in the 10–20 cm depth. The k values of OC and N in the total soil were smaller than the values in the light-fraction but larger than the values in the heavy-fraction. The MRTs of OC and N in total soil were consistently longer than those in the light-fraction but shorter than those in the heavy-fraction (Table 2).

3.3. Changes in soil δ^{13}C and δ^{15}N and the dynamics of forest- and crop-derived OC and N

The conversion of forest to cropland significantly increased soil δ^{13}C and δ^{15}N in both soil depths (Fig. 6a and b, Table 2). The amount of increase varied depending on conversion time. Soil δ^{13}C increased by 1.2‰ in the 0–10 cm depth and by 0.5‰ in the 10–20 cm depth within the first 4 years after conversion. During the same period, soil δ^{15}N increased by 1.6‰ in the 0–10 cm depth and by 1.4‰ in the 10–20 cm depth. During the first 100 years after conversion, soil δ^{13}C increased by 3.6‰ in the 0–10 cm depth and by 3.5‰ in the 10–20 cm depth. Soil δ^{15}N increased by 2.5‰ in the 0–10 cm depth and by 3.0‰ in the 10–20 cm depth.

Conversion increased crop-derived OC and N in both depths, but decreased the forest-derived OC and N (Figs. 7a,b and 8a–d). The losses of forest-derived OC and N and the gains of crop-derived OC and N increased with conversion time and were larger in the

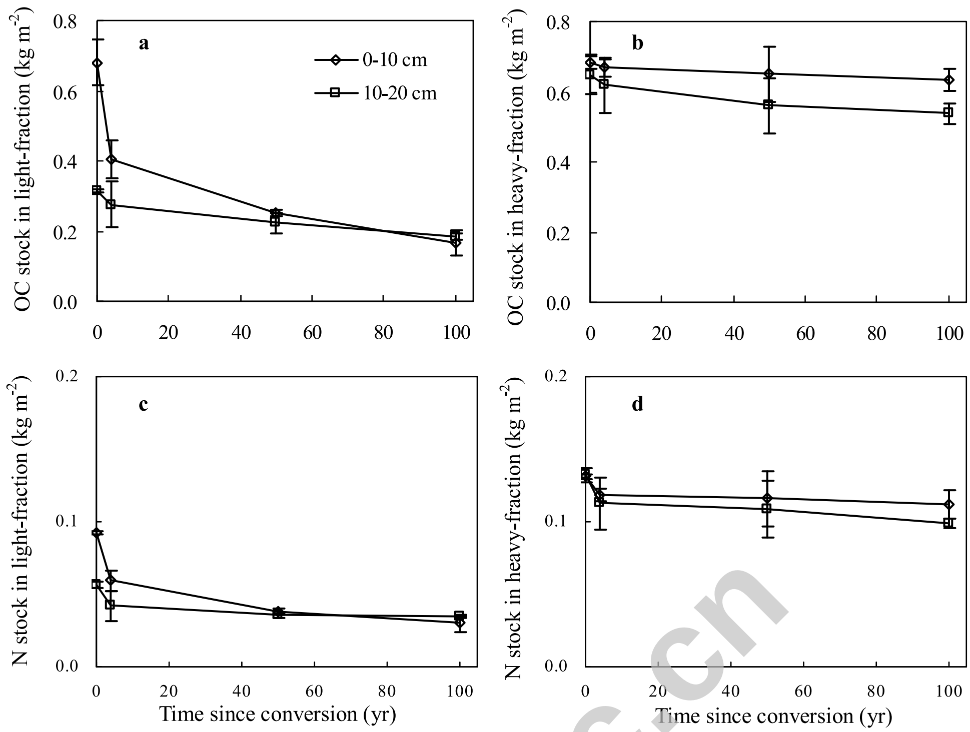

Fig. 5. Changes in the stocks of OC and N in the light and heavy-fractions at the 0–10 and 10–20 cm depths after conversion of forest to cropland. Error bars are the standard error of the mean.

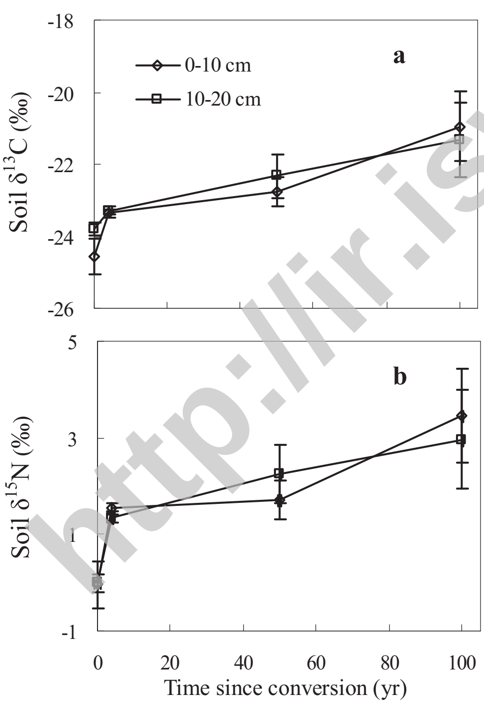

Fig. 6. Changes in soil $\delta^{13}C$ and $\delta^{15}N$ at the 0–10 and 10–20 cm depths after conversion of forest to cropland. Error bars are the standard error of the mean.

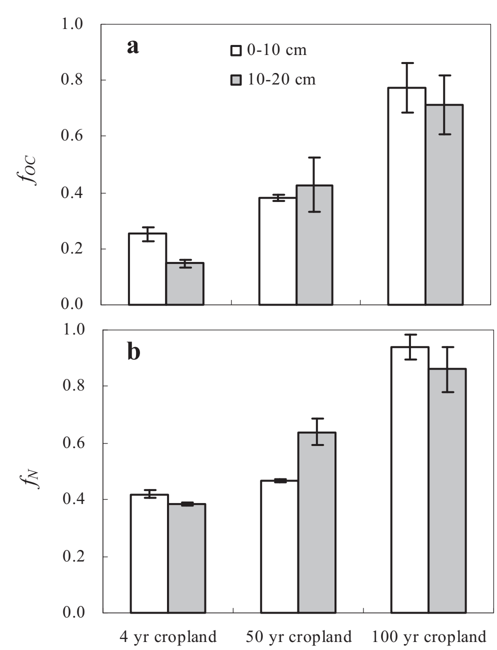

Fig. 7. The proportion of OC (f_{OC}) or N (f_N) derived from the cropland at the 0–10 and 10–20 cm depths. Error bars are the standard deviation of the mean, determined from the propagation of error.

0–10 cm depth than in the 10–20 cm depth. Forest-derived OC and N in the 0–10 cm depth decreased by 40% and 54%, respectively, within 4 years of conversion and by 85% and 96%, respectively, within 100 years of conversion. Forest-derived OC and N in the 10–20 cm depth decreased by 16% and 37%, respectively, within 4 years of conversion and by 80% and 87%, respectively, within 100 years of conversion (Fig. 8a and c). Crop-derived OC and N in the 0–10 cm depth increased to 0.28 kg m^{-2} and 0.07 kg m^{-2}, respectively, within 4 years of conversion and to 0.60 kg m^{-2} and 0.13 kg m^{-2}, respectively, within 100 years of conversion. The crop-derived OC and N in the 10–20 cm depth increased to 0.14 kg m^{-2} and to 0.07 kg m^{-2}, respectively, within 4 years of conversion and to 0.53 kg m^{-2} and 0.11 kg m^{-2}, respectively, within 100 years of conversion (Fig. 8b and d).

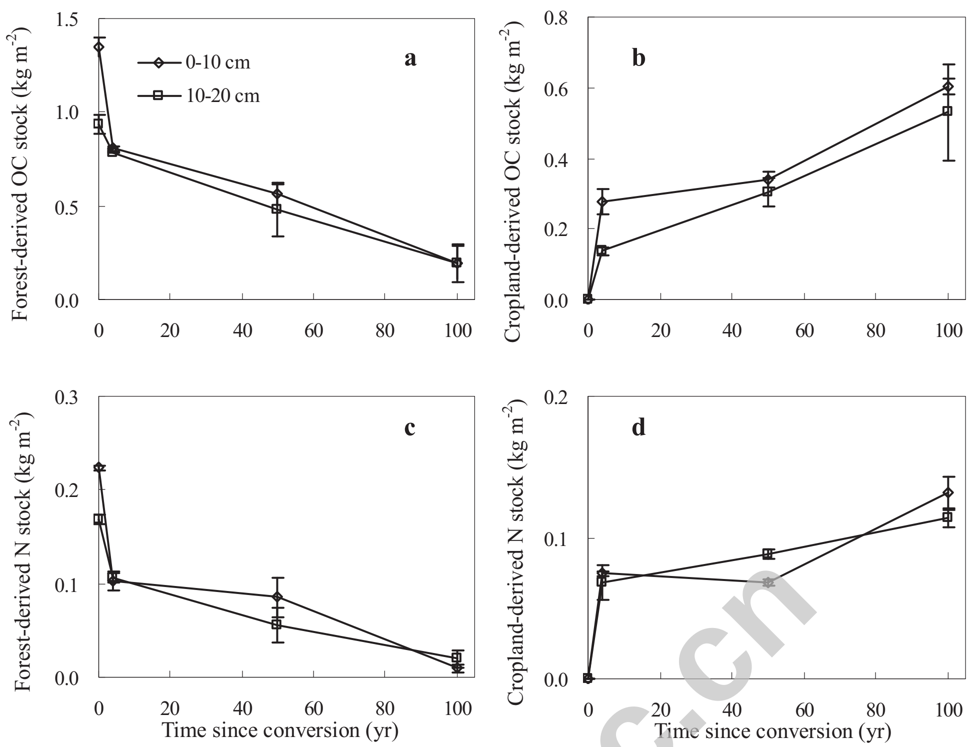

Fig. 8. Changes in the stocks of OC and N derived from forest and cropland at the 0–10 and 10–20 cm depths after conversion of forest to cropland. Error bars are the standard deviation of the mean, determined from the propagation of error.

The losses of forest-derived OC and N were larger than the gains of crop-derived OC and N at all time points after conversion. The observed losses of forest-derived OC and N in the 0–10 cm depth were 1.9–2.3 and 1.1–1.5 times, respectively, the observed gains of crop-derived OC and N. The observed losses of forest-derived OC and N in the 10–20 cm depth were 1.6–2.0 and 0.9–1.3 times, respectively, the observed gains of crop-derived OC and N. The predicted losses of forest-derived OC and N in both depths were almost 2 times the predicted total losses of soil OC and N at equilibrium state. The MRTs of forest-derived OC and N, however, were much shorter than those of the total soil OC and N in both soil depths (Table 2).

4. Discussion

Our results demonstrated that the conversion of forest to cropland led to rapid losses of OC and N in total soil and to significant decreases both in light-fraction mass and in light-fraction OC and N stocks. One explanation is that the input of organic material to cropland soil is significantly reduced both by the harvest and removal of aboveground biomass and by an overall decrease in root biomass. Both of these factors could affect light-fraction organic matter (Schrumpf et al., 2013). In addition, tillage and fertilization in cropland can increase organic matter mineralization (Fließbach and Mäder, 2000; Roscoe and Buurman, 2003), resulting in significant decreases both in light-fraction mass and in soil OC and N stocks.

The turnover of OC and N in the light-fraction after the conversion of forest to cropland dominated the turnover of OC and N in the total soil, particularly in the 0–10 cm depth. The larger decreases in light-fraction OC and N were partly due to the relatively high rates of organic matter mineralization in this fraction (Boone, 1994; Schrumpf et al., 2013; Six et al., 2002).

We observed that soil δ^{13}C increased after conversion from forest to cropland. This change can be ascribed to the introduction of C4 crops (Dawson et al., 2002; West et al., 2006), the accelerated decomposition of soil organic matter by tillage (Six et al., 1998; Wright and Hons, 2005) and the application of fertilizer, particularly P fertilizer (Inglett and Reddy, 2006; Wright and Inglett, 2009). The increases in soil δ^{13}C were lower than reports from wetter regions (Blagodatskaya et al., 2011; Osher et al., 2003). The relatively small increase in soil δ^{13}C in our study was probably mainly due to the rotation of C3 and C4 crops in converted cropland. Aridity is another factor that could have influenced our results. Arid conditions often cause reductions in stomatal conductance and in ^{13}C discrimination (Schnyder et al., 2006; Wittmer et al., 2008).

The application of chemical fertilizers was assumed to decrease soil δ^{15}N because synthetic fertilizers have levels of δ^{15}N similar to that of the atmosphere (0‰) (Bustamante et al., 2004; Choi et al., 2003), whereas the oxidation and decomposition of organic matter enriches soil δ^{15}N (Wright and Inglett, 2009). Our results showed a 0.66 ± 0.43 g kg^{-1} (mean ± S.D.) decrease in total N and a 2.0 ± 0.4‰ (mean ± S.D.) increase in δ^{15}N at the 0–20 cm depth 50 years after conversion. These changes are consistent with the 1.7 g kg^{-1} decrease in total soil N and the 4.4‰ increase in soil δ^{15}N observed at the 0–5 cm depth after 12 years of cultivation of a temperate humid pasture (Díaz-Raviñã et al., 2005). The enrichment of soil δ^{15}N due to the decomposition of organic matter is thus greater than the depletion of soil δ^{15}N due to the application of chemical fertilizers, suggesting that the amount of N lost due to the decomposition was larger than the amount of N input by fertilization after conversion.

The application of δ^{13}C techniques to partition original and newly added OC after land-use change has been well established. However, few reports have used δ^{15}N to partition original and newly added N. We demonstrated that δ^{15}N could track the dynamics of original and newly added N after conversion of forest to cropland, in agreement with other findings (Fang et al., 2011; Robinson, 2001; Russow et al., 2004).

We assumed that the δ^{13}C and δ^{15}N signals were stable over time and that old and new soil organic matter originating from the same vegetation type had the same isotopic signals. However, due to decomposition and the partial preservation of specific soil organic matter compounds (Dawson et al., 2002; Six et al., 1998; West et al., 2006; Wright and Hons, 2005; Wright and Inglett, 2009) as well as the Suess effect (Keeling, 1979), the $\delta^{13}C$ and $\delta^{15}N$ signatures of the old forest-soil organic matter still present in the converted cropland may have somewhat different $\delta^{13}C$ and $\delta^{15}N$ signatures than the bulk $\delta^{13}C_F$ and $\delta^{15}N_F$ signals. The $\delta^{13}C$ and $\delta^{15}N$ of forest-soil organic matter in converted cropland would thus increase with time, resulting in overestimation of crop-derived OC and N. Our calculation showed that a 1‰ increase in $\delta^{13}C$ and $\delta^{15}N$ would overestimate crop-derived OC and N in 100-year converted cropland by 12%. The $\delta^{13}C_F$ and $\delta^{15}N_F$, however, would also increase with time due to isotopic fractionation (Böstrom et al., 2007). This would reduce the error in our calculation. Thus, the overestimation should thus be smaller than these values. Additionally, the standard deviations of f_{OC} and f_N were less than 0.21 and 0.13, respectively; those of forest-derived OC and N stocks were less than 0.22 and 0.03 kg m^{-2}, respectively; and those of crop-derived OC and N stocks were less than 0.21 and 0.02 kg m^{-2}, respectively (Figs. 7 and 8). These results show that the propagation of error associated with calculating the proportions of OC and N derived from the cropland and the forest- and crop-derived OC and N stocks were relatively small.

The turnover rate of forest-derived OC and N was higher than that of total soil OC and N, indicating that the loss of forest-derived OC and N dominated the dynamics of soil OC and N after conversion. The gains of crop-derived OC and N, however, offset more than half the losses of forest-derived OC and N. The gains of crop-derived OC accounted for 43–52% and 67–93% of the losses of forest-derived OC in the 0–10 and 10–20 cm depths, respectively. The gains of crop-derived N accounted for 49–62% and 76–109% of the losses of the forest-derived N in the 0–10 and 10–20 cm depths, respectively. These results suggest that the crop-derived OC and N play important roles in supplementing soil OC and N after the conversion of forest to cropland. The larger contribution of crop-derived N after conversion can be attributed to the application of N fertilizer.

The decreasing rates of OC in both total soils and the light-fraction were significantly correlated with light-fraction N. These results suggested that high N availability resulted in greater losses of soil OC (Mack et al., 2004; Recous et al., 1995). One explanation is that higher N availability accelerates the decomposition of soil organic matter (Bellamy et al., 2005; Mack et al., 2004). Therefore, the rapid loss of N associated with the light-fraction shortly after the conversion could be an underlying mechanism for the decrease in the rate of OC loss as the time since conversion increased.

5. Conclusion

Our results indicated that the conversion of forest to cropland will lead to losses in the 0–20 cm depth of 2.33 kg m^{-2} and 0.28 kg m^{-2} of forest-derived OC and N, respectively, but to gains of 1.49 kg m^{-2} and 0.26 kg m^{-2} of crop-derived OC and N at equilibrium state, respectively. Calculations indicated that forest-derived OC was mainly lost 25–36 years after conversion. Forest-derived N was mainly lost 16–37 years after conversion. Crop-derived OC was predicted to have been increased mainly 87–109 years after conversion. Crop-land derived N was gained 58–70 years after conversion. The losses of forest-derived OC and N were almost twice the losses of total soil OC and N. The losses of OC and N from the light-fraction accounted for 84% and 75%, respectively, of the total losses in the 0–10 cm depth and for 58% and 60%, respectively, of the total losses in the 10–20 cm depth. These results indicated that changes in light-fraction and forest-derived organic matter dominated the dynamics of OC and N in the total soil after conversion of forest to cropland.

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References

Bateman, A.S., Kelly, S.D., 2007. Fertilizer nitrogen isotope signatures. Isot. Environ. Health S. 43, 237–247.
Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils across England and Wales 1978-2003. Nature 437, 245–248.
Blagodatskaya, E., Yuyukina, T., Blagodatsky, S., Luzyakov, Y., 2011. Turnover of soil organic matter and of microbial biomass under C3-C4 vegetation change: consideration of ^{13}C fractionation and preferential substrate utilization. Soil Biol. Biochem. 43, 159–166.
Boone, R.D., 1994. Light-fraction soil organic matter: origin and contribution to net nitrogen mineralization. Soil Biol. Biochem. 26, 1459–1468.
Böstrom, B., Comstedt, D., Ekblad, A., 2007. Isotope fractionation and ^{13}C enrichment in soil profiles during the decomposition of soil organic matter. Oecologia 153, 89–98.
Bu, X., Ruan, H., Wang, L., Ma, W., Ding, J., Yu, X., 2012. Soil organic matter in density fractions as related to vegetation changes along an altitude gradient in the Wuyi Mountains, southeastern China. Appl. Soil Ecol. 52, 42–47.
Bustamante, M.M.C., Martinelli, L.A., Silva, D.A., Camargo, P.B., Klink, C.A., 2004. ^{15}N natural abundance in woody plants and soils of central Brazilian savannas (Cerrado). Ecol. Appl. 14, 200–213.
Choi, W.J., Ro, H.M., Hobbie, E.A., 2003. Patterns of natural ^{15}N in soils and plants from chemically and organically fertilized uplands. Soil Biol. Biochem. 35, 1493–1500.
Dawson, T.E., Mambelli, S., Plamboeck, A.H., Templer, P.H., Tu, K.P., 2002. Stable isotopes in plant ecology. Annu. Rev. Ecol. System. 33, 507–559.
Díaz-Ravinã, M., Bueno, J., González-Prieto, S.J., Carballas, T., 2005. Cultivation effects on biochemical properties, C storage and ^{15}N natural abundance in the 0-5 cm layer of an acidic soil from temperate humid zone. Soil Till. Res. 84, 216–221.
Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. Global Change Biol. 17, 1658–1670.
Fang, H., Yu, G., Cheng, S., Zhu, T., Zheng, J., Mo, J., Yan, J., Luo, Y., 2011. Nitrogen-15 signals of leaf-litter-soil continuum as a possible indicator of ecosystem nitrogen saturation by forest succession and N loads. Biogeochemistry 102, 251–263.
Fließbach, A., Mäder, P., 2000. Microbial biomass and size-density fractions differ between soils of organic and conventional agricultural systems. Soil Biol. Biochem. 32, 757–768.
Goñi, M.A., Cathey, M.W., Kim, Y.H., Voulgaris, G., 2005. Fluxes and sources of suspended organic matter in an estuarine turbidity maximum region during low discharge conditions. Estuar. Coast. Shelf Sci. 63, 683–700.
Goñi, M.A., Eglinton, T.I., 1996. Stable carbon isotopic analyses of lignin-derived CuO oxidation products by isotope ratio monitoring-gas chromatography-mass spectrometry (irm-GS-MS). Org. Geochem. 24, 601–615.
Gordon, E.S., Goñi, M.A., Roberts, Q.N., Kineke, G.C., Allison, M.A., 2001. Organic matter distribution and accumulation on the inner Louisiana shelf west of the Atchafalaya River. Cont. Shelf Res. 21, 1691–1721.
Gregorich, E.G., Ellert, B.H., 1993. Light fraction and macroorganic matter in mineral soils. In: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis. CRC Press, Boca Raton, pp. 397–407.
Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol. 8, 345–360.
Harris, N.L., Brown, S., Hagen, S.C., Saatchi, S.S., Petrova, S., Salas, W., Hansen, M.C., Potapov, P.V., Lotsch, A., 2012. Baseline map of carbon emissions from deforestation in tropical regions. Science 336, 1573–1576.
Inglett, P.W., Reddy, K.R., 2006. Investigating the use of macrophyte stable C and N isotope ratios as indicators of wetland eutrophication: patterns in the P-affected Everglades. Limnol. Oceanogr. 51, 2380–2387.
John, B., Yamashita, T., Ludwig, B., Flessa, H., 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma 128, 63–79.
Keeling, C.D., 1979. The Suess effect: 13Carbon-14Carbon interrelations. Environ. Int. 2, 229–300.
Mack, M.C., Schuur, E.A.G., Bret-Harte, M.S., Shaver, G.R., Chapin III, F.S., 2004. Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. Nature 431, 440–443.
Murty, D., Kirschbaum, M.F., McMurtrie, R.E., McGilvray, H., 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Change Biol. 8, 105–123.
Odum, E.P., 1969. The strategy of ecosystem development. Science 164, 262–270.

Osher, L.J., Matson, P.A., Amundson, R., 2003. Effect of land use change on soil carbon in Hawaii. Biogeochemistry 65, 213–232.
Peng, L., 1995. Advances in the effects of chemical nitrogen, phosphorous and potassium fertilizers in the loess region. Res. Soil Water Conser. 2 (4), 62–68.
Recous, S., Robin, D., Darwis, D., Mary, B., 1995. Soil inorganic N availability: effect on maize residue decomposition. Soil Biol. Biochem. 27, 1529–1538.
Robinson, D., 2001. $\delta^{15}N$ as an integrator of the nitrogen cycle. Trends Ecol. Evol. 16, 153–162.
Roscoe, R., Buurman, P., 2003. Tillage effects on soil organic matter in density fractions of a Cerrado Oxisol. Soil Till. Res. 70, 107–119.
Russow, R., Veste, M., Littmann, T., 2004. Using the natural ^{15}N abundance to assess the main nitrogen inputs into the sand dune area of the north-western Negev Desert (Israel). Isot. Environ. Health S 40, 57–67.
Schnyder, H., Schwertl, M., Auerswald, K., Schäufele, R., 2006. Hair of grazing cattle provides an integrated measure of the effects of site conditions and interannual weather variability on $\delta^{13}C$ of temperate humid grassland. Global Change Biol. 12, 1315–1329.
Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kogel-knabner, I., Schulze, E.D., 2013. Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. Biogeosciences 10, 1675–1691.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.
Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 65, 1367–1377.
Six, J., Jastrow, J.D., 2002. Soil organic matter turnover. In: Lal, R. (Ed.), Encyclopedia of Soil Science. Marcel Dekker, New York, USA, pp. 936–942.
Spycher, G., Sollins, P., Rose, S., 1983. Carbon and nitrogen in the light fraction of a forest soil: vertical distribution and seasonal patterns. Soil Sci. 135, 79–87.
Taylor, J.R., 1997. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, second edition. University Science Books, Sausalito.
Vågen, T.G., Walsh, M.G., Shepherd, K.D., 2006. Stable isotopes for characterization of trends in soil carbon following deforestation and land use change in the highlands of Madagascar. Geoderma 135, 133–139.
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. J. Ecol. 98, 725–736.
Wei, X.R., Qiu, L.P., Shao, M.A., Zhang, X.C., Gale, W., 2012. The accumulation of organic carbon in mineral soils by afforestation of abandoned farmland. PLoS ONE 7, e32054.
Wei, X.R., Shao, M.A., Gale, W., Li, L.H., 2014. Global pattern of soil carbon losses due to the conversion of forest to agricultural land. Sci. Rep. 4, 4062.
Wei, X.R., Shao, M.A., Gale, W., Zhang, X.C., Li, L.H., 2013. Dynamics of aggregate-associated organic carbon following conversion of forest to cropland. Soil Biol. Biochem. 57, 876–883.
West, J.B., Bowen, G.J., Cerling, T.E., Ehleringer, J.R., 2006. Stable isotopes as one of nature's ecological recorders. Trends Ecol. Evol. 21, 408–414.
Wittmer, M.H.O.M., Auerswald, K., Tungalag, R., Bai, Y.F., Schäufele, R., Schnyder, H., 2008. Carbon isotope discrimination of C3 vegetation in central Asian grassland as related to long-term and short-term precipitation patterns. Biogeosciences 5, 913–924.
Wright, A.L., Hons, F.M., 2005. Tillage impacts on soil aggregation and carbon and nitrogen sequestration under wheat cropping sequences. Soil Till. Res. 84, 67–75.
Wright, A.L., Inglett, P.W., 2009. Soil organic carbon and nitrogen and distribution of carbon-13 and nitrogen-15 in aggregates of Everglades Histosol. Soil Sci. Soc. Am. J. 73, 427–433.
Yang, H.J., Hou, Y.J., 2005. The policy effect for Huanglong hilly area reclamation during Qing Dynasty. J. Chn. Hist. Geogr. 20, 125–131.
Yamashita, T., Flessa, H., John, B., Helfrich, M., Ludwig, B., 2006. Organic matter in density fractions of water-stale aggregates in silty soils. Effect of land use. Soil Biol. Biochem. 38, 3222–3234.
Zhang, Y.H., 1986. Investigation Report on Agricultural Resources and Agricultural Regionalization in Huanglong, Shaanxi. Fuxian Press, Fuxian, Shanxi.