Isotope Analysis Reveals Differential Impacts of Artificial and Natural Afforestation on Soil Organic Carbon Dynamics in Abandoned Farmland

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Abstract:

Backgrounds A multitude of studies have applied different methods to study the dynamics of soil organic carbon (SOC), but the differential impact of artificial and natural vegetation restoration on SOC dynamics are still poorly understood.

Methods and aims We investigated the SOC dynamics following artificial and natural
afforestation in Loess Plateau of China, characterizing soil structure and stoichiometry using stable isotope carbon and radiocarbon models. We aim to compare SOC dynamics under both natural and artificial afforestation and examine how soil aggregate size classes control SOC dynamics based on stoichiometry and soil respiration.

Results Total top soil SOC stocks, C:N and C:P of differently sized soil aggregates significantly increased following vegetation restoration. $^{13}$C results and Radiocarbon models indicated that the SOC decomposition rate and new SOC input rate were lower under natural afforestation than artificial afforestation and revealed the highest SOC decomposition rate under natural afforestation compared to other two ecosystems.

Conclusions Vegetation restorations can accumulate SOC in top soils. Soil aggregates alternately play a dominant role in SOC accumulation following vegetation restoration; SOC loss from soil respiration was derived from microaggregates during afforestation. Recovery time is a key factor for the accumulation of SOC following afforestation.

Keywords: soil carbon stock; vegetation restoration; soil aggregate; soil respiration; $^{13}$C; $^{14}$C
1. Introduction

Soil contains vast and dynamic pools of organic carbon that are fundamental for maintaining the balance of atmospheric CO$_2$ concentrations (Lal 2004; Post et al. 1982). The soil organic carbon (SOC) pool and its dynamics are important properties of ecosystems (Schmidt et al. 2011). A multitude of studies report ecosystem changes significantly affect SOC pool and decomposition rate (Deng et al. 2016; Don et al. 2011; Snell et al. 2015; Wei et al. 2013; Zhang et al. 2015).

The Loess Plateau is the one of the largest geographic units in China. Rapid population growth combining with climate and environmental conditions in the area have resulted in severe soil erosion in the Loess Plateau (Shi et al. 2017). The Grain for Green project was implemented in 1999 to halt soil erosion and promote ecological restoration in the region. As part of this project, both natural and artificial afforestation have been promoted as methods of ecological restoration (Shi et al. 2011).

Human ecosystem interventions such as deforestation and afforestation, can cause rapid and persistent changes in vegetation and soil. Wei et al. (2013) found SOC stocks decreased most rapidly during the first 4 years of cropland cultivation after deforesting, but Rytter (2016) reported that SOC pools were generally unchanged after five years of Salicaceae growth during afforestation of former agricultural land. Natural change refers to the dynamic nature of ecosystem succession. Studies indicate that natural regeneration is slow and patchy with low species diversity (Blackham et al. 2014), and factors controlling SOC accumulation differed along vegetation
succession (Liu et al. 2015).

Previous studies have applied different methods (e.g. space-for-time substitution, stable isotope analysis) to study SOC dynamics and have successfully answered questions related to soil structure and organic matter dynamics (Marin-Spiotta et al. 2009; Qiu et al. 2015). However, these previous studies mainly focused on natural ecosystem restoration, without considering the effects of artificial restoration. Furthermore, although Deng et al. (2016) have investigated the SOC turnover during natural succession, SOC dynamics in stable post-succession communities (climax community) following afforestation remain unstudied.

In this study, we combined (1) a radiocarbon ($^{14}$C) model to estimate SOC decomposition rates in climax stage or long-term unchanged stage; (2) a natural abundance stable carbon isotope ($^{13}$C) study to quantify old and new carbon turnover during both natural and artificial restoration; (3) measures of change of soil aggregate-associated ecological stoichiometry to investigate the sensitivity and efficiency of soil aggregate-associated organic carbon; and (4) long-term field monitoring of soil respiration to assess SOC loss. We aim to compare SOC dynamics under both natural and artificial afforestation and examine how soil aggregate size classes control SOC dynamics based on stoichiometry and soil respiration.

2. Materials and methods

2.1. Study site

The study site consisted of semi-arid forests located on Mt. Gonglushan, near Yan’an
city in Shaanxi province, China (36°25.40′N, 109°31.53′E; 1245-1395m a.s.l.). On
the Loess Plateau, precipitation and forest cover gradually decrease to the northwest,
and our study site is located in the forest–grassland transition zone (Shi et al.
2014). The 40-year averages (1971-2010) of annual precipitation and annual mean air
temperature were 504.7 mm and 10.1 °C, respectively (Shi et al. 2012a). The soils are
classified as Calcic Cambisols, which are derived from silt textured loess parent
materials (Wei et al. 2013).

2.2. Field investigation and sampling

We obtained estimates of the recovery periods of different communities from
vegetation surveys from the 1950s to the early 2000s (Chen 1954; Fan et al. 2006;
Zou et al. 2001) and records from local farmers and government (Tateno et al. 2007;
Wang et al. 2010). These results have been accepted and used widely (Deng et al.
2013; Deng et al. 2016; Qiu et al. 2015). The study examined two different types of
vegetation restoration: natural vegetation restoration from abandoned farmland to
natural forest dominated by *Quercus liaotungensis* Koidz (80 years) and artificial
restoration from abandoned farmland to plantation dominated by *Robinia
pseudoacacia* L. (40 years). We compared these restoration types to a control site of
abandoned farmland that remained unforested. The three ecosystems were at least
3km apart. To minimize the effects of area conditions on experimental results, we
selected study areas with similar topography, land-use history, and soil type. Five 20
m×20 m plots were established within each ecosystem in April 2010. Each plot was at
least 40 m from ecosystem boundary to minimize edge effects. Plots were spaced
approximately 50 m apart in each ecosystem.

In each plot, the litter on the ground was first removed and collected for measurement. We then dug a 20 cm-deep pit in center of the plot and took three soil bulk density (BD) samples. BD was measured at 0-20 cm in each subplot using a stainless steel cutting ring (5×5 cm). The soil cores were dried at 105°C for 24h.

Five soil samples (0-20 cm) were collected from the four corners and the center of each plot, and the collected samples were mixed to form one homogeneous sample for analysis of δ13C, 14C, and aggregate size distribution. Three aggregate-size classes were manually fractionated through dry sieving of fresh soil samples on a series of two sieves (0.25 and 0.053mm) as follows: macroaggregates (>0.25mm), microaggregates (0.25-0.053mm) and silt & clay (<0.053mm). Fresh soil samples were dry sieved because wet sieving compromised the *in situ* link between the aggregates obtained and their indigenous biota. Furthermore, wet sieving could cause inaccurate evaluation of soil organic carbon (Jiang et al. 2014). The subsamples of each aggregate fraction were used for soil organic carbon (SOC), total nitrogen (N), and total phosphorous (P) analysis. Each aggregate fraction was oven dried at 100°C and weighed to determine its proportion of total soil weight.

2.3. Laboratory analysis

Soil organic carbon (SOC), total nitrogen (N), and total phosphorous (P) were measured using a TOC VWP (Shimadzu, Japan), 2300 kjeltec analyzer unit (FOSS TECATOR, Sweden), and ICP-AES (Spectro, Analytical Instruments, Germany), respectively. Soil organic carbon stock was calculated as the product of soil bulk
density and SOC concentration.

Soil samples for $\delta^{13}$C analyses were pretreated with excess 1mol L$^{-1}$HCl to remove carbonates at room temperature, then rinsed and freeze dried for at least 24 h and ground into fine powder over 100$\mu$m meshes. Litters was washed with distilled water, then freeze-dried and ground into fine powder for measurement. The natural abundance of $\delta^{13}$C values in the soil organic matter and litter was analyzed with an Elemental Analyser (Eurovector) coupled to an isotope Ratio Mass Spectrometer (Delta plus, Thermo Fisher Scientific, USA) at the State key laboratory of Loess and Quaternary Geology at the Institute of Earth Environment, Chinese Academy of Sciences. Variation in the $^{13}$C/$^{12}$C was reported relative to the Vienna PDB standard, and is expressed as:

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

Where $R_{\text{sample}}$ is the $^{13}$C/$^{12}$C ratio of the sample and $R_{\text{standard}}$ is the $^{13}$C/$^{12}$C ratio in the PDB standard.

The soil samples were pretreated for $^{14}$C analyses as follows. First, the soil samples were soaked in deionized water overnight, and then transferred to an ultrasonic bath for 30 min for completely disintegration and homogenization. The wet samples were sieved using a 180$\mu$m mesh to remove root fragments. Then, 1mol L$^{-1}$HCl was added to the samples, and they were placed in a water bath at 70°C for 2 hours to remove carbonates. The samples were then rinsed repeatedly until neutral, then dried overnight in an electric oven at 60°C. Finally, the desiccated samples were transferred into glass vials and sealed tightly for subsequent combustion and
graphitization (Zhou et al. 1992). Measurement of $^{14}$C in soil organic matter was
carried out at the Xi’an Accelerator Mass Spectrometry Center in the Institute of Earth
Environment, Chinese Academy of Science. Cryogenically purified CO$_2$ was
converted to the target using the hydrogen-iron reduction method. This method was
described in detail by Zhu et al. (2010).

2.4. Measurement of soil respiration

Soil respiration was measured using an automated soil CO$_2$ flux system (LI-8100,
LI-COR, USA) equipped with a portable chamber (Model 8100-103). A PVC collar
(20.3 cm in diameter and 10 cm in height) was inserted into the forest floor to a depth
of 2.5 cm at each sampling point, approximately two months before the first
measurements. Small litter and branches were left in the collar while large items were
removed. All collars were left at the respective site for the entirety of the study period.

Soil respiration was measured over the 4-year period from 14 June 2010 to
20 June 2014, approximately once every 30 days during April-October (growing
season), and once every 45 days in other months (dormant season). The measurements
were conducted between 8:30 and 11:30 local time on each sampling day. In each plot,
five 5 m×5 m subplots were established at the four corners and the center. The PVC
collars were installed in the center of each subplot for measurements of soil CO$_2$
efflux.

2.5. Data analysis
Soil OC stocks were calculated as follow:

\[
\text{Soil } OC \text{ stocks (kg m}^{-2}\text{)} = \frac{D \times BD \times OC}{100}
\]  

(2)

Where D is the thinness (cm) of the soil layer, BD is the bulk density (g cm\(^{-3}\)), and OC is the soil organic carbon concentrate (g kg\(^{-1}\)) at 0-20 cm.

Stocks of soil OC in each soil aggregate size class were calculated as:

\[
\text{Stocks of } OC_i (kg m}^{-2}\text{)} = \frac{D \times BD \times w_i \times OC_i}{10000}
\]  

(3)

Where \(OC_i\) is the soil organic carbon concentration of the \(i\)th aggregate size class (g kg\(^{-1}\) aggregate).

During the afforestation period, the decomposition rate constants \(k_1\)(yr\(^{-1}\)) was calculated by these models based on \(\delta^{13}\)C method: The proportions of new SOC (\(f_{\text{new}}\)) and old SOC (\(f_{\text{old}}\)) were estimated based on the mass balance equations (Del Galdo et al. 2003):

\[
f_{\text{new}} = \frac{(\delta_{\text{new}} - \delta_{\text{old}}) \times 100\%}{\delta_{\text{veg}} - \delta_{\text{old}}}
\]  

(4)

\[
f_{\text{old}} = 100 - f_{\text{new}}
\]  

(5)

where \(\delta_{\text{new}}\) is the \(\delta^{13}\)C value of the soil sample from current ecosystem, \(\delta_{\text{old}}\) is the \(\delta^{13}\)C value of the soil sample prior to ecosystem succession and \(\delta_{\text{veg}}\) is the \(\delta^{13}\)C value of the mixed litter of current vegetation. Decomposition rate constants \((k_1)\) of soil OC were estimated using the following equations(Marin-Spiotta et al. 2009):

\[
k_1 = \frac{-\ln (C_i/C_0)}{t}
\]  

(6)

Where \(C_0\) is the initial SOC stock (SOC stock in the reference sites), \(C_i\) is initial SOC stock remaining (old C stock) at time t (year) since ecosystem change.
For the long-term or unchanged ecosystem, the decomposition rate constants $k_2$ (yr$^{-1}$) was obtained through the bomb-$^{14}$C model (Cherkinsky and Brovkin 1993; Torn et al. 2002; Trumbore 1993). The procedures were as follows (Tan et al. 2013):

$^{14}$C data (pMC) is defined as

$$
\text{pMC} = \frac{A_{SN}}{A_{ON} \times e^{\lambda(y-1950)}} \times 100
$$

(7)

where $A_{SN}$ is the $^{14}$C/$^{12}$C ratio of the sample corrected to a $\delta^{13}$C value of $-25\%$ to account for the assumption that plants discriminate twice as much against $^{14}$C as they do against $^{13}$C, $A_{ON}$ is the $^{14}$C/$^{12}$C ratio of the oxalic acid activity normalized to $\delta^{13}$C value of $-19\%$, $\lambda = 1/8267$ is based on the 5730 a half-life, and (y) is the year of Oxalic measurement.

The SOC turnover times were estimated using a time dependent steady-state box model. This assumes that variation in $^{14}$C in a soil with time follows a first-order kinetic law, which can be described by mass balance equation:

$$
C_y \times ^{14}C_y = C_{y-1} \times ^{14}C_{y-1} \times (1 - k_2 \cdot \lambda) + I \times ^{14}C_{atm_{y-lag}}
$$

(8)

where $C$ is the organic carbon inventory of a soil sample (g C m$^{-2}$), $^{14}$C is the pMC of a soil sample (%), $k$ is the first order decomposition constant for homogeneous C pools (a$^{-1}$), $\lambda$ is the $^{14}$C decay constant (1/8267), $I$ is the annual carbon input (g C m$^{-2}$ a$^{-1}$), $^{14}C_{atm}$ is the pMC of the atmosphere CO$_2$ (%), lag is the average number of years that atmospheric CO$_2$ is retained in plant tissue before becoming part of the soil organic matter pool. At steady state, $C_y = C_{y-1}$ and $I = kC$, eq. (7) can be transformed into:

$$^{14}C_y = ^{14}C_{atm_{y-lag}} \times k_2 + ^{14}C_{y-1} \times (1 - k_2 \cdot \lambda)
$$

(9)
The decomposition rate constant $k_2$ is obtained by matching the modeled and measured $pMC$ for the year in which the soil was sampled based on $^{14}C_{atm}$ adopt from curve of $^{14}C$ of atmospheric CO$_2$.

A method was proposed by Qiu et al. (2012) for assessing the relative contribution of changes in aggregate amount and aggregate-associated OC concentrations to the total changes in OC stocks within each aggregate fraction. It was assumed that changes in OC stock within any particular aggregate fraction were caused both by changes in OC concentration in the fraction ($F_1$) and by changes in the mass of the fraction ($F_2$). It was also assumed that the mass that was gained or lost from an aggregate fraction due to ecosystem change had the same OC concentration as the rest of that fraction after ecosystem change. We therefore calculated the contribution of $F_1$ and $F_2$ to the total change in OC stock within an aggregate fraction as follows:

$$F_1 = M \times \Delta C$$

$$F_2 = \Delta M \times C$$

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, $\Delta M$ 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 ecosystem change, $C$ is the final OC concentration of the aggregate fraction (g kg$^{-1}$) after ecosystem change and $\Delta C$ is the change in the OC concentration of the aggregate fraction (g kg$^{-1}$) due to ecosystem
change.

2.6. Calculation of Annual soil CO$_2$ emissions

Annual soil CO$_2$ emissions were estimated by interpolating the average CO$_2$ flux rate between sampling dates, and computing the sum of the products of the average flux rate and the time between respective sampling dates for each measurement period (Shi et al. 2014; Shi et al. 2012b; Sims and Bradford 2001) as follows:

$$ R = \sum F_{m,n} \Delta t_n $$ (13)

Where $\Delta t_n = t_{n+1} - t_n$, which is the number of days between each field measurement within the year; $R$ is total soil CO$_2$ emitted in the measurement period, and $F_{m,n}$ is the average CO$_2$ flux rate over the interval $t_{n+1} - t_n$ recorded by the LI-8100 Soil CO$_2$ Flux System.

2.7 Statistical analyses

One-way Analysis of Variation (ANOVA) with Pearson’s test was performed to examine the difference between abandoned farmland and artificial afforestation or abandoned farmland and natural afforestation in OC stocks of total soil and different soil aggregate size classes, soil aggregate size class distributions, C:N and C:P of different soil aggregate size classes, mean annual soil CO$_2$ emission. ANOVA also was applied to examine the different between period of artificial and natural afforestation in SOC decomposition rate constants ($k_1$) and new SOC input rate calculated with a $^{13}$C model. Repeated measures ANOVA (RMANOVA) was applied to test the significance of SOC decomposition rate constants ($k_2$) calculated with a $^{14}$C model among the three land use types using Tukeys’s HSD test at $p<0.05$. All
3. Results

3.1. Total and size class aggregate OC stocks

Fig. 1 shows the change of total and different aggregate size OC stocks. Total OC stocks in top soil (0-20 cm) significantly increased with both artificial afforestation dominated by plantation of *Robinia pseudoacacia* L (AR) and natural afforestation dominated by natural forest *Quercus liaotungensis* Koidz (NQ). Nevertheless, OC sequestration following artificial afforestation was significant lower than for natural afforestation. Under both artificial and natural afforestation, the OC stocks of macroaggregates and microaggregates significantly increased, but the OC stocks of silt & clay were nearly 0 (far lower than for any other fraction), and could thus be considered a negligible part of total OC stocks (Fig 1). The OC stock of macroaggregates was significant higher than that of microaggregate in AR (Fig. 1a), but the OC stock of macroaggregate and microaggregate were nearly the same in NQ (Fig. 1b).

3.2. Aggregate size distribution and C:N & C:P in different size aggregates

Macroaggregates and microaggregates accounted for approximate 99% of the dry soil weight in the abandoned farmland. Under both artificial and natural restoration, the amount of soil in macroaggregates significantly increased, and microaggregates significantly decreased (Fig 2). Furthermore, for both types of restorations, the amount of soils in silt & clay was less than 1% and did not
Both C:N and C:P of different aggregate classes significantly increased with both types of vegetation restoration. Compared with other size aggregates, C:N and C:P of microaggregates become higher after restoration (Fig 3).

3.3. Turnover of SOC under artificial and natural afforestation

Over the vegetation restoration period, the SOC decomposition rate ($k_1$), and new SOC input rate under artificial restoration were higher than natural restoration (Fig 4). For climax or long-term unchanged stage, the SOC decomposition rate ($k_2$) was highest ($2.6 \times 10^{-3}$) in the natural forest ecosystem (*Quercus liaotungensis* Koidz). The $k_2$ of abandoned farmland and plantation (*Robinia pseudoacacia* L.) were similar (Fig 5).

3.4. Amount of soil CO$_2$ emissions

The amount of soil CO$_2$ emissions across ecosystems was calculated from continuous measurements over 4 years. Both natural and artificial restoration significantly increased the amount of soil CO$_2$ emissions, and the increased of amount of soil CO$_2$ emissions was higher under natural restoration than artificial restoration (Fig 6).

4. Discussion

A multitude of studies found that vegetation restoration can lead to the accumulation of SOC, and the effects of land use change during vegetation restoration on soil OC are mainly due to changes in OC input and C mineralization (Deng et al.
The OC in soil physical fractions responds more sensitively and rapidly to land use change than the OC in bulk soils (Qiu et al. 2012; Wei et al. 2013); therefore, changes in aggregate-associated OC are regarded as fundamental processes for understanding the effects of vegetation restoration on SOC.

In this study, we also found that both types of restorations could accumulate SOC in top soil (Fig 1). Our study showed that changes in $F_1$ & $F_2$ under artificial and natural restoration were nearly the same, and $F_1$ and $F_2$ significantly increased and decreased respectively, for macroaggregate-OC after afforestation, but changes in $F_1$ & $F_2$ for macroaggregate-OC were more significant under natural afforestation (Fig 7 a, b). In addition, $F_1$ significantly increased and $F_2$ slightly decreased for microaggregate-OC (Fig 7 c, d).

The model results indicated that increases in SOC stocks in macroaggregates and microaggregates under artificial and natural afforestation were mainly due to increases in SOC concentration rather than mass (Fig 7). The contribution of macroaggregate-OC concentration increases under natural afforestation was more significant than under artificial, but microaggregate-OC changes under natural and artificial afforestation were similar. Therefore, we concluded that macroaggregate-OC stock is the main contributing factor to changes in total OC stock. Qiu et al. (2015) obtained a similar result. Nevertheless, under artificial afforestation we found that OC stocks in macroaggregates and microaggregates equally contributed to the dynamics of total OC stocks.

Meanwhile, we found that soil respiration was the main pathway of soil OC loss.
We found that long-term soil CO$_2$ emission during afforestation promoted SOC loss via soil respiration. Spohn and Chodak (2015) demonstrated that microorganisms increase their respiration rate with an increase in soil C/P ratio and C concentration. In this study, we found that C/N and C/P ratios in microaggregates were consistently higher than in other fractions under afforestation (Fig 3). Therefore, it was concluded that SOC loss from soil respiration was mainly originated from microaggregate resulting from higher C/P ratio after afforestation, supporting the previous inference in terms of relationship between ecological stoichiometry and soil respiration.

Moreover, although our study found higher SOC accumulation under natural afforestation than under artificial afforestation (Fig 1), and the increase in proportion of new OC in soils could be attributed to the OC inputs from the recent afforestation, which produced organic matter with different $^{13}$C/$^{12}$C ratios (Marin-Spiotta et al. 2009), based on analysis of $^{13}$C we found old C decomposition and new C inputs during natural afforestation were significantly lower than during artificial afforestation (Fig 4). Previous studies focused on the process of old C decomposition and new C input: Zhang et al. (2015) proposed the relationship between SOC decomposition and new & old litter input, and Richter et al. (1999) reported that the rates of new soil OC increase represented the net effect of new OC input and output to soil. However, time since land use change has not been considered as a key parameter for the accumulation of SOC. In this study, the period of natural afforestation was twice as long as the period of artificial afforestation. Though the new SOC input rate under natural afforestation was lower compared to artificial afforestation, the
decomposition rate under natural afforestation was also lower, which may indicate higher SOC accumulation under natural afforestation is not attributable only to higher net increases in the difference between new SOC input and old SOC decomposition. We could conclude that time since land use change is a more important factor determining the proportions of new and old OC in soil. Previous studies lend support to this hypothesis (Deng et al. 2016; Marin-Spiotta et al. 2009)

Not only climax forest but also other types of ecosystems in semiarid or arid region often maintain in stable stage for a long time (Fan et al. 2006) and the dynamics of SOC in the ecosystem could be considered as an ecosystem property (Schmidt et al. 2011). $^{14}$C dating has been proven to be an ideal tool to study the dynamics of SOC from decadal to millennial timescales, which provides a direct measure of the time elapsed since carbon in organic matter was fixed from the atmosphere (Trumbore 1993). In this study, the steady-state box model of $^{14}$C of SOC was applied to estimate the mean residence time (MRT) of SOC for the long-term or unchanged ecosystem, providing a sensitive indicator to quantify the proportion of SOC derived from the atmosphere in recent years to centuries based on the rate of incorporation of the nuclear explosion before 1960s carbon tracer (Laskar et al. 2016; Torn et al. 2009). In our study, the result of the $^{14}$C model suggested that the carbon decomposition rate was the lowest in the plantation (*Robinia pseudoacacia* L.) ecosystem, and was the same as abandoned farmland. The carbon turnover was highest in the natural forest ecosystem (*Quercus liaotungensis* Koidz) (Fig 5). The model provided a direct evidence that higher accumulation of SOC under natural
afforestation can be attributed to its longer restoration period rather than more rapid carbon turnover under natural afforestation compared to artificial afforestation. Therefore, our study suggests that longer restoration time could be more important for SOC accumulation following afforestation than any particular method of afforestation.

5. Conclusions

In conclusion, we found that both artificial and natural afforestation promoted the accumulation of SOC in top soil, and accumulation of SOC under natural afforestation was higher than under artificial afforestation. The SOC concentration of soil aggregates played a dominant role in determining the dynamics of SOC accumulation following vegetation restoration. According to analysis of soil aggregates, soil respiration, and aggregate stoichiometry, we concluded that SOC loss from soil respiration mainly originated from microaggregates during restoration. $^{13}\text{C}$ and $^{14}\text{C}$ models proved effective tools that showed that recovery time is a key factor determining the accumulation of SOC following afforestation.

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Figure captions

Fig 1 Changes in OC stocks of total soil and different soil aggregate size classes under (a) artificial and (b) natural afforestation. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).

Fig 2 Changes in soil aggregate size class distributions with afforestation under (a) artificial and (b) natural restoration. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).

Fig 3 Changes in C:N and C:P of different soil aggregate size classes with afforestation under (a-b) artificial and (c-d) natural restoration. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AF:
abandoned farmland; AR: artificial afforestation (plantation of *Robinia pseudoacacia* L); NQ: natural afforestation (natural forest - *Quercus liaotungensis* Koidz).

Fig 4 SOC decomposition rate constants \(k_1\) and new SOC input rate (kg m\(^{-2}\) yr\(^{-1}\)) calculated with a \(^{13}\)C model under (a) artificial and (b) natural afforestation. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*\(p < 0.05\)).

Fig 5 SOC decomposition rate constants \(k_2\) calculated with a \(^{14}\)C model for different land use types. Error bars represent the standard error of the mean. Significant differences are indicated by different letters (\(p < 0.05\)). AF: abandoned farmland; AR: artificial afforestation (plantation of *Robinia pseudoacacia* L); NQ: natural afforestation (natural forest - *Quercus liaotungensis* Koidz).

Fig 6 Changes in mean annual soil CO\(_2\) emission over 4 years of vegetation restoration under (a) artificial and (b) natural afforestation. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*\(p < 0.05\)); ns: no significant; AR: artificial afforestation (plantation of *Robinia pseudoacacia* L); NQ: natural afforestation (natural forest - *Quercus liaotungensis* Koidz).

Fig 7 Changes in SOC stocks in macroaggregates and microaggregates with
Afforestation under (a-b) artificial and (c-d) natural restoration. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05). AF: abandoned farmland; AR: artificial afforestation (plantation of *Robinia pseudoacacia* L); NQ: natural afforestation (natural forest - *Quercus liaotungensis* Koidz).
Changes in OC stocks of total soil and different soil aggregate size classes under (a) artificial and (b) natural afforestation. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).
Figure 2

Changes in soil aggregate size class distributions with afforestation under (a) artificial and (b) natural restoration. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).
Figure 3

Changes in C:N and C:P of different soil aggregate size classes with afforestation under (a-b) artificial and (c-d) natural restoration. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).
Figure 4

SOC decomposition rate constants ($k_1$) and new SOC input rate (kg m$^{-2}$ yr$^{-1}$) calculated with a 13C model under (a) artificial and (b) natural afforestation. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05).
Figure 5

SOC decomposition rate constants (k2) calculated with a 14C model for different land use types. Error bars represent the standard error of the mean. Significant differences are indicated by different letters (p < 0.05). AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).
Figure 6

Changes in mean annual soil CO2 emission over 4 years of vegetation restoration under (a) artificial and (b) natural afforestation. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05); ns: no significant; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).
Figure 7

Changes in SOC stocks in macroaggregates and microaggregates with afforestation under (a-b) artificial and (c-d) natural restoration. Macroaggregates were >0.25 mm; microaggregates were between 0.25 and 0.053 mm; and silt & clay were <0.053 mm. Error bars represent the standard error of the mean. Significant differences are indicated by the asterisk symbol (*p < 0.05). AF: abandoned farmland; AR: artificial afforestation (plantation of Robinia pseudoacacia L); NQ: natural afforestation (natural forest - Quercus liaotungensis Koidz).