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Soil organic carbon dynamics following afforestation in the Loess Plateau of China

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Abstract

Soil organic carbon (SOC) is the largest terrestrial carbon pool and sensitive to land use and cover change; its dynamics is critical for carbon cycling in terrestrial ecosystems and the atmosphere. In this study, we combined a modeling approach and field measurements to examine the temporal dynamics of SOC following afforestation of former arable land at six sites under different climatic conditions in the Loess Plateau during 1980–2010. The results showed that the measured mean SOC increased to levels higher than before afforestation when taking the last measurements (i.e., at age 25 to 30 yr), although it decreased in the first few years at the wetter sites. The accumulation rates of SOC were 1.58 to 6.22 % yr^{-1} in the upper 20 cm and 1.62 to 5.15 % yr^{-1} in the upper 40 cm of soil. The simulations reproduced the basic characteristics of measured SOC dynamics, suggesting that litter input and climatic factors (temperature and precipitation) were the major causes for SOC dynamics and the differences among the sites. They explained 88–96, 48–86 and 57–74 % of the variations in annual SOC changes at the soil depths of 0–20, 0–40, and 0–100 cm, respectively. Notably, the simulated SOC decreased during the first few years at all the sites, although the magnitudes of decreases were small at the drier sites. This suggested that the modeling may be advantageous in capturing SOC changes at finer time scale. The discrepancy between the simulation and measurement was a result of uncertainties in model structure, data input, and sampling design. Our findings indicated that afforestation promoted soil carbon sequestration at the study sites, which is favorable for further restoration of the vegetation and environment. Afforestation activities should decrease soil disturbances to reduce carbon release in the early stage. The long-term strategy for carbon fixation capability of the plantations should also consider the climate and site conditions, species adaptability, and successional stage of recovery.

BGD
10, 11181–11211, 2013

1 Introduction

Soil organic carbon (SOC) is the largest terrestrial carbon pool. A slight change in SOC may greatly influence ecosystem carbon cycling and atmosphere CO_2 concentration (Davidson and Janssens, 2006). SOC stock is sensitive to land use and cover change (Guo and Gifford, 2002; Wiesmeier et al., 2012), which alter both carbon inputs (amount and quality of litter mass) and losses (decomposition and mineralization).

In recent decades, human disturbances, such as deforestation, urbanization and afforestation, have caused extensive changes in land use and cover globally. The large-scale changes in terrestrial ecosystems have caused great concern about the temporal dynamics of energy and mass flows during ecosystem succession or recovery (Breña Naranjo et al., 2011). To date, soil carbon dynamics following disturbances have not been well documented, especially for the later phases of succession (Foote and Grogan, 2010).

The Loess Plateau is the largest continuous area of loess in the world (about 70 % of global loess distribution) covering an area of 640 000 km^2. It was well-known for its severe soil erosion caused by long-term cultivation and destruction of natural vegetation in the long history (Fu, 1989; Shi and Shao, 2000). Since the 1970s, a series of ecological restoration projects have been implemented in the Loess Plateau, such as the soil-water conservation projects and the Grain for Green (GfG) project. Soil erosion decreased significantly after the implementation of these ecological restoration projects (Fu et al., 2011). Currently, the main ecological problems in this area have turned from erosion control to ecosystem recovery and coordination between water and vegetation development especially in the dry areas. Accurate estimates of carbon sequestration and prediction of their future carbon fixation capacity (mitigation potential to climate change) are among the most important aspects for evaluation of the ecological and social effects of these restoration projects.

Stand age and climate are two important factors closely related to the changes in soil carbon stock of forest ecosystem (Peltoniemi et al., 2004). Soil carbon estimates may lead to a large bias if stand age is considered as a static variable. However, in-depth understanding of the temporal changes of SOC and its controlling mechanisms with stand age is still lacking (Stockman et al., 2011). In the Loess Plateau, many studies have quantified and evaluated SOC stock and the variation caused by land use and cover change (Fu et al., 2010; Han et al., 2010; Liu et al., 2012), but most of them focused on comparing SOC differences among various land use types or its static spatial heterogeneity. In addition, since the area of the Loess Plateau ranges over a precipitation gradient of 200–800 mm (Fig. 1), the trans-regional comparison of soil carbon dynamics in different climate conditions also needs further investigation for the wide range of afforestation at the regional scale.

Typical methods for estimating soil carbon dynamics include repeated field surveys, paired sites, chronosequence (or "space for time substitution"), and modeling. SOC estimate from direct measurement is most accurate but usually suffers from long time interval of repetition (e.g., 5–10 yr) due to limitations of time and labor. Chronosequence is advantageous for getting the measurements of varied stand ages in a relatively short time, but it is often difficult to find continuous series of stand ages in reality, and therefore a chronosequence can provide only a few points of time for the temporal sequences (Mäkipää et al., 2012). Modeling is an effective alternative or complement to repeated field surveys in studying soil carbon change following disturbance (FAO report 2004; Palosuo, 2008; Oelbermann and Voroney, 2011), but model parameterization and validation are indispensable of field measurements.

In this study, we estimated the SOC stock and changes following afforestation in the Loess Plateau by using the Yasso07 model integrated with chronosequence field investigations. The central aim of this study was to examine the temporal dynamics of SOC and factors controlling these dynamics after afforestation at site scale during 1980–2010. The specific objectives were to: (1) Quantify SOC stock and changes following afforestation at six sites with different climatic conditions. (2) Examine the factors and processes that affected SOC dynamics and their differences among sites. (3) Evaluate the performance of the Yasso07 model application in the Loess Plateau.

2 Materials and methods

2.1 Study sites

The six study sites are located in the Shannxi province, which is in the southern to central part of the Loess Plateau (Fig. 1). The soil types are loessal soil with low SOC and clay content and high water permeability. The annual mean temperature (T) ranges from 8.1 to 10.6 °C for the six sites. The annual precipitation (P) is around 600 mm at sites 1 and 2 (refer to wetter sites in this study) and 450–500 mm at sites 3, 4, 5 and 6 (refer to drier sites in this study) (Fig. 2). More detailed site information was summarized in Table 1.

2.2 Sampling

The field measurements were taken in July 2009 or 2010 by using the chronosequence approach. At each of the six sites, a series of plots of different-aged black locust (*Robinia pseudoacacia*) plantations, which was the main plantation type in this region, were selected for vegetation and soil investigations (Table 1). We tried to select separated age classes and keep minimum differences in stand characteristics, including slope position (upper position) and degree (slight grade). The plot area for the plantations was 20 m × 20 m (or 20 m × 10 m). In each plot, the diameter at breast height (DBH), the number of trees, and the average tree height were measured. One subplot 1 m from the trunk of the standard trees (four trees in one plot) and one or two subplots (1 m × 1 m) in the forest gap(s) were established, respectively. In each subplot, the soil samples were taken from the mineral soil layers at the intervals 0–5, 5–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm along the soil vertical profile using cylindrical cores, with four replicates for each soil layer (Chang et al., 2012a,b). The biomass of forest floor vegetation was harvested for each subplot.

At each site, a cropland plot adjacent to the plantation plots (dozens to hundreds of meters) was established. The soil samples were taken at the same depth intervals as in the plantation plots with four to five replicates for each depth. The species of the croplands were wheat, soybean and millet, and they were planted with the rotation method yearly in recent decades.

2.3 Soil analysis

The fraction of SOC (SOC_i) in a given soil depth was estimated by the potassium-dichromate oxidation method. The total amount of SOC ($Mg\,C\,ha^{-1}$) above a given soil depth (i.e., 20, 40, and 100 cm in our analyses) was estimated as sum of the products of SOC_i, bulk density ($g\,cm^{-3}$) and different soil intervals above that depth. The fine roots (< 2 mm in diameter) were extracted from the soil samples by washing. The biomasses of fine root and forest floor vegetation were weighed after dried at 65 °C to constant. Bulk density was estimated as the ratio of dry soil mass at 105 °C to the volume of cylindrical core. Soil texture was estimated with the laser particle size analyzer (Mastersizer, 2000, Marlven, Ltd. UK). Total soil carbon (TC) and total nitrogen (TN) were analyzed by the dry combustion method with a Vario EL Element Analyzer.

2.4 Model structure

Yasso07 is a dynamic soil carbon model developed from its earlier version Yasso (Liski et al., 2005). The model consists of five decomposition components and two litter components of woody and non-woody litters (Fig. 3). It calculated SOC stock and its probability density based on litter input (quantity and chemical quality of litter, and their standard deviations (SD)) and climate (P, T and temperature amplitude). It is assumed that decomposition rate is determined by climate and quality of litter (including soluble in ethanol (E) or water (W), hydrolysable in acid (A), and neither soluble nor hydrolysable (N)) (Tuomi et al., 2011). Information about the model parameterization and main equations can be found in literatures (Peltoniemi et al., 2007; Karhu et al., 2011; Thum et al., 2011).

BGD
10, 11181–11211, 2013

2.5 Model input data

We chose four nearest stations to the study sites for climate input to the model (Fig. 1, Table 1). The initial litter input of each site was estimated based on the annual crop yield (4000–5000 kg ha^{-1}), harvest index and crop water content (Fang et al., 2007). It was assumed that the SOC level of the plantation in the beginning of afforestation was the same to the corresponding cropland at each site. The annual carbon inputs were estimated based on biomass estimation and turnover rates. Biomass of stem, bark, branch, leaf, and coarse roots were estimated individually using specific empirical models with DBH (Tian et al., 1997). The biomass of fine root and forest floor vegetation were directly measured from the field samples. The estimated and measured biomass components were converted to carbon mass by multiplying by 0.5 and extrapolated to stand scale by area conversion and multiplying by the stand tree density. We assumed that the litter biomass of each component and the total changed linearly from 1980 to 2010 (Figs. 4 and 5), and the changes of total biomass input to different soil layers were dependent on the changes of fine root biomass.

2.6 Model simulations

The model was operated for the soil depths 0–20 cm, 0–40 cm, and 0–100 cm from 1975 to 2010 on an annual basis. In the model simulations, woody litter and non-woody litter were summed and input to the mode as two data lines for each time step. When initializing the model, we assumed that the SOC was at steady state with the litter inputs from the crops. The model was run for five years before afforestation (i.e., 1975–1980), during which time the litter inputs were adjusted to make the simulated SOC equal to the measured SOC values of the croplands.

The SD values of turnover rates for each litter type were obtained by the Monte Carlo method. Since the turnover rate was highly varied and uncertain, we set the low and high values to be 0.5 and 1.5 times the average values, respectively (Zhai et al., 2002; Peltoniemi et al., 2004; Liski et al., 2006). The SD values for other litter components estimated using the DBH-biomass functions were obtained by multiplying the estimated litter mass by the coefficients of variation (0.2). The values of EWAN fractions were taken or calculated based on the literature (Adamopoulos et al., 2005; Jensen et al., 2005; Wang et al., 2011).

2.7 Statistical analysis

The ANOVA and the Repeated Measures ANOVA analyses were conducted to test the differences in the initial SOC stocks and SOC changes since afforestation among sites, respectively. To predict annual litter production based on the biomass estimations of the measured discontinuous-aged plantation plots, the linear regression analysis was conducted to estimate the annual biomass at each site. The general linear model (GLM) was used to examine the effects of climate factors and litter input in explaining the interannual dynamics of SOC changes after afforestation. And the Pearson correlation analysis was used to test the correlations between the model residuals and soil property parameters and plantation age to reveal the potential systematic deficiencies of the model. The statistical analyses were conducted by using the Statistical Analysis System (SAS 9.0).

3 Results

3.1 Measured SOC stock and dynamics

The initial SOC stocks were significantly higher at the wetter (1 and 2) than the drier (3, 4, 5, and 6) sites ($p < 0.01$) (Figs. 6–8). The means of the 0–20, 0–40, and 0–100 cm soil layers were respectively 16.7, 27.0, and 38.3 Mg C ha^{-1} at the wetter sites, and 6.8, 10.9, and 16.1 Mg C ha^{-1} at the drier sites.

After afforestation, the SOC stocks were also significantly higher at the wetter than the drier sites in each of the three soil layers ($p < 0.01$) (Figs. 6–8). The stock was a little smaller at site 1 than site 2 ($p < 0.05$), but there were no significant differences between the drier sites 3, 4, 5, and 6 ($p > 0.05$). The variance estimates of the site-time interaction indicated that the changes in SOC were site specific over time ($p < 0.002$).

The measured mean SOC decreased at the wetter sites (1–2) and remained more or less the same at the drier sites (3–6) during the first few years after afforestation (Figs. 6–8). Thereafter, SOC increased gradually except for the drop-off points at site 4 and 5 at the age of 30 yr. The SOC stock was higher than before afforestation at each site at the time of taking the last measurements.

According to the linear trends fitted to the measurements from 1980 to 2010, the overall rate of SOC accumulation was 0.54, 0.30, 0.39, 0.21, 0.16, and 0.29 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ in the 0–20 cm soil layer of sites 1 to 6, respectively. In the 0–40 cm soil layer, it was 0.79, 0.36, 0.57, 0.17, 0.23, and 0.55 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$. The relative rates of carbon accumulation (i.e., linear trend divided by the initial value, ΔSOC %) were 1.58–6.22 % $\mathrm{yr^{-1}}$ in the 0–20 cm soil layer and 1.62–5.15 % $\mathrm{yr^{-1}}$ in the 0–40 cm layer. The relative rates were higher at the drier than the wetter sites. The rate for 0–100 cm was not calculated because of too few samples.

3.2 Modeled SOC stock and dynamics

The simulations produced the same basic characteristics of SOC dynamics as the measurements. Notably, the simulated SOC decreased during the first few years after afforestation at all the sites although they were small at the drier sites (Figs. 6–8). The SOC reached its minimum value 3 to 8 yr after afforestation. After this, it recovered to the original levels and increased until the end of the simulations. The soils were thus carbon sources for the first 3 to 8 yr after afforestation and turned to carbon sinks thereafter (Fig. 9). The soils of the wetter sites lost more carbon and remained as carbon sources for a longer time after afforestation than the soils of the drier sites did.

In addition to these basic patterns, the simulated changes in SOC were highly variable from year to year (Fig. 9). The annual mean T and annual P accounted for 26–67 %, 19–65 %, 16–57 % variances of annual SOC changes in 0–20 cm, 20–40 cm, and 40–100 cm of soil depths at the six sites, respectively. By including annual T, P, and lit-

BGD
10, 11181–11211, 2013

ter input, the efficiency of the GLM models were improved and they explained 88–96, 48–86 and 57–74 % of variations in SOC changes for 0–20, 20–40 and 40–100 cm of soil depths for the six sites, respectively, noting that annual litter input was correlated with climate variability. The variations of SOC changes were more accounted for by litter input and climate in the upper soil depths, suggesting that some other factors may affect the SOC dynamics in deeper soil depths. In addition, different soil depths have varied contributions to the annual SOC changes in the 0–100 cm depth of soil at all of the six sites, where SOC changes in the 0–20 cm were the major causes (Fig. 9).

3.3 The model performance

The modeled SOC stocks agreed generally well with the measurements of the different soil layers and study sites. The measured SOC means fell mostly within the upper and lower 95 % confidence levels (Figs. 6–8). The model tended to underestimate the SOC stock in deeper soil depths at early ages for the wetter sites and overestimate the SOC stock at late ages for the drier sites. The model residuals (modeled-measured means) of 0–20 and 0–40 cm soil layers over the six sites increased with plantation age, suggesting that the modeling overall overestimated the SOC stocks at old ages (Fig. 10). These discrepancies between the modeled and measured SOC indicated that there were deficiencies or uncertainties from the methods or measurements.

The results of the residual analyses showed that the residuals had no significant correlations with TN, C : N ratio or clay content. However, the residuals were negatively correlated with P/PET ratios (an index of soil moisture) and these trends were statistically significant in the 0–20 and 0–40 cm soil layers (Fig. 10), which suggested that the modeling approach tended to underestimate SOC in wetter soil water conditions.

BGD
10, 11181–11211, 2013

4 Discussion

4.1 Soil carbon dynamics following afforestation

This study estimated the SOC stocks and changes following afforestation at six sites in the Loess Plateau. The results showed that the SOC generally decreased in the first few years, recovering to the original levels and then continued increasing with further growth of the plantation. The time of source-to-sink transition (3–8 yr) and SOC recovery (10–15 yr) were comparable to other studies of SOC dynamics after afforestation (Paul et al., 2002; Poeplau et al., 2011; Li et al., 2012).

A decrease of SOC in the first few years following afforestation has been frequently observed and attributed to decreased litter inputs and increased decomposition rates compared to those prior to afforestation (Paul et al., 2002; Laganiere et al., 2010; Karhu et al., 2011). In some studies where the initial soil carbon stock was very low (2–3 $kg\,C\,m^{-2}$ at 0–10 cm soil depths), SOC was found to linearly increase with time after afforestation (Foote and Grogan, 2010). In our study, the decreases of SOC in the first few years after afforestation were not detected and could be linearly fitted with time based on the field measurements at the drier sites. This may be related to the low initial SOC stocks of the croplands at the drier sites (~ 1.6 $kg\,C\,m^{-2}$ at 0–20 cm). It was also possible that the detailed changes of SOC were concealed by the relatively large age intervals between the plantations. In this aspect, the modeling may be advantageous in capturing small SOC changes at finer temporal scale.

The larger SOC decreases at the wetter than the drier sites in the first a few years may be because the larger initial SOC stock and higher soil water availability caused more intensive biotic activities and higher soil carbon decomposition rates under disturbances at the wetter sites (Jandl et al., 2007), such as land preparation and planting. This indicated that decrease of soil disturbance could help to reduce carbon release in afforestation. Nevertheless, the vegetations have accumulated carbon on average 10.75 at the wetter sites and 8.56 $Mg\,C\,ha^{-1}$ at the drier sites at age of 8 yr, which

BGD
10, 11181–11211, 2013
SOC dynamics following afforestation in the Loess Plateau
N. Lu et al.

compensated the losses of carbon from the soils (4.59 and 3.03 Mg C ha^{-1} in the upper 40 cm).

4.2 SOC accumulation rate

Land use conversions from cropland to tree plantations are regarded as the "most" efficient aggrading systems for soil carbon sequestration (Stockman et al., 2011), although there are also findings of negative or no effects (Laganiere et al., 2010; Wiesmeier et al., 2012). The measured relative rates of carbon accumulation during the study period ranged from 1.58 to 6.22 % yr^{-1} in the upper 20 cm, and 1.62 to 5.15 % yr^{-1} in the upper 40 cm of soil in this study. These values are higher on average than the finding in a meta-study of 1.22 ± 1 % yr^{-1} at soil depths of 30 ± 6 cm for cropland-converted plantations in the first 20 yr (Poeplau et al., 2011). Our results suggest that black locust is relatively efficient in soil carbon sequestration in our study region, which could be partly explained by the N fixation ability of the mycorrhizae in its roots (Geesing et al., 2000).

High precipitation and soil clay content are usually favorable for soil carbon accumulation (Laganiere et al., 2010). Our results do not support this conclusion as the relative accumulation rates (ΔSOC %) were a little lower at the wetter than the drier sites. This may be partly caused by the relatively lower rates of fine root litter input to the soil at the wetter sites (Fig. 5). The relationships between fine root biomass, water availability and fertility were not consistent among species and sites as both positive and negative relations have been reported (Chang et al., 2012b). The negative relationship we found here could be a strategy of the species to adapt to the environment. That is to say, the trees tried to get access to more water and nutrients by growing more fine roots at the drier sites. The effects of fine root dynamics on the changes of SOC needs further studies in the future as it is a critical contributor to total litter input of soil.

BGD
10, 11181–11211, 2013

4.3 Interannual variability in soil carbon change

The annual changes of SOC showed high interannual variability in addition to the general increasing trends following afforestation. This variability has not been examined in our study region because the annual estimates of SOC have not been obtained from previous field inventories. The plantations were free from human activities at our study sites during 1980–2010, and therefore, the SOC dynamics was mainly affected by the variability in climate and litter productions of the plantations (accounted for 87.8–96.0 % of SOC variations in 0–20 cm). Interestingly, the climate was regulating the annual variability of litter productivity and decomposition simultaneously. Warmer temperature and higher precipitation can increase biomass production and decomposition rate at the same time. The trend of carbon accumulation in the soil was the result from all of the combined factors, such as the general increasing trend of litter production and the changing climate in the study period (Figs. 2, 4, 5). In addition, the weaker explanation of annual SOC changes by climate and litter in deeper soil depths indicated that some other processes may affect the SOC dynamics, e.g., the redistribution of SOC along the soil profile by eluviation due to intense rainfall in summer time and high water permeability of the loess soil in the study region.

4.4 Model performance

The simulations reproduced the basic characteristics of SOC dynamics as the measurement. This suggested that the quantity and quality of litter input to the soil and the climatic factors accounted for in the simulations were major causes for the temporal changes in SOC after afforestation and the differences among the sites. Some studies have found that soil N and clay content can greatly influence SOC alteration after land use change (Chapin et al., 2009). However, we did not find significant correlations between soil N or clay content and the model residuals. This may be because black locust is a N-fixing species and N was not the primary limiting factor to soil carbon sequestration in our study region. Soil clay content may be important for SOC stabi-

BGD
10, 11181–11211, 2013

lization at century time scale (Torn et al., 1997; Karhu et al., 2011), and its effect could be negligible in short time period.

Soil water availability is another factor that influences soil carbon stabilization but not included in Yasso07. Although precipitation was included in the model, the model sensitivities may not follow the same patterns when changed by precipitation and soil water (Rantakari et al., 2012). As indicated by Häkinen et al. (2011), the sensitivity of predicted SOC annual changes by Yasso07 may be too high in response to precipitation. And the effects of soil moisture on SOC dynamics remain large uncertainties in the model (Rantakari et al., 2012). Soil water decrease following afforestation has been widely reported in the Loess Plateau due to high evapotranspiration of the plantations exceeding regional rainfall (He et al., 2003; Li et al., 2008). The significant correlations between P/PET ratio with model residuals in 0–20 and 0–40 cm soil depths suggested that soil water availability was an important factor for SOC sequestration in the upper 40 cm soil. The drop-off points of SOC measurements at older ages at the drier sites may be partially accounted for by the decreased ecosystem productivity due to water limitation (Eamus, 2003). Model validation tests against long-term soil carbon monitoring and direct soil water measurements along the vertical soil profile will be useful in further studies.

4.5 Uncertainties of the study

The major uncertainties of the study include four aspects. First, the use of SOC in croplands measured in recent years (2009 or 2010) as the initial soil carbon stock may bring errors since it could have changed at the time of sampling compared to that of 1980 (Yu et al., 2012). Second, the litter input estimates and turnover rates may bring uncertainties to the modeling. The variations in tree DBH and turnover rates of varied biomass components were considered in the calculation of confidence limits of the model by including the standard deviations of the input parameters. However, some uncertainties may root in the biomass allocation models as well as the assumption of linear correlation between annual litter input and stand age. Third, some uncertainties

BGD
10, 11181–11211, 2013

came from the chronosequence method since the stand conditions, such as slope aspect and degree, could not be identical in reality (Foereid et al., 2011). Lastly, the sample sizes of measurements for the soil property parameters and fine root biomass were relatively small at some sites, which may bring along uncertainties for predictions of annual fine root biomass and the results of residual analyses.

4.6 Long-term sustainabilities of the plantations

The role of afforestation in carbon sequestration has been increasingly studied in recent years. After the primary focus on the short-term benefits from the plantations, the long-term effects and sustainability have started to cause more concern (Foote and Grogan, 2010; Novara et al., 2011). The plantations of black locust are effective in improving SOC and soil quality after 10–20 yr of growth, a conclusion supported by this and some other studies (Matos et al., 2012). However, this species is a pioneer species in forest succession and has a relatively short life span. Specifically, sprouting and seedling are rarely successful, and the soil seed bank is lacking of late-successional species but only perennial herbs due to the long-term and large-scale cultivation in the study region (Wang and Ren, 2004). Therefore, the long-term carbon sequestration capability of the plantations and their further recovery to natural vegetation communities are indispensable of suitable stand management, including timber harvesting, seedling supplementation and seed source introduction (Zhang et al., 2008). Future afforestation activities should consider the climate and site conditions, species adaptability, and the successional stage.

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BGD
10, 11181–11211, 2013

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BGD
10, 11181–11211, 2013

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BGD

10, 11181–11211, 2013

SOC dynamics following afforestation in the Loess Plateau

N. Lu et al.

Table 1. Description of site characteristics. *P*: annual precipitation, *T*: annual mean temperature, PET: potential evapotranspiration, amplitude: inter-annual temperature change, C : N: ratio of soil total carbon to nitrogen. Soil property parameters are for soil depths of 0–20 cm.

Site ID[a]	Name of the closest met-station	*P* (mm)	*T* (°C)	P/PET	Amplitude (°C)	Bulk density (g cm^{-3})	Clay content (%)	Soil C : N ratio	No. of plots
1	Tongchuan	604	9.8	0.62	13.3	1.14	27.1	27.7	8
2	Luochuan	598	10.6	0.63	13.2	1.20	34.9	13.5	7
3	Yan'an	519	10.2	0.52	14.4	1.17	16.1	36.4	8
4	Wuqi	454	8.1	0.51	14.7	1.22	19.3	37.2	4
5	Yan'an	519	10.2	0.52	14.4	1.08	n.a.	n.a.	6
6	Yan'an	519	10.2	0.52	14.4	1.19	n.a.	n.a.	4

[a] Land use history of the six study sites: for site 1 and 2, secondary forest developed on a fallow field abandoned in the 1860s due to emigration (Zou et al., 2002); the land was reclaimed in the 1950s and afforested in the 1980s. For site 3, 4, 5, and 6, the land has been cultivated for hundreds to thousands of years before afforestation in the 1970s.

BGD
10, 11181–11211, 2013
SOC dynamics following afforestation in the Loess Plateau
N. Lu et al.

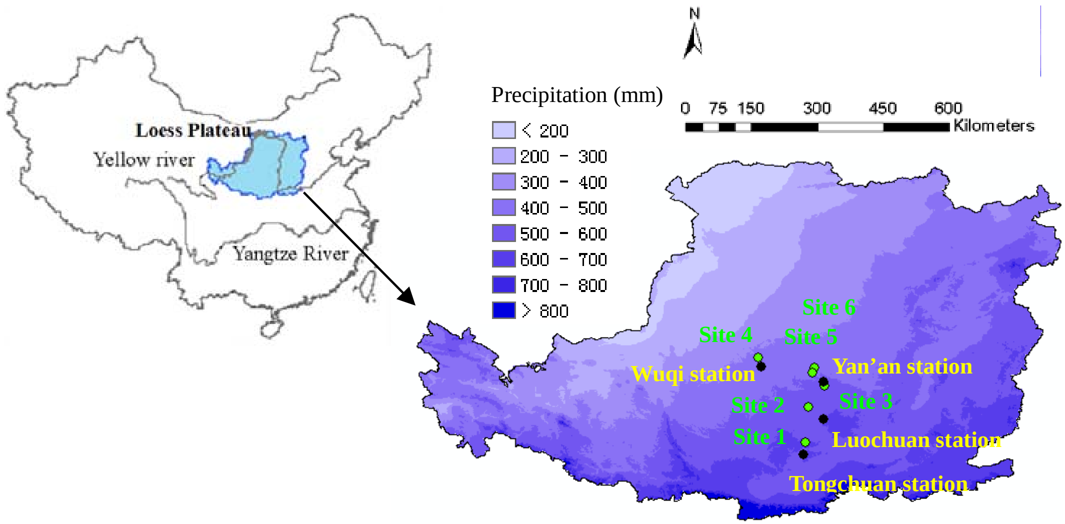

Fig. 1. Location of the six sites studied in this study and the adjacent long-term meteorological stations in the Loess Plateau, China.

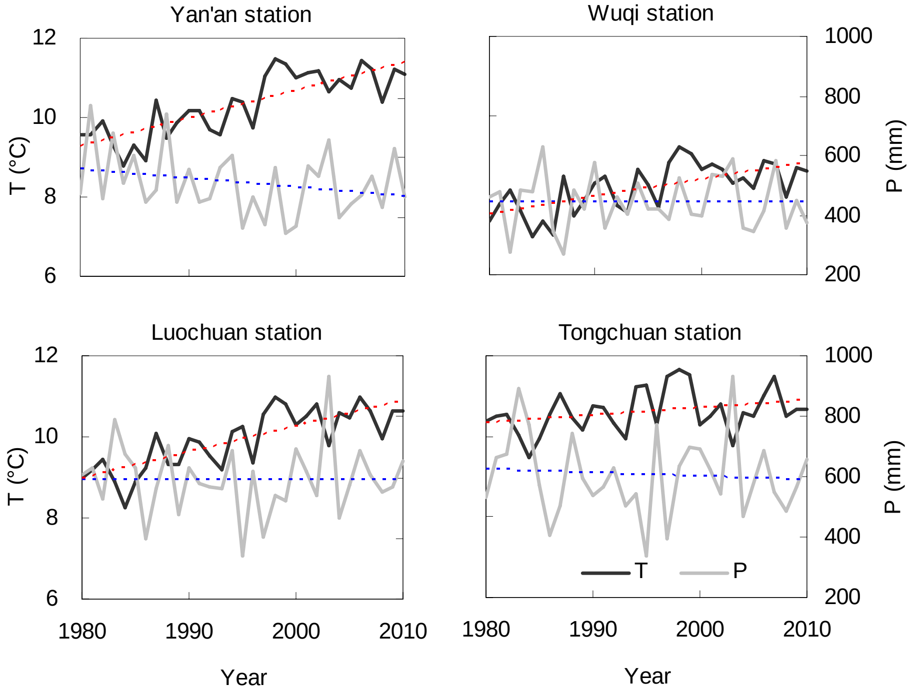

Fig. 2. The variations of annual mean temperature (T) and precipitation (P) at the four meteorological stations from 1980–2010. The dotted lines are linear trends for T in red and P in blue, respectively. The trends are all significant for T except for the Luochuan station and insignificant for P for all the stations ($p < 0.05$).

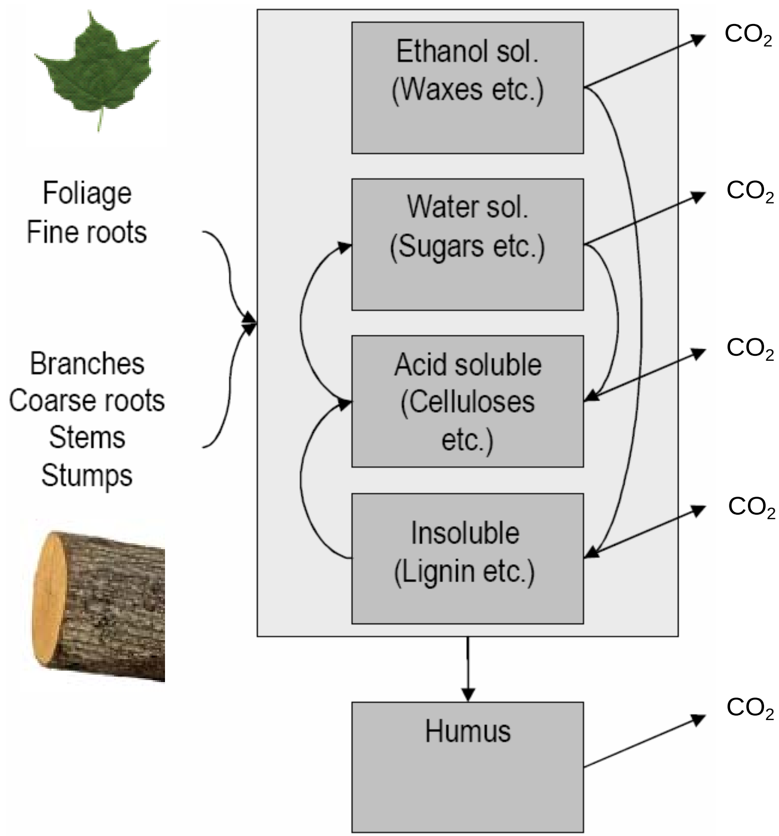

Fig. 3. Flow chart of Yasso07 model. The boxes represent carbon compartments and the arrows are carbon fluxes among compartments, into (litter input to the soil) or out of compartments (CO_2 release by decomposition).

BGD
10, 11181–11211, 2013

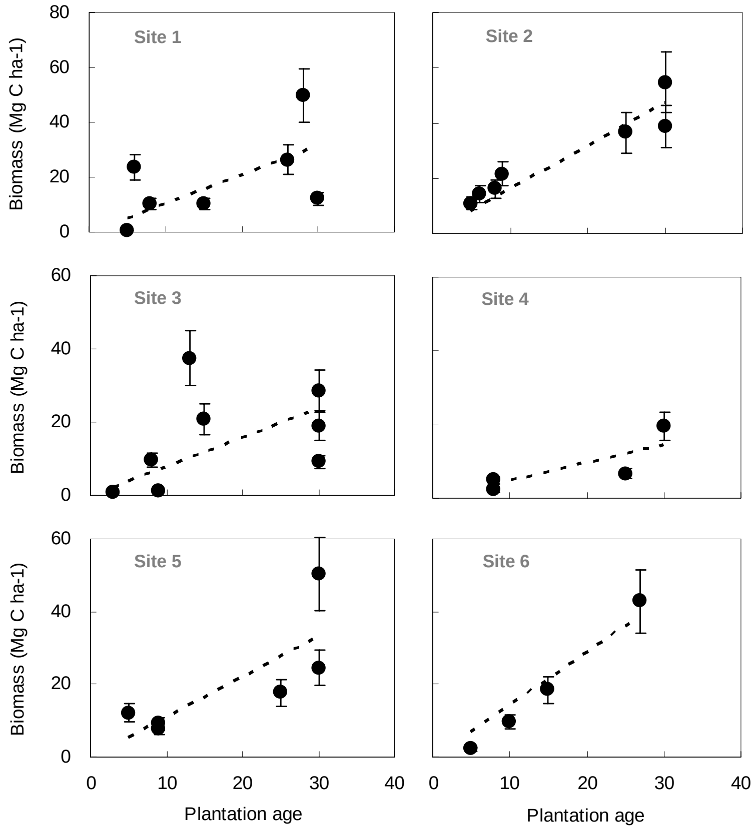

Fig. 4. The changes of total carbon biomass (excluding fine root) with plantations age. Error bars are standard deviations. The dotted lines are linear fits with the intercept forced to be zero.

BGD
10, 11181–11211, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

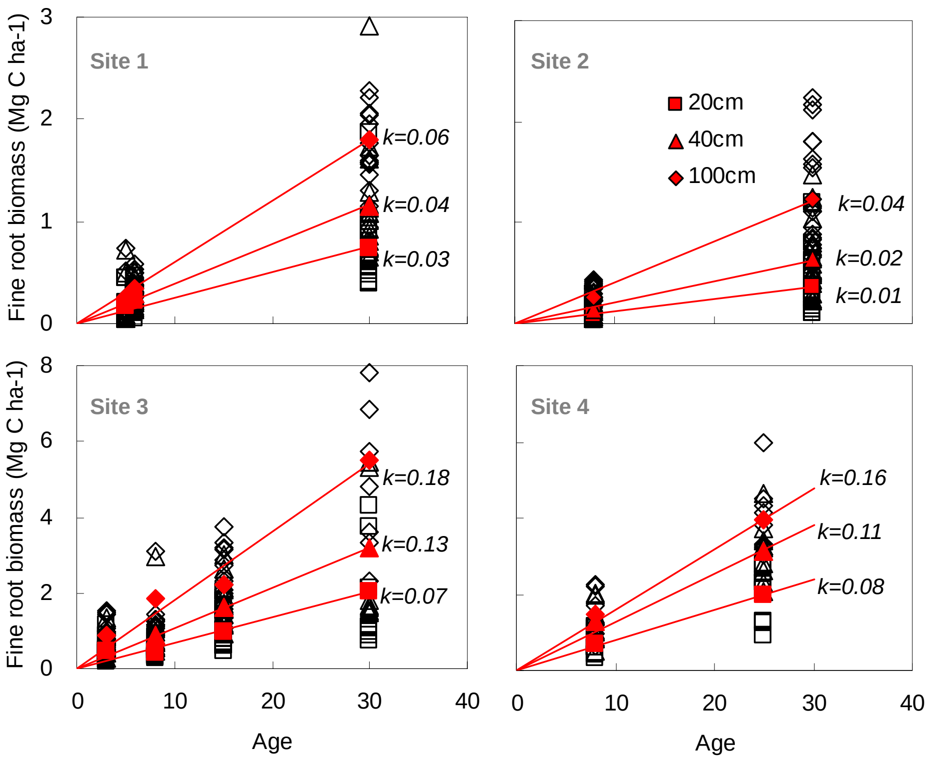

Fig. 5. The changes of mean fine roots carbon biomass with plantation age at different soil depths. The black symbols are samples and the red symbols are means. The red lines are linear fits between plantation age and the means with the intercept was forced to be zero. k is the regression slope. The coefficients of determination of the linear regressions are $R^2 \geq 0.96$ at $p < 0.05$. Figures are not shown for sites 5 and 6.

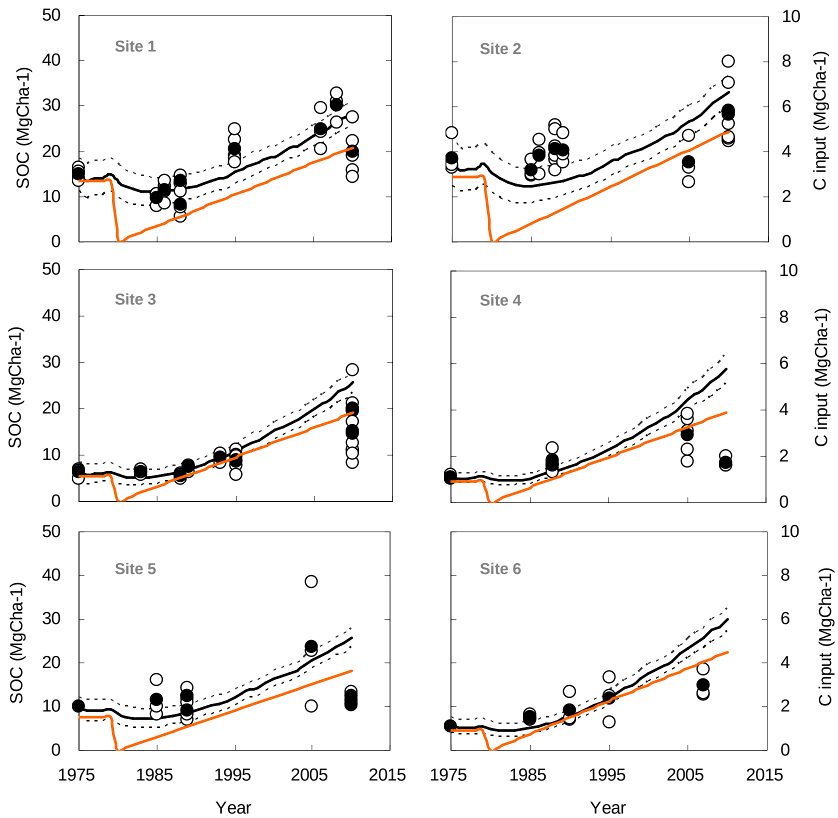

Fig. 6. Comparison of simulated and measured SOC stock in the 0–20 cm soil depth following afforestation. The first y-axis represents SOC stock. The solid curves are modeled means, the black dots are measured means of each plot, and the circles are plot measurements. The dotted curves are 95 % confidences limits. The second y-axis represents litter carbon biomass (orange polylines) which was used for modeling inputs.

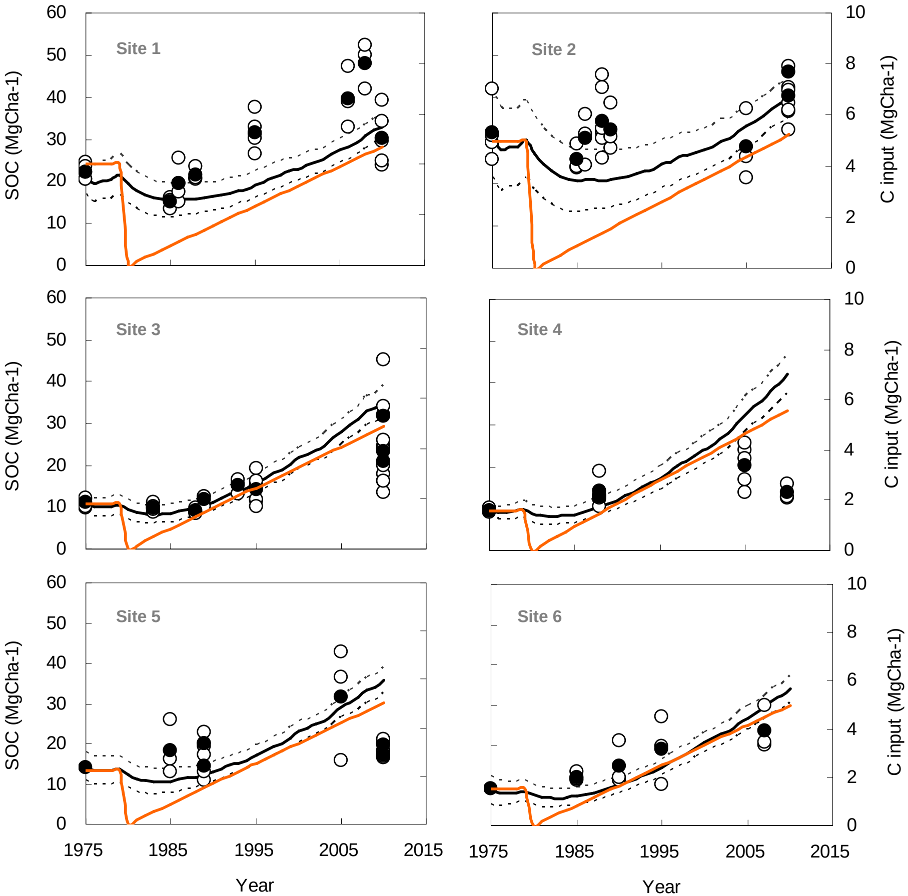

Fig. 7. Comparison of simulated and measured SOC stock in the 0–40 cm soil depth following afforestation. All other designations are the same as those in Fig. 6.

BGD

10, 11181–11211, 2013

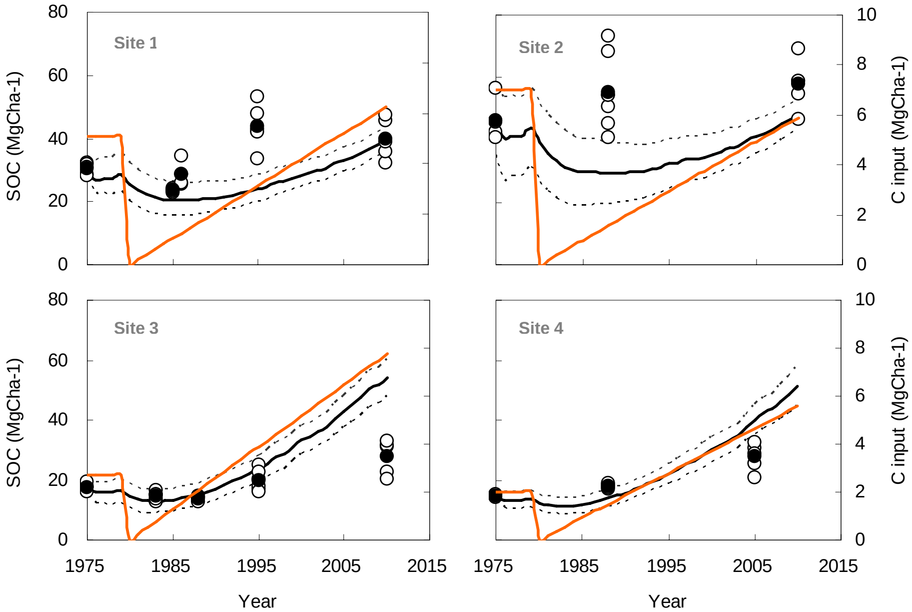

Fig. 8. Comparison of simulated and measured SOC stock in the 0–100 cm soil depth following afforestation. Data is not available for sites 5 and 6. All other designations are the same as those in Fig. 6.

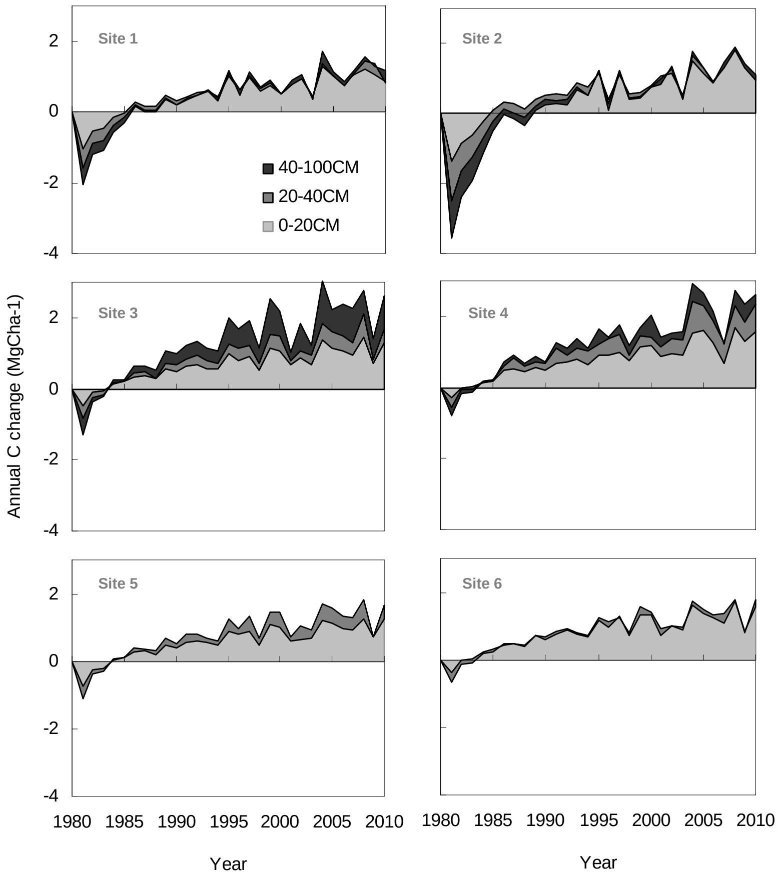

Fig. 9. Simulated annual SOC change over time since afforestation at the six study sites.

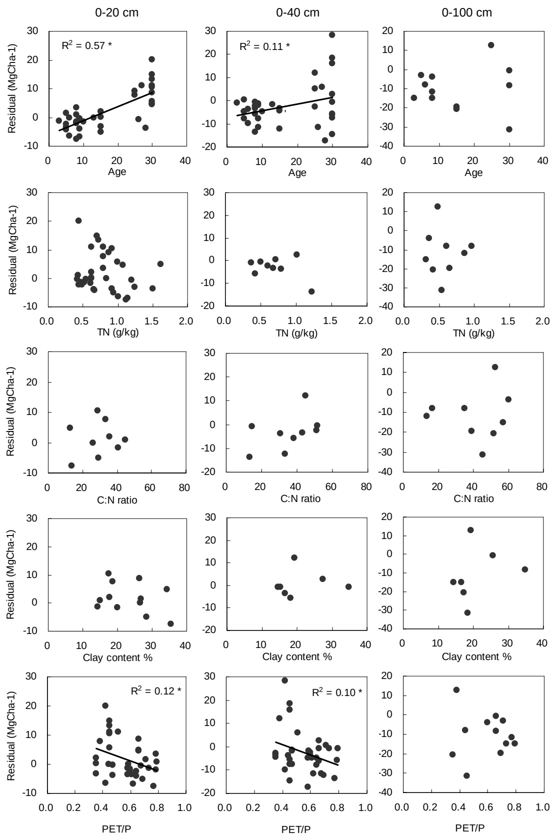

Fig. 10. Correlations of model residuals (modeled-measured mean) with plantation age, total soil TN, soil C : N ratio, clay content, and PET/P in three soil depths. Star indicates the correlation is significant at $p < 0.05$.