Global Change Biology

Global Change Biology (2014) 20, 3544–3556, doi: 10.1111/gcb.12508

Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis

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Abstract

The establishment of either forest or grassland on degraded cropland has been proposed as an effective method for climate change mitigation because these land use types can increase soil carbon (C) stocks. This paper synthesized 135 recent publications (844 observations at 181 sites) focused on the conversion from cropland to grassland, shrubland or forest in China, better known as the 'Grain-for-Green' Program to determine which factors were driving changes to soil organic carbon (SOC). The results strongly indicate a positive impact of cropland conversion on soil C stocks. The temporal pattern for soil C stock changes in the 0–100 cm soil layer showed an initial decrease in soil C during the early stage (<5 years), and then an increase to net C gains (>5 years) coincident with vegetation restoration. The rates of soil C change were higher in the surface profile (0–20 cm) than in deeper soil (20–100 cm). Cropland converted to forest (arbor) had the additional benefit of a slower but more persistent C sequestration capacity than shrubland or grassland. Tree species played a significant role in determining the rate of change in soil C stocks (conifer < broadleaf, evergreen < deciduous forests). Restoration age was the main factor, not temperature and precipitation, affecting soil C stock change after cropland conversion with higher initial soil C stock sites having a negative effect on soil C accumulation. Soil C sequestration significantly increased with restoration age over the long-term, and therefore, the large scale of land-use change under the 'Grain-for-Green' Program will significantly increase China's C stocks.

Keywords: carbon sequestration rate, China, cropland conversion, land-use change, soil carbon

Received 7 August 2013; revised version received 1 December 2013 and accepted 6 December 2013

Introduction

Land-use change has a significant effect on the global carbon (C) cycle through changing soil C accumulation rates and turnover, soil erosion, and vegetation biomass (Post & Kwon, 2000; Fang *et al.*, 2001; Lal, 2002; Degryze *et al.*, 2004; Laganière *et al.*, 2010; Li *et al.*, 2012). Following the cultivation of land that was previously covered in perennial vegetation, soil organic carbon (SOC) can be rapidly lost due to enhanced C decomposition and erosion brought about by soil disturbance (Degryze *et al.*, 2004; Lal, 2005; Van der Werf *et al.*, 2009). Lal (2005) reported that up to 50% of soil C was lost within the first 20 years. In contrast, converting cropland into perennial vegetation is found to accumulate SOC by increasing C derived from the new vegetation thereby simultaneously decreasing C loss from decomposition and erosion (Guo & Gifford, 2002; Lal, 2004; Laganière *et al.*, 2010; Chang *et al.*, 2011; Deng *et al.*, 2013). Thus, increasing forested land area through reforestation has become one of the major available strategies for climate change mitigation (IPCC, 2000; Vesterdal *et al.*, 2002; Miles & Kapos, 2008; Zhang *et al.*, 2010; Li *et al.*, 2012), as proposed in Article 3.3 of the Kyoto Protocol (UNFCCC, 2005).

Losses in soil C caused by the conversion of natural to cultivated vegetation is well documented (Yan *et al.*, 2012). Globally, 24% of the SOC stock has been lost through the conversion of forest to cropland (Murty *et al.*, 2002) and 59% through the conversion of pasture to cropland (Guo & Gifford, 2002). In contrast, where cropland is withdrawn from farming and converted into natural vegetation, soil C accumulates and is locked up for greater periods of time due to the slower turnover rates associated with natural vegetation (Post & Kwon, 2000; Degryze *et al.*, 2004; Zhang *et al.*, 2010). Soil C stocks can be increased by preventing soil erosion (Lal, 2002), increasing organic matter inputs (Smith, 2008) and decreasing both weathering and microbial breakdown (Post & Kwon, 2000; Lal, 2005; Smith, 2008). Martens *et al.* (2003) found that soil C accumulated at an average rate of 0.62 and 1.60 Mg ha^{-1} yr^{-1} during cropland conversion into pasture and secondary forest, respectively, in Central America. In China, an average gain of 0.37 Mg ha^{-1} yr^{-1} has been estimated following

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the establishment of perennial vegetation on cropland (Zhang *et al.*, 2010). Globally, Post and Kwon (2000) found that the average rates of soil C accumulation for forest and grassland established on land cultivated for 100 years were similar at 0.34 and 0.33 Mg ha^{-1} yr^{-1}, respectively. Guo and Gifford (2002) concluded that soil C stocks significantly increased when cropland was converted to pasture (+19%), tree plantation (+18%) and secondary forest (+53%). Importantly, however, Vesterdal *et al.* (2002) observed that afforestation on former arable land did not lead to an increase in SOC within 30 years, but instead led to the redistribution of SOC in the soil profile. A decrease in soil C was also found in the initial years (<5 years) following the abandonment of arable land (Zhang *et al.*, 2010). The seeming inconsistencies drawn by these studies likely arise because the magnitude and direction of soil C dynamics are affected by multiple factors, including climate, soil type, soil depth, tree species, and nutrient management (Paul *et al.*, 2002; Lal, 2004; Laganière *et al.*, 2010; Li *et al.*, 2012). Exploring the general patterns and the major factors controlling soil C accumulation is a necessary informational backdrop allowing ecosystem management practices to more precisely relate C sequestration values to either revegetation or afforestation (Post & Kwon, 2000; Lal, 2004; Li *et al.*, 2012).

Although several authors (Post & Kwon, 2000; Paul *et al.*, 2002; Laganière *et al.*, 2010; Zhang *et al.*, 2010; Chang *et al.*, 2011) have analyzed the factors determining soil C stocks during the establishment of perennial vegetation, a consensus on the relative significance of these factors has yet to be achieved (Chang *et al.*, 2011; Li *et al.*, 2012). While Paul *et al.* (2002) found that climate is one of the most important factors influencing soil C change after cropland conversion, Laganière *et al.* (2010) concluded that climate had a smaller effect on soil C accumulation during afforestation when compared to previous land use, tree species planted, soil clay content and preplanting disturbance. Furthermore, the impact of these factors depends on spatial scale (Chang *et al.*, 2011). For example, at a local scale, converting cropland to forest plantation had a greater effect on soil C sequestration than conversion to grassland (Del Galdo *et al.*, 2003; Martens *et al.*, 2003). At a national or global scale, the change in soil C stock was similar for grassland and forest establishment (Post & Kwon, 2000; Guo & Gifford, 2002; Zhang *et al.*, 2010). One explanation for the inconsistency could be that soil C stock changes following afforestation vary with depth (Paul *et al.*, 2002; Don *et al.*, 2011; Li *et al.*, 2012), but most reviews have not adequately considered sampling depth in their analyses (Guo & Gifford, 2002; Berthrong *et al.*, 2009; Laganière *et al.*, 2010; Zhang *et al.*, 2010; Chang *et al.*, 2011; Don *et al.*, 2011).

In China, long-term agricultural exploitation has led to soil degradation and desertification (Lal, 2002; Wu *et al.*, 2003), for example, SOC losses in cultivated soils of 7.1 Pg (Wu *et al.*, 2003). In 1999, China launched the 'Grain-for-Green' Program (usually cropland is converted into grassland, shrubland or forest), one of the world's most ambitious conservation set-aside programs (Deng *et al.*, 2012; Feng *et al.*, 2013), and the nation's largest ecological restoration project since the 1970s (Cao *et al.*, 2009). The large scale of land-use change undertaken for the 'Grain-for-Green' Program may indeed enhance C sequestration capacity in the terrestrial ecosystems of China, however, so far there has been little comprehensive assessment of the changes in soil C stocks for the entire program despite many observations made at the local level (Chang *et al.*, 2011; Feng *et al.*, 2013). At present, only one report has focused on changes in soil C stocks in surface soils (0–20 cm) (Zhang *et al.*, 2010). It is also necessary to understand how the deeper soil C stock has changed since cropland conversion. To understand which factors drive soil C sequestration dynamics following cropland conversion it is crucial to explore both the rate of change and its temporal pattern.

The objectives of this study were threefold: (1) establish the temporal pattern of soil C sequestration rates for different land use changes; (2) determine the temporal pattern of soil C sequestration rates at different soil depths; and (3) study those factors driving the changes in soil C. To achieve these objectives we synthesized the findings of 135 recent publications from the literature in which land use conversion (cropland to natural secondary succession or plantation) was related to changes in soil C values.

Materials and methods

Data preparation

The following criteria were used to select papers for synthesis: soil C stocks were provided or could be calculated based on SOC or SOM concentration, bulk density and soil depth; there were data for both the afforested sites (LUn) and the prior land use sites (LU0); the experiments used paired site, chronosequence or retrospective designs, had similar soil conditions for both LUn and LU0; the number of years since cropland conversion were either clearly given or could be directly derived. In the studies, only afforestation of the first rotation was considered and data for both the 0–20 and 0–100 cm soil layers were extracted. In addition, studies were excluded if they lacked replications or if the paired sites or sites of chronosequence were confounded by different soil types. In total, the final dataset comprised 135 studies published between 2000–2013, including 844 observations at 181 sites in 29 provinces or municipalities (Fig. 1) of which 686

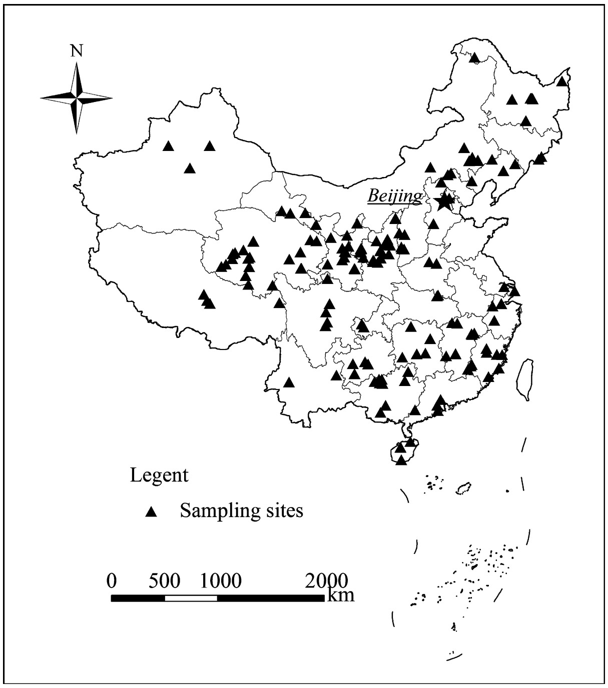

Fig. 1 Distribution of sampling sites in the dataset.

observations had a clearly known chronosequence and 158 observations were on farmland.

The raw data were either obtained from tables or extracted by digitizing graphs using the GetData Graph Digitizer (version 2.24, Russian Federation). For each paper, the following information was compiled: source(s) of data, location (longitude and latitude), climatic information (averages of annual temperature and precipitation), land-use type [cropland, grassland, shrubland, forest (arbor, divide tree type into conifer and broadleaf, and evergreen and deciduous)], years since cropland conversion (afforestation, planted grass or revegetation), soil depth, experimental design (paired site, chronosequence or retrospective design), soil bulk density, and amount of SOC or soil C stocks in each layer of 0–100 cm soil. In studies that sampled many replicate plots over a landscape, those plots with the same age, edaphic conditions and land use were pooled. When more than one depth was sampled, C stocks at all the depths were summed together. Where a particular chronosequence or retrospective study had observations at a number of plantation ages, each age was regarded as an independent study and included in the analysis. The final dataset was separated into two subsets – one each for the 0–20 and 0–100 cm soil layers – as not all studies considered both layers and this separation would therefore reduce uncertainty. The age of afforestation or revegetation was divided into five groups: 0–5, 6–10, 11–30, 31–40, and >40 years. Prior land use type was cropland in all cases.

Data calculation

Of the data collected from the literature, the soil C stocks units of 'kg m^{-2}' were transformed into 'Mg ha^{-1}'.

If the samples reported only SOM, their SOC values were calculated by the relationship between SOM and SOC (Guo & Gifford, 2002) using the formula:

$$\mathrm{SOC} = 0.58 \times \mathrm{SOM} \tag{1}$$

For those studies in which soil bulk density (BD) had not been measured, we used the empirical relationship between organic C content and BD (Wu *et al*., 2003):

$$\mathrm{BD} = -0.1229 \ln(\mathrm{SOC}) + 1.2901 \;\; (for SOC < 6\%) \tag{2}$$

$$\mathrm{BD} = 1.3774\, e^{-0.0413\mathbf{SOC}} \;\; (for SOC > 6\%) \tag{3}$$

The SOC stocks were calculated using the following equation (Guo & Gifford, 2002):

$$C_s = \frac{\mathrm{SOC} \times \mathrm{BD} \times D}{10} \tag{4}$$

in which, C_s is soil organic carbon stocks (Mg ha^{-1}); SOC is soil organic carbon concentration (g kg^{-1}); BD (g cm^{-3}); and D is soil thickness (cm).

While comparing changes in soil C stocks between land uses based on common soil mass rather than on volume because of compaction was desirable, it was impossible to correct data for all the studies, as not all reported bulk densities, especially for different soil depths. Thus, in keeping with the method employed in the synthesis (Guo & Gifford, 2002; Laganière *et al*., 2010; Powers *et al*., 2011), we did not adjust reported data to a common mass, but used mass-corrected soil C stocks when the authors had provided them. Not adjusting for an equivalent mass of soil could only result in a slight bias in the estimation of changes in soil C stocks; a finding supported by our data as well as by others (Laganière *et al*., 2010).

To increase the comparability of data derived from different studies, the methodology adopted by Yang *et al.* (2011) was used. The original soil C data were converted to soil C stocks in the top 100 cm using the depth functions developed by Jobbágy and Jackson (2000) according to the following equations:

$$Y = 1 - \beta^{d} \tag{5}$$

$$X_{100} = \frac{1 - \beta^{100}}{1 - \beta^{d0}} \times X_{d0} \tag{6}$$

For observations that only had 0–100 cm soil C stocks, using Eqn (6) we can derive:

$$X_{d0} = \frac{1 - \beta^{d0}}{1 - \beta^{100}} \times X_{100} \tag{7}$$

where Y represents the cumulative proportion of the soil C stock from the soil surface to depth d (cm); β is the relative rate of decrease in the soil C stock with soil depth; X_{100} denotes the soil C stock in the upper 100 cm; $d0$ denotes the original soil depth available in individual studies (cm); and X_{d0} is the original soil C stock. Although Jobbágy and Jackson (2000) provided the depth distribution of soil C for 11 biome types globally, there was no significant difference in the depth distribution among biome types or between individual biomes and the global average. Therefore, in the present study, the global average depth distributions for C were adopted to calculate β (i.e., 0.9786) in the equations.

It should be noted that potential uncertainties may be introduced by this dataset standardization, mainly due to the difference in C distribution through the soil profile between prior land-use types and afforested sites, and among the different stages of vegetation (forest, shrubland, and grassland) development. However, as has been stated, there was no significant difference among the 11 biome types included in Jobbágy and Jackson (2000) or between individual biomes and the global average in terms of soil C distribution with depth. The same method (i.e., converting original C stocks to stocks in the top 100 cm using the depth functions to increase comparability) was used by Yang *et al.* (2011) and Li *et al.* (2012), both of whom concluded that depth correction did not alter the overall pattern of soil C stock dynamics during vegetation development.

The C sequestration rate is estimated depending on changes to soil C stocks in different time sequences. The study set the C stocks of cropland as the baseline for calculating the rate of C stock change in the restoration process after cropland conversion into forest or grassland. We first calculated the C sequestration value for each afforested site following cropland conversion, C sequestration (ΔCs, in Mg ha^{-1}):

$$\Delta C_S = C_{LUn} - C_{LU0} \tag{8}$$

in which, C_{LUn} represents soil C stocks at afforested sites (Mg ha^{-1}), and C_{LU0} is soil C stocks at the initial stage of cropland (Mg ha^{-1}).

Secondly, we constructed a linear regression equation [y = f(x) = y$_0$ + *k*x] between C sequestration (ΔCs) and age for each age group:

$$\Delta C_s = f(\Delta \mathrm{Age}) = y_0 + k \times \Delta \mathrm{Age} \tag{9}$$

The equation's first derivative represents the rate of change of the curve, so Eqn (9)'s first derivative of ΔCs vs. ΔAge represents the rate of C stock change:

Rate of C stock change

$$(\mathrm{Mg\ ha^{-1} yr^{-1}}) = f'(\Delta \mathrm{Age}) = \frac{df(\Delta \mathrm{Age})}{d\Delta \mathrm{Age}} = k \tag{10}$$

in which, y_0 is a constant; k is the rate of C stock change (Mg ha^{-1} yr^{-1}), and also represents the slope of Eqn (9); and ΔAge is the time interval (yr).

Data analysis

Two-way ANOVA was performed to test the effects of land-use change types, tree species or age groups in different soil layers. Differences were evaluated at $P < 0.05$. To reflect the dynamics of soil C stocks, the average rates of stock changes for the 0–20, 20–100, and 0–100 cm soil layers were summed for each category. Stepwise regression analysis was used to analyze the relationship between soil C sequestration (ΔCs) after cropland conversion and annual average temperature (T), annual average precipitation (P), years since cropland conversion (A) and initial soil C stocks in the 0–20 cm (I_1) and 0–100 cm (I_2) in each age group. Pearson's correlation coefficients were used to study the relationship between ΔCs after cropland conversion and T, P, A, I_1 and I_2 of all data. Statistical analyses were performed using the software program SPSS, ver. 18.0 (SPSS Inc., Chicago, IL, USA).

Results

Change in soil C stocks after cropland conversion under the entire 'Grain-for-Green' Program

Land-use change altered the soil C stock in the 0–100 cm soil following cropland conversion to perennial vegetations under the whole 'Grain-for-Green' Program (usually cropland is converted into grassland, shrubland or forest) in China (Fig. 2). Soil C decreased most during the first 5 years after cropland conversion (Fig. 2), moreover, the rates of soil C change were greater in surface (0–20 cm) than in deeper soil (20–100 cm) (Fig. 2a and d). After land use was changed, the rates in surface soil (0–20 cm) had a different pace of change compared with that of deeper soil (20–100 cm), and the deeper soil C sequestration function lagged behind that of the surface soil (Fig. 2a and b). However, 0–20 and 0–100 cm soil showed the same pace of change (Fig. 2a and c). After the cropland had been converted for 30 years, the 0–100 cm soil C stock tended to stabilize. For the periods 0–5, 6–10, 11–30, 31–40 and >40 years, the rates of soil C change were −0.63, 0.04, 0.01, −0.05 and 0 Mg ha^{-1} yr^{-1} for 0–20 cm soil, respectively, and correspondingly −1.969, 0, 0.03, −0.10 and −0.01 Mg ha^{-1} yr^{-1} for 0–100 cm (Fig. 2a and c).

Changes in C stocks due to different land use changes

Cropland to forest. The effect of land-use change from cropland to forest on soil C stocks (Fig. 3) was significant. Soil C decreased most during the first 5 years after cropland conversion to forest (Fig. 3); moreover, the rates of soil C change were higher in surface (0–20 cm) than in deeper soil (20–100 cm) (Fig. 3a and d). After land use change, the deeper soil C sequestration function lagged behind the surface soil (Fig. 3a and b). However, 0–20 cm and 0–100 cm soil depths showed the same pace of change (Fig. 3a and c). The rates of soil C sequestration were highest during 11–30 years after cropland conversion (Fig. 3) and then tended to decrease, but forest always served a C sequestration function. During the periods 0–5, 6–10, 11–30, 31–40 and >40 years, the rates of soil C change were −0.93, 0.89, 1.30, 0.05 and 0.13 Mg ha^{-1} yr^{-1} for 0–20 cm soil, respectively, and correspondingly −3.15, 0.83, 3.59, 1.15 and 0.02 Mg ha^{-1} yr^{-1} for 0–100 cm (Fig. 3a and c).

Tree species affected the magnitude of soil C stocks after cropland was converted to forest (Figs 4 and 5).

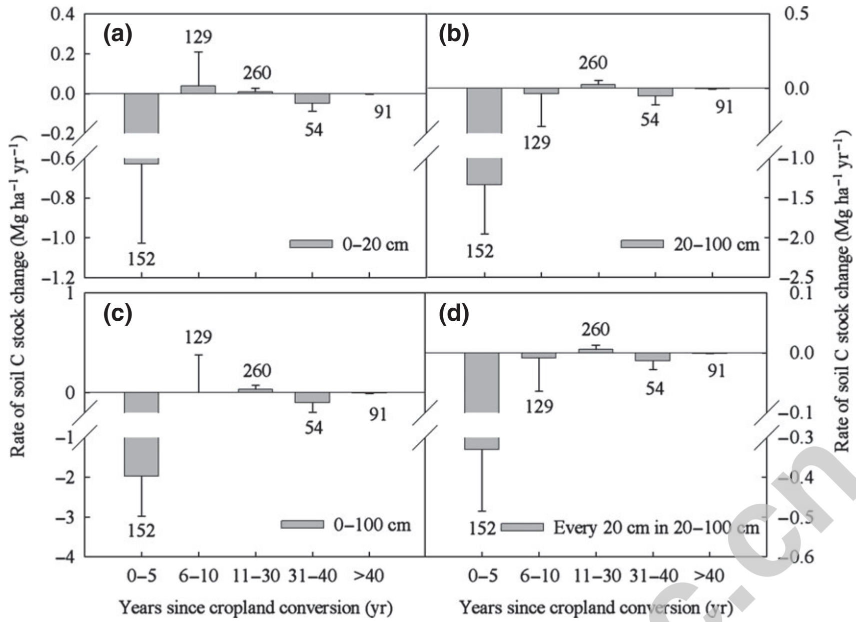

Fig. 2 Change in soil C stocks in response to the time after cropland conversion to perennial vegetation under the whole 'Grain-for-Green' Program in China for: (a) soil C in 0–20 cm; (b) soil C in 20–100 cm; (c) soil C in 0–100 cm; (d) soil C in 20–100 cm every 20 cm. The error bars represent standard errors for the slope of Eqn (9) (*k*) and values above the bars are the corresponding number of observations.

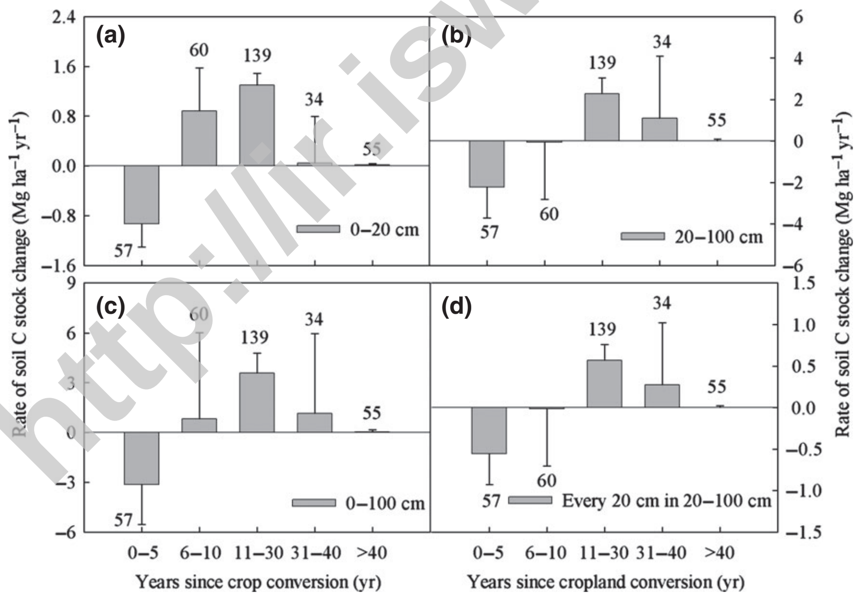

Fig. 3 Change in soil C stocks in response to length of time after cropland conversion to forest for: (a) soil C in 0–20 cm; (b) soil C in 20–100 cm; (c) soil C in 0–100 cm; (d) soil C in 20–100 cm every 20 cm. The error bars represent standard errors for the slope of Eqn (9) (*k*) and values above the bars are the corresponding number of observations.

Conifer and broadleaf forests had different pace of changes (Fig. 4). Conifer forest started to increase C stock after cropland had been converted for 5 years, for broadleaf forest after 10 years (Fig. 4). By 30 years, soil C stock in broadleaf forest had begun to decrease, while for conifer forest this was after 40 years (Fig. 4). For the conifer forest, the highest C sequestration rate in the surface soil (0–20 cm) was at 6–10 years, and at 31–40 years for deeper soil (20–100 cm) and the 0–100 cm soil depth overall. For the broadleaf forest,

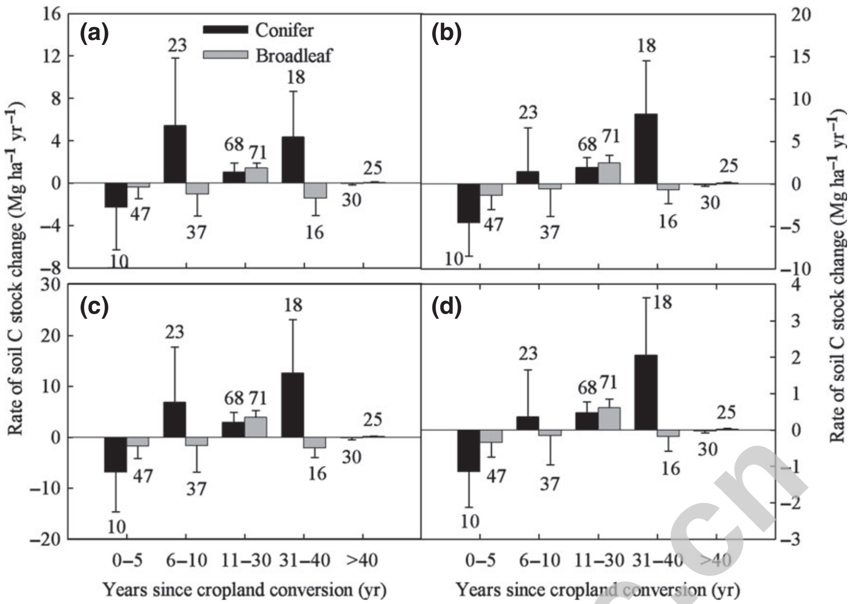

Fig. 4 The difference between the two tree types (conifer and broadleaf) in relation to change in soil C stocks in response to time after cropland conversion to forest for: (a) soil C in 0–20 cm; (b) soil C in 20–100 cm; (c) soil C in 0–100 cm; (d) soil C in 20–100 cm every 20 cm. The error bars represent standard errors for the slope of Eqn (9) (*k*) and values above the bars are the corresponding number of observations.

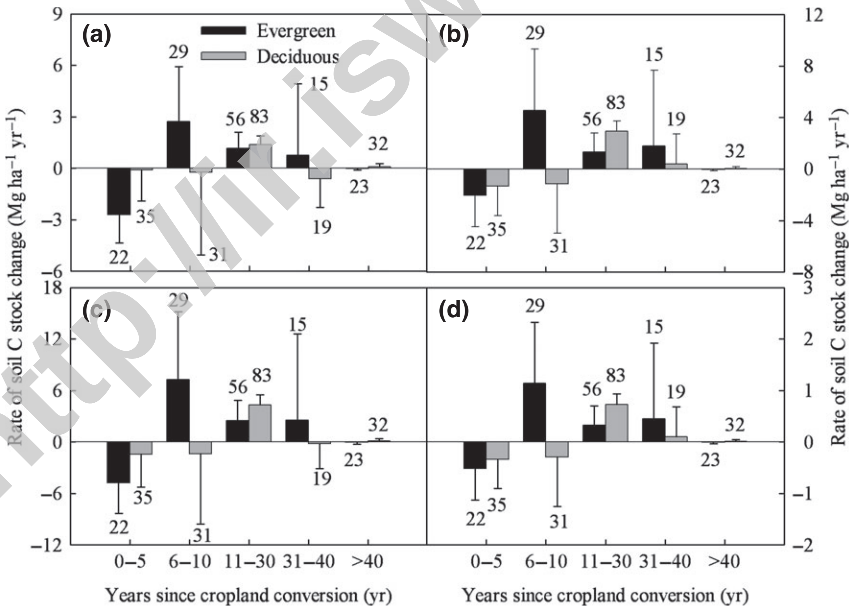

Fig. 5 The difference between the two tree types (evergreen and deciduous) in relation to the change in soil C stocks in response to time after cropland conversion to forest for: (a) soil C in 0–20 cm; (b) soil C in 20–100 cm; (c) soil C in 0–100 cm; (d) soil C in 20–100 cm every 20 cm. The error bars represent standard errors for the slope of Eqn (9) (*k*) and values above the bars are the corresponding number of observations.

the highest C sequestration rate for all soil depths was at 11–30 years (Fig. 4); moreover, in the process of C sequestration at 11–30 years, the rate was a little higher in broadleaf than conifer forest (Fig. 4).

Also, evergreen and deciduous forest had different pace of changes (Fig. 5). Evergreen forest started to increase C stock after cropland had been converted for 5 years, and deciduous forest after 10 years (Fig. 5). By

30 years, soil C stock in deciduous forest started to decrease, while in evergreen forest this was after 40 years (Fig. 5). For the evergreen forest, the highest C sequestration rate at all soil depths was during 6–10 years (Fig. 5); for the deciduous forest, this was at 11–30 years. In the process of C sequestration during 11–30 years, the rate was a little higher for deciduous over conifer forest; moreover, the rates in surface soil (0–20 cm) had different pace of change compared to deeper soil (20–100 cm) after cropland had been converted for 30 years (Fig. 5).

Cropland to shrubland. With the land-use change from cropland to shrubland, soil C sequestration in the 0–20 and 0–100 cm soil increased gradually during 0–10 years (Fig. 6); however, during 11–30 years, the soil C stock decreased slightly. After 30 years, soil C stock had significantly decreased. Also, the rates of soil C change were higher in surface (0–20 cm) than in deeper soil (20–100 cm) (Fig. 6a and d), and they had the same pace of change (Fig. 6a and b).

Cropland to grassland. Similar to shrubland, with land-use change from cropland to grassland, soil C sequestration in the 0–20 and 0–100 cm soil depths increased gradually during 0–30 years, with the highest rate occurring during 11–30 years (Fig. 7). After 30 years, soil C stock had significantly decreased. Also, the rates of soil C change were higher in the surface (0–20 cm) than in the deeper soil (20–100 cm) (Fig. 7a and d), and they showed the same pace of change (Fig. 7a and b).

Factor effects on soil C stocks

ANOVA showed significant effects of land-use types ($P < 0.05$) and number of years since cropland conversion ($P < 0.01$) on soil C sequestration in the 0–20 and 0–100 cm soil, but their interactions were not significant ($P > 0.05$) (Table 1); for the deeper soil, only years since cropland conversion had significant effects on soil C sequestration ($P < 0.01$) (Table 1). For conifer and broadleaf forests, there were significant effects for tree species and years since cropland conversion (both $P < 0.05$) on soil C sequestration in the 0–20 and 0–100 cm soil, but their interactions were not significant ($P > 0.05$) (Table 1); for the deeper soil, only tree species had any significant effect on soil C sequestration ($P < 0.05$) (Table 1). For evergreen and deciduous forests, there were significant effects for tree species and years since cropland conversion (both $P < 0.05$) on soil C sequestration in the 0–100 and 20–100 cm soil, but their interactions were not significant ($P > 0.05$) (Table 1); for the surface soil, only years since cropland conversion had any significant effect on soil C sequestration ($P < 0.01$) (Table 1).

Stepwise regression revealed that years after land-use change was the main factor affecting the soil C stock in the 0–100 cm soil (Table 2). Annual average temperature was the main factor affecting the soil C

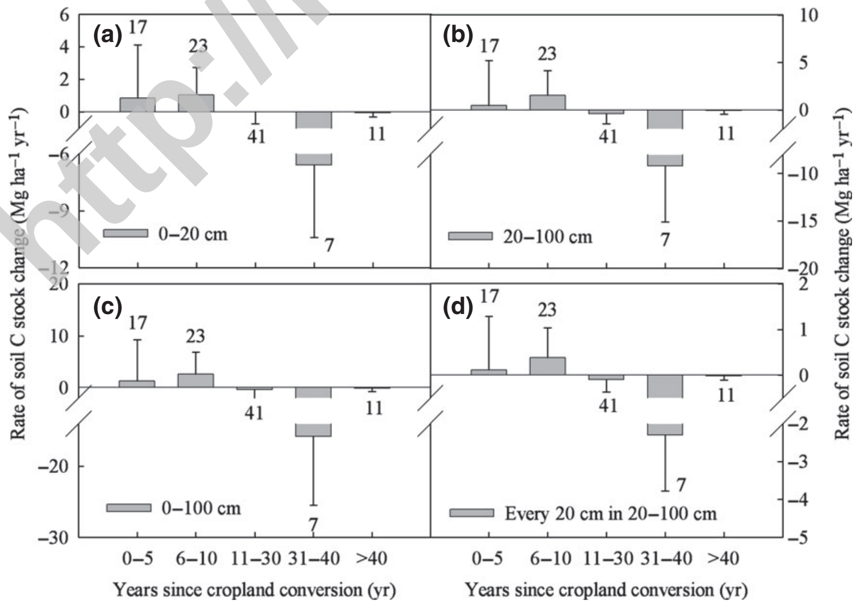

Fig. 6 Change in soil C stocks in response to the time after cropland conversion to shrubland for: (a) soil C in 0–20 cm; (b) soil C in 20–100 cm; (c) soil C in 0–100 cm; (d) soil C in 20–100 cm every 20 cm. The error bars represent standard errors for the slope of Eqn (9) (*k*) and values above the bars are the corresponding number of observations.

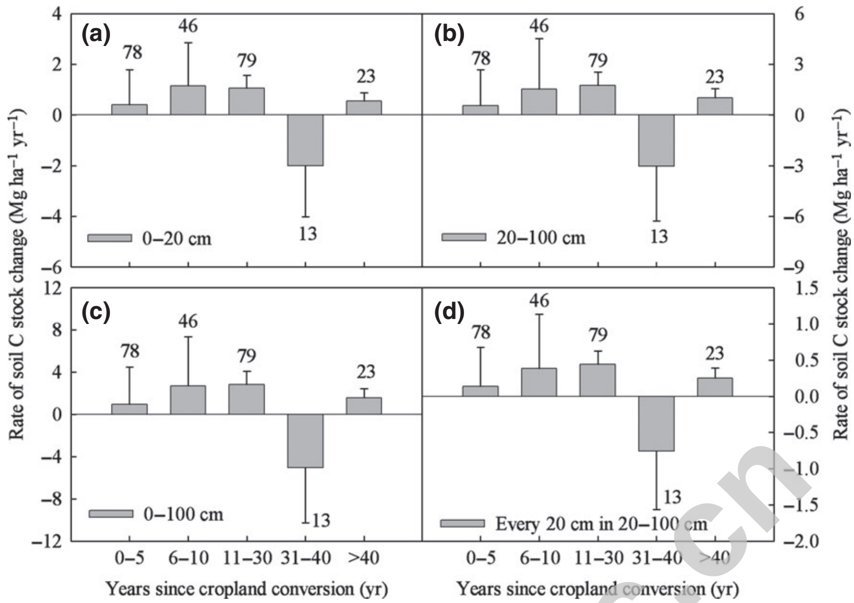

Fig. 7 Change in soil C stocks in response to time after cropland conversion to grassland for: (a) soil C in 0–20 cm; (b) soil C in 20–100 cm; (c) soil C in 0–100 cm; (d) soil C in 20–100 cm every 20 cm. The error bars represent standard errors for the slope of Eqn (9) (k) and values above the bars are the corresponding number of observations.

Table 1 Two-way ANOVA results of between-subjects effects of land-use type, tree species and years since cropland conversion, and their interactions on soil C sequestration (ΔCs) after cropland conversion

		ΔCs (0–20 cm)		ΔCs (0–100 cm)		ΔCs (20–80 cm)	
Source	df	*F*	Sig. (*P*)	*F*	Sig. (*P*)	*F*	Sig. (*P*)
Land-use type	2	4.391	0.013*	3.611	0.028*	2.919	0.055
Age	4	10.161	0.000**	10.407	0.000**	9.113	0.000**
Land-use type × Age	8	0.793	0.609	1.217	0.286	1.460	0.169
Tree species 1	1	4.953	0.027*	5.728	0.017*	5.143	0.024*
Age	4	2.712	0.030*	2.495	0.043*	2.103	0.080
Tree species 1 × Age	4	1.497	0.203	1.674	0.156	1.646	0.162
Tree species 2	1	2.251	0.134	4.267	0.040*	5.099	0.025*
Age	4	4.443	0.002**	4.116	0.003**	3.293	0.012*
Tree species 2 × Age	4	0.520	0.721	0.389	0.817	0.509	0.729

Land-use types: forest, shrubs and grass; Tree species 1: Conifer and broadleaf; Tree species 1: Evergreen and deciduous. Significant at $^{*}P < 0.05$ and at $^{**}P < 0.01$.

stock in the surface soil during the first 5 years following land use change (Table 2). The time since cropland conversion had significant effects on soil C stock after land use had been changed for 11–30 years (Table 2). After cropland had been converted for 30 years, annual average precipitation was the main factor affecting the soil C stock in deeper soil (20–100 cm), while initial soil C stock was the main factor negatively affecting the soil C stock in 0–100 cm soils after 40 years since cropland conversion. However, annual average temperature was the main factor affecting the soil C stock in deeper soil (20–100 cm) (Table 2).

Discussion

Temporal patterns of soil C stocks after land use change

Restoration age is an important factor to consider when estimating soil C stocks after cropland conversion (Table 1), and soil C sequestration was significantly and positively correlated with restoration age in the long term (Table 3). With increased time, there is an increase in the quantity of C inputs, accompanied by a new microclimatic regime and enhanced organic matter protection that promotes SOC accumulation (Laganière

Table 2 Stepwise regression to detect factors determining soil C sequestration in the 0–100 cm soil following cropland conversion

		0–20 cm			0–100 cm			20–100 cm		
Age group	*n*	Equation	*R*	Sig. (*P*)	Equation	*R*	Sig. (*P*)	Equation	*R*	Sig. (*P*)
0–5	152	$\Delta Cs = -3.908 + 0.606T$	0.227	0.005**	$\Delta Cs = -9.156 + 1.522T$	0.234	0.004**	$\Delta Cs = -5.247 + 0.917T$	0.231	0.004**
6–10	129	$\Delta Cs = 7.330 - 1.183T + 0.016P + 0.452A - 1.067I_1 + 0.376I_2$	0.239	0.200	$\Delta Cs = 7.031 - 1.156T + 0.023P + 1.376A - 1.073I_1 + 0.34\ I_2$	0.149	0.733	$\Delta Cs = -0.298 + 0.027T + 0.007P + 0.924A - 0.005I_1 - 0.036I_2$	0.126	0.849
11–30	260	$\Delta Cs = -6.08 + 1.105A$	0.197	0.001**	$\Delta Cs = -20.695 + 3.005A$	0.211	0.001**	$\Delta Cs = -14.616 + 1.9A$	0.21	0.001**
31–40	54	$\Delta Cs = 80.568 + 0.798T - 0.019P - 1.623A - 12.650I_1 + 5.106I_2$	0.744	0.000**	$\Delta Cs = 186.971 + 2.232T - 0.054P - 3.518A - 30.814I_1 + 12.375I_2$	0.775	0.000**	$\Delta Cs = 54.736 - 0.027P$	0.279	0.041*
>40	91	$\Delta Cs = 41.337 - 0.403I_1$	0.407	0.000**	$\Delta Cs = 87.643 - 0.704I_1$	0.364	0.000**	$\Delta Cs = 20.834 + 1.783T$	0.269	0.011*
All data	686	$\Delta Cs = 9.268 + 0.212A$	0.231	0.000**	$\Delta Cs = 23.303 + 0.470A$	0.217	0.000**	$\Delta Cs = 14.035 + 0.258A$	0.193	0.000**

ΔCs (Mg ha^{-1}) is soil C sequestration since cropland conversion; T (°C) is annual average temperature; P (mm) is the annual average precipitation; A (year) is the time since cropland conversion; I_1 is the initial SOC stock in the 0–20 cm and I_2 in 0–100 cm (Mg ha^{-1}).
Significant at $^*P < 0.05$ and at $^{**}P < 0.01$.

et al., 2010). Stepwise regression in the synthesis also revealed that plantation age was a major variable affecting soil C stock change after cropland conversion (Table 2), especially at 11–30 years after land-use change (Table 2). Although there are different mechanisms controlling the accumulation rate following cropland conversion and affecting soil C stocks (McLauchlan, 2006), similar temporal patterns of soil C stocks changes following cropland conversion have been reported in a number of field studies: (1) increase (Morris *et al.*, 2007; Mao *et al.*, 2010; Deng *et al.*, 2013); (2) decrease (Kirschbaum *et al.*, 2008; Smal & Olszewska, 2008); (3) unchanged (Sartori *et al.*, 2007); and (4) an initial decrease in soil C during the early stage, followed by a gradual return of C stocks to cropland levels and then an increase to net C gains (Ritter, 2007; Zhang *et al.*, 2010; Karhu *et al.*, 2011). The duration of the initial decrease in C was reported to last for 3–35 years following agricultural abandonment (Paul *et al.*, 2002). In a review, Paul *et al.* (2002) tried to determine the temporal pattern of C stocks change with age. However, the derived pattern was not very clear, as different depths were mixed together and there was great difference among depths in terms of temporal C stock changes (Li *et al.*, 2012). Despite this, there was a significant net accumulation of soil C by 30 years after afforestation (Paul *et al.*, 2002). On the whole, our study calculated the average soil sequestration rate [Slope (k) of the linear regression equation ($y = kx+y_0$)] in the top 20 cm of soil to be 0.33 Mg ha^{-1} yr^{-1} following perennial vegetation establishment from cropland under the whole 'Grain-for-Green' Program in China (Fig. 8a), which was a little lower than Zhang *et al.*'s (2010) result of 0.37 Mg ha^{-1} yr^{-1}. In addition, our result estimated the average soil sequestration rate to be 0.75 Mg ha^{-1} yr^{-1} in the 0–100 cm soils (Fig. 8b).

Our synthesis revealed that the temporal patterns, up to 30 years after cropland conversion, for C stocks change in the 0–100 cm soil were similar to the pattern (4) described above, and tended to stabilize after cropland had been converted for 30 years. The phenomenon of decreases in soil C is probably due to the lower productivity of new vegetation in earlier years and higher C loss from soil disturbance (Vesterdal *et al.*, 2002; Don *et al.*, 2009; Laganière *et al.*, 2010; Zhang *et al.*, 2010). For this reason, there is often a time lag between plant production and soil C accumulation (Li *et al.*, 2012). For example, nearly the entire increase in ecosystem C went into standing biomass, but not soil C, during 30 years of forest development in North Carolina (Compton & Boone, 2000). Similar to the findings reported by Paul *et al.* (2002), our synthesis also indicated that accumulation of C commenced >5 years after cropland conversion in the entire 'Grain-for-Green' Program (Fig. 2).

Table 3 Comparisons of factors affecting soil C sequestration after land use change with other regions

		Rates of soil C stock change since cropland conversion (Mg ha^{-1} yr^{-1})							Correlation coefficients				
Soil depth (cm)	Region	Forest	Shrub	Grassland	Conifer	Broadleaf	Evergreen	Deciduous	Age	Initial soil C stock	*T*	*P*	Reference
0–40	Cool temperate	(0.34)		(0.55)	<0								Post & Kwon (2000)
0–60	Warm temperate	(0.12)			(0.15)								Post & Kwon (2000)
0–50	Subtropical	(1.64)		(0.33)									Post & Kwon (2000)
0–55	Tropical	(0.58)		0.36									Post & Kwon (2000); Don *et al*. (2011)
0–20	Global	(0.45)	0.47	(1.10)	<0	Unchanged			0.04		−0.21**	0.23**	IPCC (2000); Guo & Gifford (2002); Murty *et al*. (2002); Vleeshouwers & Verhagen (2002); Shi *et al*. (2013)
0–20 (forest floor)	Global	−0.01									0.70**	0.44**	Yang *et al*. (2011)
0–30	Global	0.14			Unchanged	>0					**	**	Paul *et al*. (2002)
0–30	Global	>0								**	ns	ns	Laganière *et al*. (2010)
0–100	Global	0.95											Li *et al*. (2012)
0–30	Europe	0.50		0.51									Poeplau & Don (2013)
0–50	North America	0.04											Degryze *et al*. (2004)
0–33	Central America	1.60		0.62									Martens *et al*. (2003)
0–20	China	(0.40)	0.39	0.39					*	*	ns	ns	Zhang *et al*. (2010); Chang *et al*. (2011)
0–20	China	0.13	0.29	0.60	0.03	0.17	0.08	0.21	0.23**	−0.12**	0.03	0.04	This study
0–100	China	0.26	0.71	1.52	0.00	0.38	0.17	0.41	0.22**	−0.08*	0.03	0.03	This study

Values in parentheses (e.g., 0.40), indicate mean values; Age, years since cropland conversion; T, annual average temperature; P, annual average precipitation; ns represents levels of significance are not significant, *$P < 0.05$ and **$P < 0.001$; >0 indicates soil C stock increased since cropland conversion, and <0 indicates soil C stock decreased since cropland conversion; in this study, all data used in the analysis were the sums of each category.

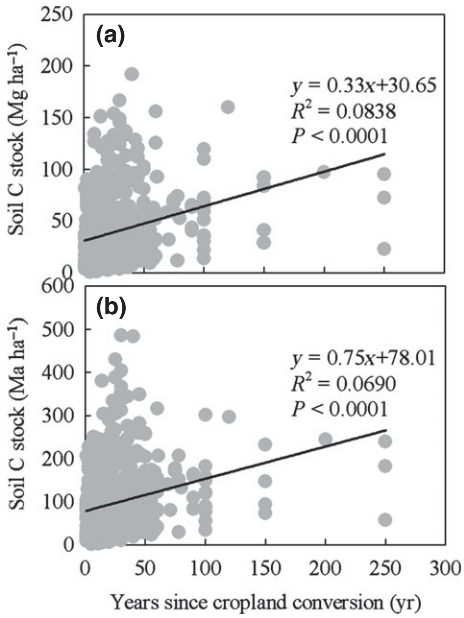

Fig. 8 The linear regression equation ($y = kx + y_0$) between soil carbon stocks and restoration age in the whole 'Grain-for-Green' Program of China. *Note*. (a) soil C stocks in 0–20 cm; (b) soil C stocks in 0–100 cm.

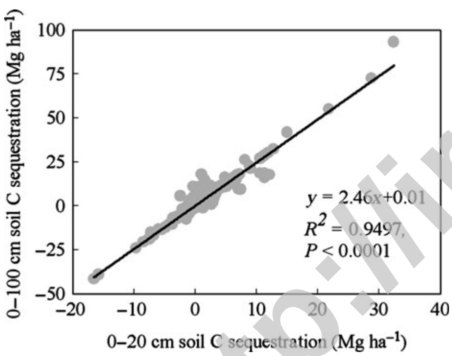

Fig. 9 Relationship between 0–100 and 0–20 cm soil C sequestration following cropland conversion.

Laganière *et al.* (2010) reported that the average changes in soil C stocks increased with different age classes, from losses of 5.6% in 'younger' (<10 years), to gains of 6.1 and 18.6% in 'medium-aged' (10–30 years) and 'older' (>30 years) plantations, respectively. This is in agreement with our observation that initial losses in soil C stocks occur during the early years after cropland is converted to forest, followed by a gradual return of C stocks, which then increase to generate net C gains. In addition, our study indicates that initial soil C stocks (previous cropland soil C stock) was the main factor affecting the soil C stock after cropland had been converted for 40 years (Table 2), and the higher initial soil C stock sites had a negative effect on soil C accumulation (Table 3). This may be attributed to the different rates of decomposition in soils with various nutrient conditions (Zhang *et al.*, 2010).

Our synthesis also revealed that the rate of soil C change was higher in the surface (0–20 cm) than in the deeper soil (20–100 cm) with increasing time after cropland conversion, which was similar to the results of Guo & Gifford (2002). After land use changed, the deeper soil C sequestration function lagged behind that of the surface soil (Fig. 2a and b). This suggests that the surface and deeper soil have different C sequestration mechanisms. However, the 0–20 and 0–100 cm soils showed the same pace of change (Fig. 2a and c). This also shows that the surface soil is more active at sequestering C from the atmosphere after land-use change (Guo & Gifford, 2002). In our study, there was a significant (P < 0.0001) linear relationship between 0–100 and 0–20 cm soil C sequestration following cropland conversion (Fig. 9), allowing us to conclude that 0–20 cm soil C sequestration accounts for about 40% of the 0–100 cm soil. Thus, the soil C sequestration in the 0–100 cm soil could be estimated using values for the 0–20 cm layer. Jobbágy & Jackson (2000) also found that the percentage of SOC in the top 20 cm (relative to the first meter) averaged 42, 33 and 50% for grassland, shrubland and forest, respectively.

Effects of land-use types on soil C stock changes

During the process of cropland conversion, the rates of soil C stock changes had significant effects on soil C sequestration (Table 1), a finding supported by others (Gong *et al.*, 2006; Chang *et al.*, 2011). However, the effects of cropland converted to forest, shrubland, and grassland were varied (Figs 3, 6 and 7; Table 3). For example, cropland converted to forest led to a reduction in soil C stocks in the early years, which is similar to the findings of Paul *et al.* (2002); however, conversion to shrubland and grassland always fixed C in this period. Martinea-Mena *et al.* (2002) reported that the magnitude of loss of soil C was dominated by erosion rather than mineralization during the initial years following a change in land use suggesting that soil erosion is serious during early periods following forest planting no doubt caused by the greater disturbance to soils during plantation preparation, and most likely related to the low NPP in the early years following forest planting (Laganière *et al.*, 2010). Moreover, while forest played a C sequestration function in the long term, soil C stocks had significantly decreased in shrubland and grassland after cropland had been converted for 30 years. This is attributed to more soil C gain from aboveground litter and roots and less soil C loss from erosion after forest planting (Chang *et al.*, 2011). The lack of soil disturbance during forest growth and the multistorey structure aboveground, and possibly belowground, could also play a role (Guo & Gifford, 2002). In addition, our synthesis showed that the rates of soil C stock change in 0–20 cm soils after cropland conversion were lower than the worldwide average (Table 3; IPCC, 2000; Guo & Gifford, 2002; Murty *et al.*, 2002; Vleeshouwers & Verhagen, 2002; Shi *et al.*, 2013); and 0–100 cm soil C stock change rate after cropland was converted to forest was also lower than the worldwide average (Table 3; Li *et al.*, 2012). This may be because most of the study sites were from warmer temperate regions where soil C stock change rates are lower than those for other climate zones (Post & Kwon, 2000) and the global average (Table 3).

A number of studies have shown that the tree species planted can have a major effect on the recovery of the soil C pool following afforestation (Guo & Gifford, 2002; Vesterdal *et al.*, 2002; Paul *et al.*, 2003; Lemma *et al.*, 2006; Laganière *et al.*, 2010; Li *et al.*, 2012). Our synthesis yielded similar conclusions (Figs 4 and 5; Table 1). The magnitude and dynamics of SOC stocks using different tree species after cropland conversion showed differences in pace of change (Figs 4 and 5), due to the variability in their C inputs (quantity and quality) and potential losses (Laganière *et al.*, 2010). In fact, species characteristics regulate soil C stocks by controlling C assimilation, transfer and stocks in the belowground biomass, and its release through soil respiration and leaching (De Deyn *et al.*, 2008). Different tree types have different biomass allocation strategies. A higher belowground biomass should therefore generate higher SOC inputs originating from the roots (Laganière *et al.*, 2010), and soil C stocks differences are largely regulated by species differences in aboveground litterfall inputs and decomposition, which is mainly controlled by litter quality (Hobbie *et al.*, 2007). For example, compared with the leaves of broadleaf forest (mainly *Eucalyptus* and hardwoods), the substrate quality of conifer forest is poorer, which leads to slower decomposition (Paul *et al.*, 2002). In our study, planting broadleaf forest had a greater effect on soil C stocks than planting conifer forest (Table 3). Moreover, globally, despite some discrepancies, most reviews agree that C stocks tend to decrease following afforestation with pine (conifer forest) but increase following afforestation with hardwoods (broadleaf forest) (Guo & Gifford, 2002; Paul *et al.*, 2002; Berthrong *et al.*, 2009; Laganière *et al.*, 2010; Li *et al.*, 2012). In addition, converting cropland into deciduous forest had a greater effect on soil C stocks than conversion to evergreen forest (Table 3). These differences may be related to their biomass allocation strategies and litter quality.

Effect of climate on soil C stocks change

Climate may affect soil C accumulation through those biotic processes associated with both the productivity of vegetation and decomposition of organic matter (Li *et al.*, 2012). At the global scale, the restoration of soil C stocks after afforestation was found to vary with climate (Guo & Gifford, 2002; Paul *et al.*, 2002; Yang *et al.*, 2011; Shi *et al.*, 2013), but Laganière *et al.* (2010) found that soil C stocks had no significant correlations with either annual average temperature or precipitation. Our synthesis found a similar result to that of Laganière *et al.* (2010) (Table 3) – some previous studies in China also found similar results to our study (Table 3, Chang *et al.*, 2011; Yang *et al.*, 2011). Annual average temperature and precipitation were likely to affect some stages after land use change, although they were not key factors affecting soil C stock change in general (Table 3). Our synthesis showed that annual average temperature was the main factor affecting the soil C stock in surface soil (0–20 cm) during the first 5 years following cropland conversion (Table 2). This suggested that the higher temperature sites displayed a higher C sequestration in the initial stage of cropland conversion. Those findings may be explained by slower plant growth and consequent lower soil C input observed in the colder regions and higher decomposition of soil organic matter in high temperature regions. Post and Kwon (2000) found a trend of increasing rates of soil C accumulation when moving from cool temperate to subtropical regions inferring that the amount of organic matter inputs, which increased with temperature and moisture, were the major factors determining the rate of accumulation. Although high temperature and high precipitation contribute to a high NPP and a higher C accumulation in plant biomass than in other biomes, the climatic conditions in tropical regions stimulate decomposition and thus reduce SOC stocks (Lal, 2005). Yet, Zhang *et al.* (2010) reported annual average precipitation was significantly and negatively correlated with the rate of SOC change, while Paul *et al.* (2002) observed that soil C accumulation increased with increasing annual average precipitation. This discrepancy may be attributed to evaluation methods, study area and data composition in the synthesis. In addition, after cropland had been converted for 30 years, annual average precipitation was the main factor affecting soil C stocks in the deeper soil (20–100 cm), and annual average temperature was the main factor by 40 years after conversion (Table 2). Thus, temperature and precipitation are the main factors determining soil C stock change in the later stage (>30 years) following cropland conversion.

Acknowledgements

The study was funded by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05060300), the Major Program of the National Natural Science Foundation of China (41390463) and the Scholarship Award for Excellent Doctoral Student granted by the Ministry of Education, PRC.

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