

Effects of Vegetation Restoration on Soil Organic Carbon in China: A Meta-analysis

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Abstract: Vegetation restoration has been proposed as an effective method for increasing both plant biomass and soil carbon (C) stocks. In this study, 204 publications (733 observations) were analyzed, focusing on the effects of vegetation restoration on soil organic carbon (SOC) in China. The results showed that SOC was increased by 45.33%, 24.43%, 30.29% and 27.98% at soil depths of 0–20 cm, 20–40 cm, 40–60 cm and > 60 cm after vegetation restoration, respectively. Restoration from both cropland and non-cropland increased the SOC content. The conversion of non-cropland was more efficient in SOC accumulation than the conversion of cropland did, especially in > 40 cm layers. In addition, the conversion to planted forest led to greater SOC accumulation than that to other land use did. Conversion period and initial SOC content extended more influence on soil C accumulation as the main factors after vegetation restoration than temperature and precipitation did. The SOC content significantly increased with restoration period after long-term vegetation restoration (> 40 yr), indicating a large potential for further accumulation of carbon in the soil, which could mitigate climate change in the near future.

Keywords: soil carbon content; vegetation restoration; land-use change; conversion period; restoration approach; China

Citation: Gong Li, Liu Guohua, Wang Meng, Ye Xin, Wang Hao, Li Zongshan, 2017. Effects of vegetation restoration on soil organic carbon in China: a Meta-analysis. *Chinese Geographical Science*, 27(2): 188–200. doi: 10.1007/s11769-017-0858-x

1 Introduction

Soil carbon accounts for 75% of total terrestrial carbon, and plays a significant role in the variation of atmospheric carbon dioxide (CO₂) concentrations (Henderson, 1995; Song *et al.*, 2014). In the past two centuries, conversion of natural vegetation to cropland is believed to increase the atmospheric CO₂ concentrations (Houghton *et al.*, 1999; Paul, 2002; Foley, 2005; Nouvellon *et al.*, 2012). Conversion of forest and pasture to cropland caused carbon loss from soil. Soil carbon stocks decreased by 42% and 59% after the conversion of forest and pasture to cropland, respectively (Guo and Gifford, 2002). Soil organic carbon (SOC) decreased by 25.2%, 21.3% and 10.4% by conversion of primary forest, sec-

ondary forest and grassland to cropland in the tropics, respectively (Don *et al.*, 2011). In contrast, SOC accumulated after conversion of cropland to perennial vegetation via increasing carbon derived from the new vegetation, thus alleviating the carbon loss from decomposition and erosion (Richter *et al.*, 1999; Lal *et al.*, 2002; Lal, 2004; Laganière *et al.*, 2010; Chang *et al.*, 2011). Soil carbon increased by 53%, 19% and 18% after conversion of cropland to secondary forest, tree plantation and pasture, respectively (Guo and Gifford, 2002). SOC increased by 25.7% and 17.5% after conversion of cropland to grassland and conversion of grassland to secondary forest in tropical areas, respectively (Don *et al.*, 2011). Therefore, vegetation restoration has been one of the significant strategies for climate change

Received date: 2016-07-12; accepted date: 2016-11-17

Foundation item: Under the auspices of Strategic Priority Research Program of Chinese Academy of Sciences (No. XDA05060104)

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mitigation (Zhang *et al.*, 2010). However, some studies reported that reforestation and afforestation of farmlands did not increase soil carbon (Bashkin and Binkley, 1998; Vesterdal *et al.*, 2002), or decreased SOC stocks during the initial 4–5 yr (Zhang *et al.*, 2010; Deng *et al.*, 2014).

SOC accumulation following land use change is affected by multiple factors including climate condition, land use history, vegetation type and site management, etc. (Guo and Gifford, 2002; Paul *et al.*, 2002; Lal, 2004; Laganière *et al.*, 2010; Li *et al.*, 2012). In addition, SOC accumulation can be affected by variant factors under different scale. Paul *et al.* (2002) concluded that climate ranked a significant factor influencing change in soil carbon (< 30 cm) after afforestation based on global data. However, land-use change such as the Grain for Green Program (GGP) largely increased the SOC in central and western China (Deng *et al.*, 2014; Song *et al.*, 2014). Therefore, knowing the factors affecting SOC accumulation under different land-scale and utilizing appropriate ecosystems management would benefit for soil carbon sequestration via afforestation (Post and Kwon, 2000; Lal, 2004; Li *et al.*, 2012).

In China, soil degradation and desertification has been caused by long-term agricultural exploitation (Lal, 2002). In order to restore the degraded environment, GGP project, the nation's largest ecological restoration project since the 1970s, was launched by the Chinese government. By 2012, 9.06×10^6 and 6.40×10^5 ha cropland had been converted to forest and grassland, respectively (State Forestry Administration, 2013). The large scale change in land use undertaken in China may indeed affect carbon sequestration capacity in terrestrial ecosystem. However, studies on the changes in soil carbon were based on forest-stand and/or regional scale, which brought about conflicting results due to variant restoration period and climate conditions (Li *et al.*, 2005; Xiao *et al.*, 2013), limiting the evaluation on the capacity of soil carbon accumulation during restoration. In addition, studies on the effects of the conversion of cropland have been reported (Song *et al.*, 2014). However, few studies were reported on the conversion of non-agricultural land to natural forest and/or grassland (Zhou *et al.*, 2006).

Meta-analysis, a powerful statistical technique for comparing and integrating the results from multiple independent studies, has been successfully used to evalu-

ate the effects of land-use change (Guo and Gifford, 2002), enhancement of biodiversity and ecosystem Services (Benayas *et al.*, 2009), tillage management (Van *et al.*, 2013), forest management (Johnson and Curtis, 2001), and grassland management (Conant *et al.*, 2001). In this study, a meta-analysis was conducted by analyzing previous studies conducted in China, as to investigate whether the directions and magnitudes of the vegetation restoration effects on SOC content differ based on the following variables: 1) ex-land use (non-cropland or cropland), 2) plantation type (conversion of cropland to forest, shrub land, grassland; conversion of pasture to grassland, conversion of plantation to natural forest and conversion of wasteland to plantation), 3) conversion period (i.e., time since conversion), and 4) mean annual temperature (MAT) and mean annual precipitation (MAP).

2 Materials and Methods

2.1 Data sources and calculations

Data and site information, as widely collected from literatures concerning soil carbon change following conversion of crop land, long-time closing hillsides, grassland fencing and establishment, were utilized in meta-analysis. Literature searching was performed via online reference database including Web of Science and The China Knowledge Resource Integrated Database, with 'vegetation restoration' and 'land use change' identified as key words. Data were extracted from publications reporting on the SOC or soil organic matter (SOM) contents in both restoration plots and control plots (i.e., cropland). Factors including climate conditions (precipitation and temperature), longitude, latitude, soil bulk density, soil sampling depth, restoration period and restoration modes were also extracted.

In some studies, only SOM was reported, soil organic carbon concentration (SOC_c) (g/kg) values are calculated as following (Guo and Gifford, 2002):

$$SOC_c = SOM \times 0.58 \quad (1)$$

where SOC_c is soil organic carbon concentration (g/kg); SOM represents soil organic matter (g/kg),

In other studies, only soil organic carbon stocks (SOC_s) was reported, SOC_c (g/kg) values are calculated as following (Guo and Gifford, 2002):

$$SOC_c = \frac{10 \times SOC_s}{D \times BD} \quad (2)$$

where SOC_s is soil organic carbon stocks (Mg/ha); BD is soil bulk density (g/cm) and D is soil thickness (cm).

A total of 137 publications containing 777 observations in 29 provinces, municipalities and autonomous region (from 1998 to 2016) (Fig. 1) were selected to conduct a comprehensive analysis. The selected observations were divided into four categories (based on the SOC sampling depth) as follows: 0–20 cm, 20–40 cm, 40–60 cm and > 60 cm. In addition, the observations were subdivided for each soil layer based on the initial SOC content in land use types (cropland or non-cropland), plantation types (forest, shrub land, grassland), as to better understand the factors regulating the direction and magnitude of SOC following restoration. Mean annual temperature (MAT) and mean annual precipitation (MAP) were also collected.

2.2 Meta-analysis

The effect size for each investigation (i.e., the response ratio) was calculated as follows (Cooper and Hedges, 1994):

$$r = \chi_e / \chi_c \quad (3)$$

where r represents the response ratio, χ_e is the mean SOC_c in restoration plots, χ_c is the mean SOC in the associated control plots.

To be used statistically, r must be log transformed as follows:

$$\ln(r) = \ln(\chi_e) - \ln(\chi_c) \quad (4)$$

In order to maximize the number of observations in the selected studies, an unweighted meta-analysis was used as described previously (Guo and Gifford, 2002).

Mean effect size for each categorical subdivision was calculated via Meta-Win 2.0 software, with a bias-corrected 95% confidence intervals (CIs) generated by a bootstrapping procedure (Song *et al.*, 2014). The effect of vegetation restoration on the SOC within a categorical subdivision was considered significant at $P < 0.05$ if the 95% CIs did not include 0 (Guo and Gifford, 2002). The total heterogeneity among groups (Q_t) was partitioned into within-group heterogeneity (Q_w) and between-

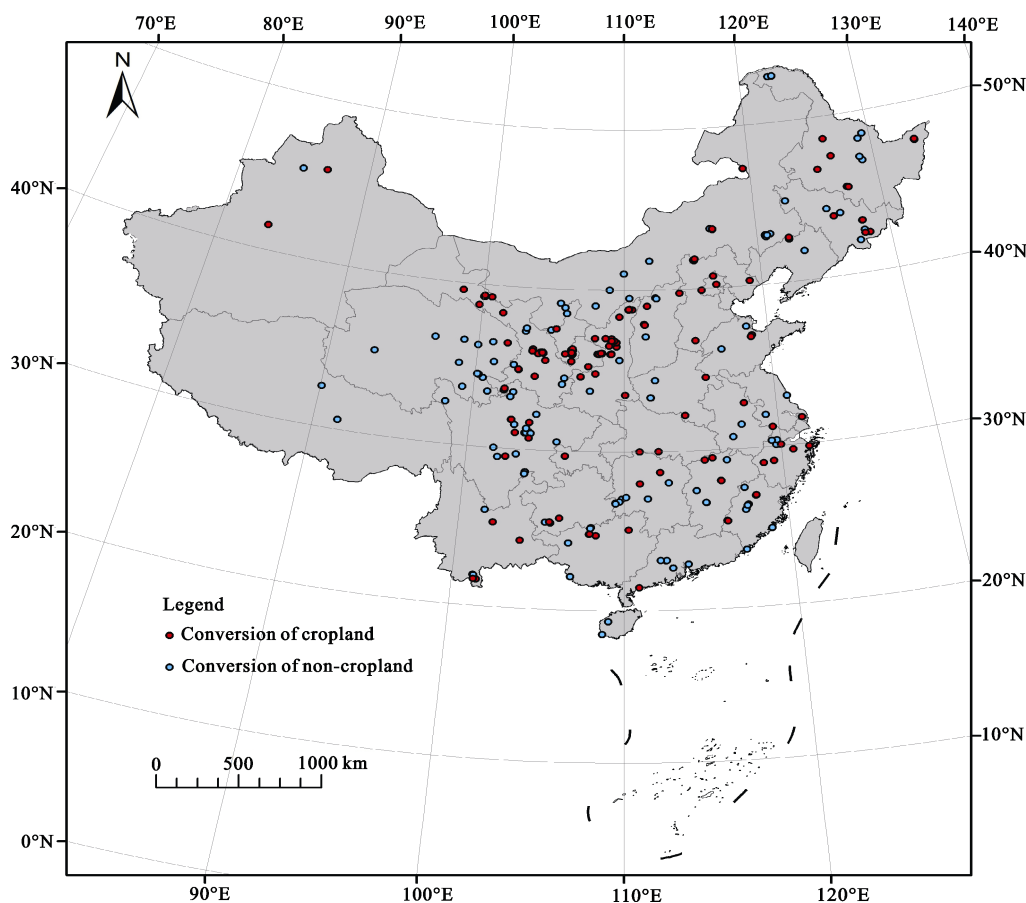


Fig. 1 Site distribution of studies on vegetation restoration included in the meta-analysis

group heterogeneity (Q_b) (i.e., $Q_t = Q_w + Q_b$). The Q_b for each categorical variable was determined for the response variable. A significance of Q_b indicated that effect size was different between different categorical subdivisions.

3 Results

Studies on the effects of vegetation restoration on SOC included 733 observations from 204 papers, in which 333 observations were related to restoration from cropland and 400 observations were related to restoration from non-cropland. The database covers provinces, municipalities and autonomous region in China, but most studies under restoration from cropland were in the following Loess Plateau, Middle-lower Yangtze Area and the Region of Hengduan Mountains.

3.1 Effects of vegetation restoration on SOC

Fig. 2 shows the SOC contents changes at different soil depths in response to vegetation restoration. The SOC content increased by 45.3%, 24.4%, 30.3% and 28.0% after vegetation restoration at the soil depth of 0–20 cm, 20–40, 40–60 cm and > 60 cm, respectively. In response to the restoration from cropland, SOC contents increased by 41.7% at soil depth of 0–20 cm, which was greater than the incensement at soil depths of 20–40 cm (19.3%), 40–60 cm (11.0%) and > 60 cm (18.6%). Similarly, In response to the restoration from cropland, the SOC contents increased by 48.4% and 51.2% at soil

depths of 0–20 cm and 40–60 cm, which are greater than the increase at soil depth of 20–40 cm (29%) and > 60 cm (35.1%). The results indicated that the increase in SOC content at soil depth of 0–20 cm under restoration from cropland showed no significant difference from the restoration from non-cropland. In contrast, the increase in SOC content at soil depth of 20–40 cm, 40–60 cm and > 60 cm under restoration from non-cropland were significantly higher than that under the restoration from cropland ($P > 0.05$).

3.2 Effects of vegetation restoration approach on SOC

Fig. 3 shows the changes of SOC contents following restoration from cropland (Fig. 3a) and non-cropland (Fig. 3b) via variant restoration types. SOC contents increased by 17.7%, 2.1% and 25.5% at soil depths of 0–20 cm, 20–40 cm and > 60 cm, while decreased by 10.3% at soil depth of 40–60 cm under the conversion of cropland to grassland (Fig. 3a). However, SOC contents increased by 59.8%, 33.8%, 17.4% and 41.6% at soil depths of 0–20 cm, 20–40 cm, 40–60 cm and > 60 cm, respectively, following the conversion of cropland to shrub land. Besides, increase of SOC contents by 55.8%, 25.3%, 20.8% and 6.5% at soil depths of 0–20 cm, 20–40 cm, 40–60 cm and > 60 cm were caused by the conversion of cropland to forests. The results suggested that the response ratios of the SOC content were increased under the restoration from cropland to natural vegetation, and conversion of cropland to shrub land or forest were higher than grassland in the 0–20 cm and 20–40 cm soil layers. Following the conversion of pasture to grassland, the SOC contents increased by 54.0%, 29.4% and 51.9% at soil depth of 0–20 cm, 20–40 cm and > 60 cm, while decreased by 26.03% at soil depth of 40–60 cm (Fig. 3b). Under the conversion of grassland to forest, SOC content increased by 65.2%, 45.2% and 58.5% at soil depths of 0–20 cm, 20–40 cm and 40–60 cm, while decreased by 55% at soil depth of > 60 cm. These results suggested that the response ratios of the SOC content under the conversion of grassland to forest were lower than the conversion of pasture to grassland at the no obvious land use change in < 40 cm soil layers. However, the response ratios of the SOC content under conversion of grassland to forest were higher than the conversion of pasture to grassland at the no obvious land use change in > 40 cm soil layers. With the conversion

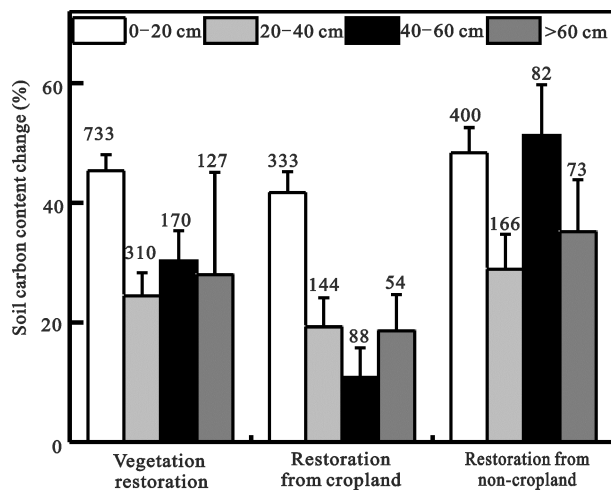


Fig. 2 Response ratios pertaining to effects of vegetation restoration on soil organic carbon contents at different soil depths. The error bars represent 95% confidence intervals (CI) and values above the bars are the corresponding number of observations

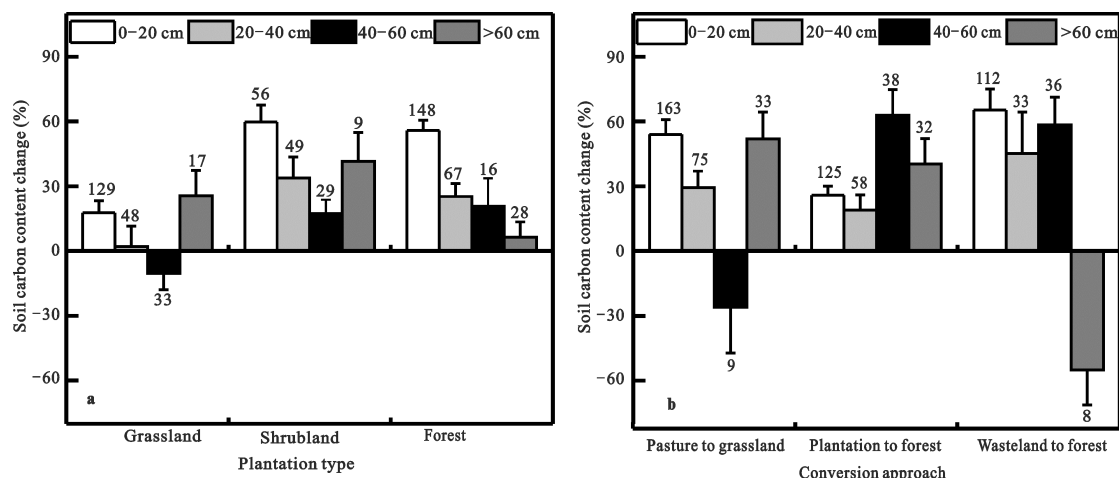


Fig. 3 Response ratios pertaining to the effects of plantation on SOC contents at different soil depths. (a) Restoration from cropland, (b) Restoration from non-cropland. The error bars represent 95% confidence intervals (CI) and values above the bars are the corresponding number of observations

of wasteland to forest, SOC contents increased by 25.9%, 19%, 62.9% and 40.4% at soil depths of 0–20 cm, 20–40 cm, 40–60 cm and > 60 cm, respectively. These results indicated that the restoration from forest was conducive to the accumulation of the SOC in deeper soil layers.

3.3 Effects of conversion period on SOC

Fig. 4 shows the effects of the restoration period on SOC contents at different soil depths after conversion. Generally, SOC content increased with increasing years since vegetation restoration from cropland (Fig. 4a) and non-cropland (Fig. 4b). SOC content in the 0–20 cm soil slightly decreased by 1.4% during 1–5 yr, then dramatically increased by 30.7% during 6–10 yr, followed by 89.8% increase after 30 yr restoration from cropland (Fig. 4a). SOC content at 20–40 cm soil started to decrease by 19.1% during 1–5 yr, then increased by 0.6 % during 6–10 yr, followed by 48.2% increase after 30 yr. SOC content was decreased by 26.4% at 40–60 cm soil during 1–5 yr restoration from cropland, then increased by 53.4% after 30 yr. However, SOC content at >60 cm soil increased by 31.9% during 1–5 yr, then decreased by 21.3% after 30 yr restoration from cropland. These results indicated that the response ratios of the SOC content decreased at the early stage of the vegetation restoration from cropland to natural vegetation (1–5 yr), and the loss of SOC could be reduced by reasonable management and restoration types.

SOC content at the 0–20 cm soil increased by 11.4%

during 1–5 yr restoration from non-cropland, and then gradually increased by 64.4% during 31–40 yr, followed by 106.1% increase after 40 yr (Fig. 4b). SOC content at 20–40 cm soil tended to increase by 7.4% during 1–5 yr, then increased by 17.2 % during 21–30 yr, followed by dramatic increase of 98.4% after 40 yr. SOC content decreased by 9.6% at 40–60 cm soil during 1–5 yr, then increased by 40.5% during 6–10 yr restoration from non-cropland, followed by increase of 75.2% after 40 yr. 4.6% increase of SOC content was observed at > 60 cm soil during 1–5 yr, followed by 50.4% increase of SOC content during 21–30 yr restoration from non-cropland. Then 33.4% increase of SOC content was observed at > 60 cm soil after 40 yr. These results indicated that the response ratios of the SOC content did not decrease at the early stage due to the no obvious land use change or conversion of grassland to forest, and suggested that the loss of SOC at early stage in the process of vegetation restoration could be prevented by the protection of natural vegetation and plantation.

3.4 Effects of mean annual precipitation on SOC

Fig. 5 depicts the effects of multi-year average precipitation on the SOC content at different soil depths. With restoration from cropland, SOC content at 0–20 cm soil gradually increased by 17.8%, 46.2% and 50.7% with the regional precipitation < 400 mm, 400–800 mm and > 800 mm, respectively (Fig. 5a). SOC content at 20–40 cm was reduced by 0.5% with precipitation < 400 mm, while tended to increase by 18.7% and 37.3% with

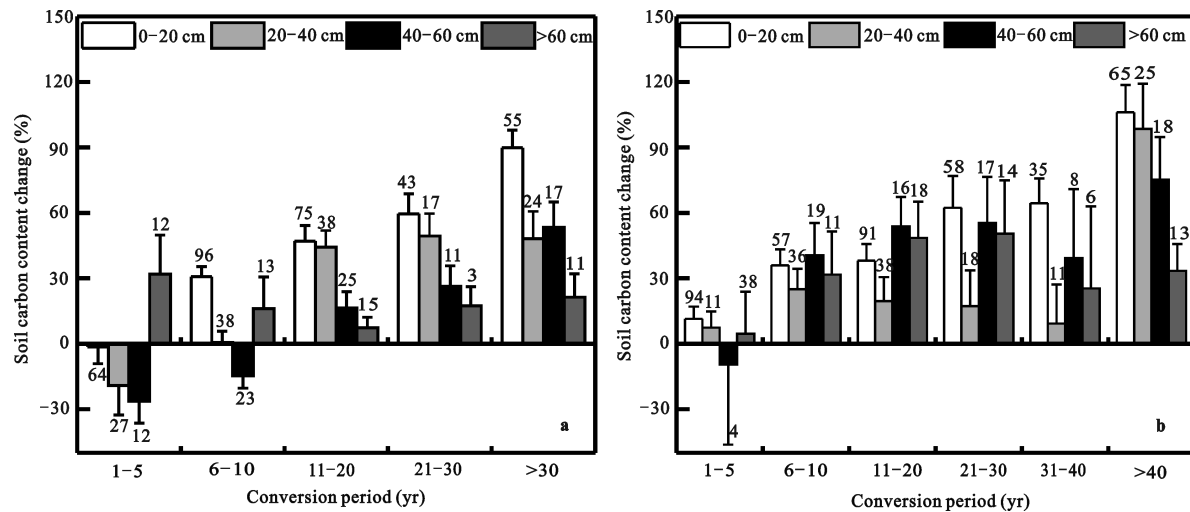


Fig. 4 Response ratios pertaining to the effects of conversion period on SOC contents at different soil depths. (a) Restoration from cropland, (b) Restoration from non-cropland. The error bars represent 95% confidence intervals (CI) and values above the bars are the corresponding number of observations

precipitation 400–800 mm and > 800 mm, respectively. At soil depth of 40–60 cm, SOC content was decreased by 23.3% and 7% with precipitation < 400 mm and > 800 mm, while increased by 18.7% with 400–800 mm precipitation. SOC content at > 60 cm layers was reduced by 9.7% with precipitation < 400 mm, followed by 21.9% and 10.6% increase with precipitation 400–800 mm and > 800 mm. The results indicated that the accumulation of SOC content after restoration from cropland in middle and high-precipitation regions were higher than that in low precipitation region in 0–20 cm and 20–40 cm soil layers. However, the accumulation of SOC content after restoration from cropland in middle-precipitation was higher than high and low precipitation regions in deeper layers. In addition, in low-precipitation region, the SOC content was decreased in soil layer > 20 cm, indicating the loss of SOC in deeper soil layers may occur by restoration from cropland in arid area.

After the restoration from non-cropland, SOC content at 0–20 cm soil was increased by 70.5%, 54.1% and 31.4% with precipitation < 400 mm, 400–800 mm and > 800 mm, respectively (Fig. 5b). While increase of 26.6%, 38.6% and 18.4% in SOC content at 20–40 cm soil were observed with precipitation < 400 mm, 400–800 mm and > 800 mm. For the 40–60 cm soil, SOC content at which increased by 41%, 62.7% and 43.8% with precipitation < 400 mm, 400–800 mm and > 800 mm, respectively. However, SOC content at > 60 cm soil increased by 42.9%, 46.5% and 17.6% with precipitation < 400 mm, 400–800 mm and > 800 mm, respectively.

These results suggested that the response ratios of the SOC content in the restoration from non-cropland were higher than that in the restoration from cropland, with no conspicuous land-use change, the SOC content were increased in three group regions in all soil layers, and the accumulation rates of SOC content decreased with MAP increasing in surface 0–20 cm layer. In addition, the accumulation rates of SOC content in middle-precipitation was higher than high and low precipitation regions.

3.5 Effects of mean annual temperature on SOC

The effects of MAT on SOC at different soil depth were shown in Fig. 6. SOC contents tended to increase as MAT elevated. After cropland conversion, SOC content at surface soil (0–20 cm) increased by 38.7%, 41.5% and 44.2% with MAT < 6°C, 6°C–10°C and > 10°C, respectively (Fig. 6a). In the deeper soil (20–40 cm), SOC content increased by 11.5%, 16.5% and 31.9% with MAT < 6°C, 6°C–10°C and > 10°C, respectively. In soil depth of 40–60 cm, SOC content showed highest increase by 14.7% with MAT 6°C–10°C, followed by 5% increase with MAT > 10°C, while reduced by 11.7% with MAT < 6°C. SOC content at > 60 cm soil increased by 21.2% and 9.3% with MAT 6°C–10°C and > 10°C, but decreased by 2.8% with MAT < 6°C (Fig. 6a). These results indicated that the response ratios of the SOC content in the restoration from cropland was not significantly different among the three groups in surface

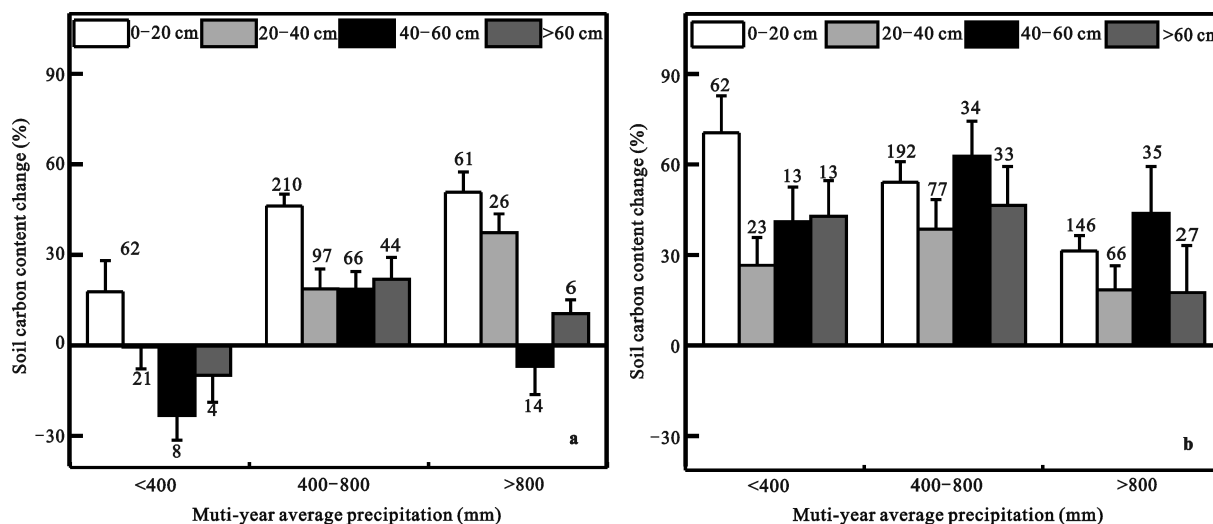


Fig. 5 Response ratios pertaining to the effects of MAP on soil organic carbon contents at different soil depths. (a) Restoration from cropland, (b) Restoration from non-cropland. The error bars represent 95% confidence intervals (CI) and values above the bars are the corresponding number of observations

0–20 cm, and increased in 20–40 cm layers with the MAT increased. In addition, in deeper soil layers, the SOC content was decreased in cold regions and the accumulation rates of SOC in middle-temperature was higher than that in warmer and colder regions.

Following non-cropland conversion, SOC content at 0–20 cm soil increased by 43.1%, 78.2% and 24.5% with MAT < 6°C, 6°C–10°C and > 10°C, respectively (Fig. 6b). At 20–40 cm soil, highest increase of SOC (63.9%) was observed with MAT < 6°C, followed by 27.9% and 11.8% increase with MAT 6°C–10°C and > 10°C. SOC content at 40–60 cm soil gained highest in-

crease (116%) with MAT < 6°C, followed by 41% and 34.2% increase with MAT > 10°C and 6°C–10°C. In addition, SOC content at > 60 cm soil increased by 75%, 46.2% and 8.1% with MAT < 6°C, 6°C–10°C and > 10°C following the restoration from non-cropland. These results suggested that the response ratios of the SOC content in the restoration from non-cropland were significantly higher than that in the restoration from cropland. Partly due to no conspicuous land-use change, the SOC contents were increased in three group regions in all soil layers, and the accumulation rates of SOC decreased with the MAT increased except in surface 0–20 cm layer.

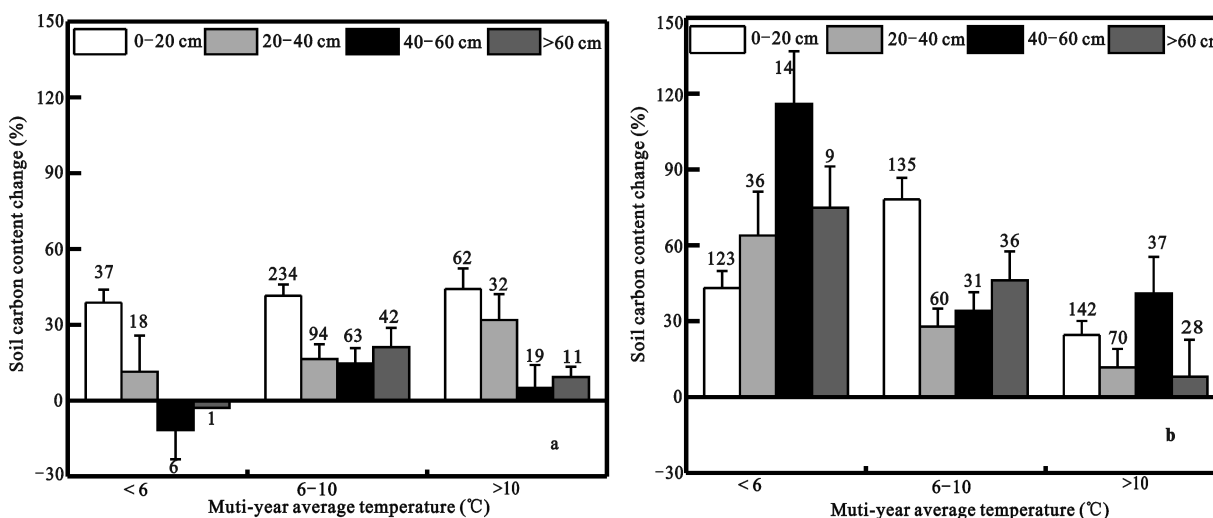


Fig. 6 Response ratios pertaining to the effects of MAT on soil organic carbon contents at different soil depths. (a) Restoration from cropland, (b) Restoration from non-cropland. The error bars represent 95% confidence intervals (CI) and values above the bars are the corresponding number of observations

3.6 Factors affecting SOC under vegetation restoration

The statistical analysis of the between-group heterogeneity (Q_b) showed that the vegetation restoration had significant effects on the SOC at depths of 40–60 cm ($P < 0.01$, Table 1). After the restoration from cropland, both the plantation type ($P < 0.05$) and conversion period ($P < 0.001$) had significant effects on the SOC in the 0–20 cm, 20–40 cm and 40–60 cm of soil, whereas these effects were not significant at a depth of > 60 cm. After restoration from non-cropland, both the plantation type and conversion period ($P < 0.001$) had significant effects on the SOC in the 0–20 cm layer, whereas these effects were not significant at a depth of 40–60 cm. Conversion period ($P < 0.001$) had significant effects on the SOC at a depth of 20–40 cm, while the plantation type ($P < 0.001$) had no significant effects on the SOC at the depth of > 60 cm.

Pearson correlation analysis showed that the response ratios of the SOC to vegetation restoration had correlation with mean annual precipitation (MAP) at the depth of top 0–20 cm (Table 2). Significant negative relationships were observed between the response ratios of the

SOC and MAT in soil layers > 20 cm after restoration from non-cropland, while positive correlation was observed between the response ratios of the SOC and MAP both in 0–20 cm and 20–40 cm soil layers. In addition, significantly negative relationships were also showed between the responses ratios of the SOC and the initial SOC content in cropland (control plot). in the 0–20 cm, 20–40 cm and > 60 cm layers.

4 Discussion

The SOC content was determined by the carbon input from plant litter and the carbon output due to soil respiration (Vesterdal *et al.*, 2002). Vegetation restoration has the potential to result in C accretion through the buildup of plant biomass and soil C (Zinn *et al.*, 2005), and a large number of results were proved that the vegetation restoration may increase the SOC content in several ways: increasing the soil carbon input by affecting the net primary productivity (NPP) (Smith, 2008); reducing the loss of soil carbon while preventing soil erosion (Don *et al.*, 2011); Decreasing soil carbon output by altering soil biological and chemical processes

Table 1 Effects of vegetation on between-group heterogeneity (Q_b) in relation to soil organic carbon response ratio

Depth (cm)	Conversion type	Categorical variable	Q_b	F
0–20	Total	Cropland/non-cropland	0.80	1.40
		Plantation type	12.23***	16.63
	Restoration from cropland	Conversion period	27.34***	21.10
		Conversion approach	10.02***	7.26
		Conversion period	7.89***	5.67
20–40	Total	Cropland/non-cropland	0.72	1.59
		Plantation type	2.26**	3.49
	Restoration from cropland	Conversion period	9.74***	8.86
		Conversion approach	1.45	1.33
		Conversion period	14.90***	6.32
40–60	Total	Cropland/non-cropland	6.94***	17.33
		Plantation type	1.40**	3.53
	Restoration from cropland	Conversion period	6.60***	11.74
		Conversion approach	6.07***	5.58
		Conversion period	2.88	0.95
> 60	Total	Cropland/non-cropland	0.84	2.08
		Plantation type	0.97	2.61
	Restoration from cropland	Conversion period	0.42	0.51
		Conversion approach	7.52***	8.16
		Conversion period	1.75	0.62

Notes: *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$

Table 2 Pearson correlation coefficients between soil organic carbon response ratio and other factors

	Soil layer (cm)	MAT	MAP	SOC _{in}	N
Total	0–20	0.010	0.120**	–0.129**	733
	20–40	–0.105	0.023	–0.197**	310
	40–60	–0.109	–0.024	–0.006	170
	>60	–0.167	–0.117	–0.356**	127
Restoration from cropland	0–20	0.044	0.157**	–0.216**	333
	20–40	0.173*	0.200*	–0.306**	144
	40–60	0.035	–0.056	–0.116	88
	>60	0.008	–0.038	–0.180**	54
Restoration from non-cropland	0–20	–0.003	0.094	–0.105*	400
	20–40	–0.260**	–0.102	–0.144*	166
	40–60	–0.263*	–0.098	–0.054	82
	>60	–0.259*	–0.184	–0.406**	73

Notes: MAT: mean annual temperature; MAP: mean annual precipitation; N: number of samples. *: $P < 0.05$; **: $P < 0.01$; SOC_{in}: the initial SOC content

(Post and Kwon, 2000; Laganière *et al.*, 2010). In China, Song *et al.* (2014) reported that SOC contents in 0–20 cm layer significantly increased by 55.6% and 36.9% after the conversion of cropland to forest and grassland. In this work, abovementioned results suggested that the SOC content could be increased by vegetation restoration in china. The SOC content increased by 41.7% after vegetation restoration from cropland at soil depth of 0–20 cm (Fig. 2) was slightly lower than Song's report that SOC increased by 48.1% (Song *et al.*, 2014). Moreover, the SOC accumulation rates (Fig. 2) under vegetation restoration from non-cropland were higher than that under vegetation restoration from cropland, indicating that SOC contents gained more incensement under non-cropland restoration than that under cropland restoration, especially in deeper soil layers (> 20 cm). This phenomenon was probably due to longer conversion period of non-cropland than that of cropland in China. In addition, partly due to the cropland with slope gradient over 25° and degraded/decertified barren land will be restored in China (Chang *et al.*, 2011), soil carbon could be decreased during the early stage by soil erosion, resulting in a certain period of time for restoring the original level need (Turner *et al.*, 2006).

4.1 Conversion type

The restoration type could also greatly affect the SOC accumulation by affecting carbon inputs and loss. It was widely accepted that SOC increased after the conversion of cropland to natural vegetation (Guo and Gifford, 2002; Don *et al.*, 2011; Song *et al.*, 2014). Guo and

Gifford (2002) reported that SOC stocks significantly increased by 18%, 53% and 19% after the conversion of cropland to plantation, secondary forest and pasture, respectively. Don *et al.* (2011) also proved that SOC stocks increased by 29% and 26% after conversion of cropland to forest and grassland. This study showed a similar rate of increase (Fig. 3a) to the rate reported by Guo and Gifford (2002). The result implied that the conversion of cropland to forest or shrub land was a more efficient way to accumulate carbon in soil than the conversion of cropland to grassland did. Moreover, the SOC was higher in shrub land than that in forest, which could be speculated that this trend occurred because 90% of the shrubs used in cropland restoration are N-fixing. Such shrubs allocated more of their photosynthetic production into the deep soil layer compared to trees (Song *et al.*, 2013). According to the previous studies, confusing results of soil C change were reported following the conversion of non-cropland to another vegetation type. For example, Guo and Gifford (2002) reported that SOC stocks increased by 8% after conversion of forest to pasture. Don *et al.* (2011) indicated that SOC stocks declined by 6.3% after conversion of forest to grassland. However, SOC stocks declined after the conversion of cropland or pasture to grassland at the early conversion period (Hopkins *et al.*, 2009). When no conspicuous vegetation type change occurred after vegetation restoration, like pasture closure, forest tending and natural forest protection, the SOC increased by loss of carbon (Zhang *et al.*, 2015), decreasing mechanical disturbance (Oudenhoven *et al.*, 2015) and increasing aboveground biomass input (Cook *et al.*, 2014).

The response ratios of the SOC content in conversion of pasture to grassland was higher than conversion of plantation to forest at soil depths of 0–20 cm, 20–40 cm, while the SOC content conversion of pasture to grassland was less than conversion of plantation to forest at soil depths of 40–60 cm and > 60 cm (Fig. 3b). The reason might be that the growth of SOC need longer recovery time in deep soil layer, and the period of conversion of pasture to grassland was less than that of conversion of plantation to forest (Ni *et al.*, 2012). In this study, these result implied that forest protection could be conducive to the accumulation of SOC in deep soil.

4.2 Conversion period

With increasing period of vegetation restoration, there was an increase in carbon inputs due to the accumulation of the aboveground and below-ground biomass, accompanied by decrease of the soil temperature, enhancing water holding capacity and promoting SOC accumulation (Laganière *et al.*, 2010; Shi *et al.*, 2013). It was reported that conversion period was the important factors which affected SOC content after restoration. Because of the different local environmental conditions, land use history and restoration and management strategies (Shi *et al.*, 2013), the amount of the SOC loss and the beginning time of net SOC accumulation were variable. The different results could be summarized as the following: 1) an increase (Mao *et al.*, 2010; Deng *et al.*, 2013); 2) a decrease (Muf *et al.*, 2008; Smal and Olszewska, 2008); and 3) an initial decrease in soil C during the early stage, followed by a gradual return of C stocks to cropland levels and then continue to grow (Zhang *et al.*, 2010; Karhu *et al.*, 2011). In this study, SOC content decreased at the early stage of the restoration from the cropland to natural vegetation (1–5 yr), and return of SOC content to previous land use level may take 10 years or more in deep soil (Fig. 4a). This result could be explained by soil erosion on steep (most of the cropland were restored with slope gradient over 25°) slopes (Chang *et al.*, 2011), by lack of litter input at the early stage because of the lower NPP (Knorr *et al.*, 2005), and by increasing soil respiration rate via reducing vegetation (Curtis and Wang, 1998) and increasing dead roots pool. The result also showed that there were significant increases in the SOC content after 30 yr restoration later as compared with that during 10–30 yr,

especially in deeper layers, and indicated that vegetation types might change again after 30 yr. The increased rate of the SOC content in deeper layers was less than that of the surface layers and need a long restoration period back to the original level. However, under the restoration from non-cropland, due to the soil erosion reduced by unobvious land use and less disturbance after restoration, SOC content did not decrease at the early stage (except 40–60 cm), and the increased rate of the SOC content in deeper layers was faster for the surface layers in 6–20 yr, it could be explained by the SOC content with high level in surface layer and large dead roots pool in deeper layers in previous land. However, the significant increases of SOC content was delayed until 40 yr later, and the SOC content after restoration 40 yr was still lower than that in the natural forest (> 40 cm), implying that the soil still have large carbon sequestration potential after vegetation restoration in China in the future.

4.3 Climate factors

Climate could affect soil C accumulation through temperature and precipitation, and influence both the productivity of vegetation and decomposition of litter by different soil and vegetation types (Li *et al.*, 2012; Deng *et al.*, 2014). At the global scale, the soil C accumulation after afforestation was found to vary with precipitation (Guo and Gifford, 2002; Shi *et al.*, 2013). In China, annual average temperature and precipitation were not key factors affecting soil C stock change (Chang *et al.*, 2011; Yang *et al.*, 2011), and might affect some stages after land use change (Deng *et al.*, 2014). In this study, it was found that the relative SOC change in the top soil (0–20 cm) after restoration was sensitive to MAP, while the relative SOC change in the top soil (0–20 cm) after restoration was sensitive to MAT after restoration from cropland. In addition, the relative SOC changes correlated with MAT significantly. However, annual average temperature and precipitation were not key factors affecting soil C stock change after both the restoration from cropland and non-cropland, such as the initial SOC or plantation type, these results could be supported by the study of Laganière *et al.* (2010). The reasons might be as follows: i) For the restoration from cropland, most sites involved in the current study were located in the arid and semiarid regions, especially the Loess Plateau of China, and the soil moisture significantly affected the

accumulation of SOC (Chang, 2011), ii) the litter layer on the former grassland or forest might weaken the effects of climate factors on the SOC. In this study, the accumulation of SOC content after the restoration from cropland in middle-precipitation and high-precipitation regions were higher than that in low-precipitation region in 0–20 cm and 20–40 cm soil layers. In addition, the influence of MAT on the accumulation of SOC content was similar to MAP. In the low-precipitation and high-precipitation condition, SOC content was decreased in the deeper (> 40 cm) layers. The reason might be that in the arid and semi-arid regions, slow accumulation of SOC was resulted from the slow input of the underground biomass at the early period (Beniston *et al.*, 2014). Higher level precipitation increased NPP (Qiu *et al.*, 2012), however, soil erosion might slow down the accumulation of soil organic carbon (Ma *et al.*, 2016).

The response ratios of the SOC content after the restoration from non-cropland were increased in three group regions in all soil layers, which showed that the SOC content might decrease in the arid and cold regions after the restoration from cropland. Reasonable vegetation restoration types and managements might be need in arid and semi-arid regions.

4.4 Uncertainty analyses

In this study, the accumulation of SOC under the conversion to forest was higher than other restoration types in deeper layers (> 40 cm), indicating an effective direction of carbon sequestration for terrestrial ecosystems as well as climate change mitigation in the future. However, the data available was limited especially in deeper soil layers (> 60 cm) by the slow process in soil C accumulation, which might weaken the certainty of the results to some extent. In addition, 733 sites reviewed in this study, including 29 provinces, municipalities, and autonomous regions, which were mainly distributed in the eastern and middle parts (especially in the Loess Plateau) of China (Persson *et al.*, 2013). Therefore, the results might affect by some dominant data from certain region. Moreover, the effect of tree species (Song *et al.*, 2014), soil types (Chai *et al.*, 2015) and topographical variations (Schulp and Verburg, 2009) on soil C change were not analyzed in this study, which might weaken the determination of the factors about soil organic carbon accumulation. During the Grain for Green Project, di-

versities of soil erosion in different regions led to the significantly different changes of SOC content at the early period of restoration (Olson *et al.*, 2016). In addition, community dynamics during the process of vegetation restoration had a significant impact on the accumulation of soil organic carbon (Liu *et al.*, 2016). These differences could lead to unpredictable results.

5 Conclusions

Vegetation restoration could accumulate SOC in China. The SOC increased by 45.33%, 24.43%, and 30.29%, 27.98% at soil depths of 0–20 cm, 20–40 cm, 40–60 cm and > 60 cm, respectively. The response of carbon accumulation to vegetation restoration was greater in the surface soil layer than in the deeper soil layers. The restoration from non-cropland was more efficient regarding the accumulating SOC than the restoration from cropland, especially in > 40 cm layers, and conversion to forest leads to greater SOC accumulation than conversion to other land use did. The initial time since the vegetation restoration was positively correlated with the SOC accumulation, and was contrast with the restoration from cropland. SOC content did not decrease at the early stage (except 40–60 cm) after the restoration from non-cropland. In addition, carbon sequestration still increased after 40-year vegetation restoration in China. Moreover, this study showed that the SOC content might decrease after the restoration from cropland in the low-precipitation and the low-temperature region, while the SOC content showed highest increase in the mid-precipitation and the mid-temperature region after the restoration from cropland. In addition, the SOC content significantly increased after the restoration from non-cropland in the low-precipitation and the low-temperature region, while increased slowly in high-precipitation and high-temperature region.

In China, most research on vegetation restoration has focused exclusively on conversion of cropland to forest or grassland. This work focused on SOC accumulation and changing rule after different conversion approaches in China. These findings provided more appropriate types to the accumulation of SOC stocks after the vegetation restoration, implying that SOC accumulation in terrestrial ecosystems after vegetation restoration had great potential to mitigate the effects of climate change in the future.

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