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Soil Carbon Sequestration Potential for "Grain for Green" Project in Loess Plateau, China

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Abstract Conversion of cropland into perennial vegetation land can increase soil organic carbon (SOC) accumulation, which might be an important mitigation measure to sequester carbon dioxide from the atmosphere. The "Grain for Green" project, one of the most ambitious ecological programmes launched in modern China, aims at transforming the low-yield slope cropland into grassland and woodland. The Loess Plateau in China is the most important target of this project due to its serious soil erosion. The objectives of this study are to answer three questions: (1) what is the rate of the SOC accumulation for this "Grain for Green" project in Loess Plateau? (2) Is there a difference in SOC sequestration among different restoration types, including grassland, shrub and forest? (3) Is the effect of restoration types on SOC accumulation different among northern, middle and southern regions of the Loess Plateau? Based on analysis of the data collected from the literature conducted in the Loess Plateau, we found that SOC increased at a rate of 0.712 TgC/year in the top 20 cm soil layer for 60 years under this project across the entire Loess Plateau. This was a relatively reliable estimation based on current data, although there were some uncertainties. Compared to grassland, forest had a significantly greater effect on SOC accumulation in middle and southern Loess Plateau but had a weaker effect in the northern Loess Plateau. There were no differences found in SOC sequestration between shrub and grassland across the entire Loess Plateau. Grassland had a stronger effect on SOC sequestration in the northern Loess Plateau than in the middle and southern regions. In contrast, forest could increase more SOC in the middle and southern Loess Plateau than in the northern Loess Plateau, whereas shrub had a similar effect on SOC sequestration across the Loess Plateau. Our results suggest that the "Grain for Green" project can significantly increase the SOC storage in Loess Plateau, and it is recommended to expand grassland and shrub areas in the northern Loess Plateau and forest in the middle and southern Loess Plateau to enhance the SOC sequestration in this area.

Keywords SOC · Restoration age · General linear model · Grassland · Shrub · Forest

Introduction

Soils play a significant role in the global carbon cycle. Soil organic carbon (SOC) storage is estimated at approximately 1500 Pg globally, about two and three times the size of carbon pools in the atmosphere and vegetation, respectively (Jobbágy and Jackson 2000; Lal 2004). In recent years, the interest in using soil as a carbon sink has been rapidly increasing (Izaurralde and McGill 2000; Lal 2004; Thuille and Schulze 2006; Heimann and Reichstein 2008; Lu and others 2009), as it was proposed in Article 3.4 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change and prescribed in later Marrakech accord to include carbon sequestration in soil to partially meet Quantified Emission Limitation or Reduction Commitments.

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Soil can lose up to 40 percent of its organic carbon into the atmosphere when perennial vegetation land is converted into cultivation land (Houghton and others 1999; Murty and others 2002; Liu and others 2003; van der Werf and others 2009). In contrast, conversion from cultivation land into perennial vegetation land is found to accumulate SOC by increasing carbon derived from new vegetation and decreasing carbon loss from decomposition and erosion (Richter and others 1999; Post and Kwon 2000; Guo and Gifford 2002; Martens and others 2003; Lal 2004; Paul and others 2002; Laganière and others 2010). Martens and others (2003) found that soil carbon accumulated at an average rate of 61.5 and 160 gC/m^2/year during cropland conversion into pasture and secondary forest, respectively, in Central America. An average gain of 37 gC/m^2/year is estimated following perennial vegetation establishment from cropland around China (Zhang and others 2010a). Globally, the average rate of soil carbon sequestration is similar between grassland and forest establishment (33.2 gC/m^2/year for grassland and 33.8 gC/m^2/year for forest) for 100 years according to Post and Kwon (2000). Although the potential of soil carbon sequestration is large after cropland conversion into perennial vegetation land, there are still contradictory findings. For example, no change in soil carbon after afforestation was observed in some cases (Bashkin and Binkley 1998; Vesterdal and others 2002; Degryze and others 2004). Bashkin and Binkley (1998) found that soil carbon increased in the top 10 cm of soil following afforestation of sugarcane fields in 10–13 years in Hawaii, but it was offset by a loss of post sugarcane-derived carbon from the lower layer (10–55 cm), and the total SOC did not change. A decrease in soil carbon was also found in initial years after arable land abandonment (Johnston and others 1996; Li and others 2005). Nevertheless, the phenomenon of decrease or no change in soil carbon is probably due to lower productivity of new vegetation in early years and higher carbon loss from soil disturbance (Bashkin and Binkley 1998; Vesterdal and others 2002; Nouvellon and others 2008; Don and others 2009; Zhang and others 2010a; Laganière and others 2010).

Some reviews have analyzed the factors that determine soil carbon sequestration during perennial vegetation establishment (Post and Kwon 2000; Guo and Gifford 2002; Paul and others 2002; Laganière and others 2010). Many factors play significant roles that affect the direction and magnitude of soil carbon change after land use change, such as previous land use, soil property, climate, and soil management (Post and Kwon 2000; Guo and Gifford 2002; Paul and others 2002; Laganière and others 2010), but there is not yet a consensus on the relative significance of these factors. For instance, Paul and others (2002) have found that climate is one of the most important factors influencing soil carbon change after cropland conversion. However, climate had a smaller effect on soil carbon accumulation during afforestation compared to other factors, including previous land use, tree species planted, soil clay content, and preplanting disturbance (Laganière and others 2010). Furthermore, the effects of these factors depend on the spatial scale. For example, at a local scale, forest plantation from cropland had a greater effect on soil carbon sequestration than grassland establishment (Del Galdo and others 2003; Martens and others 2003). At a national or global scale, the change in soil carbon was similar between grassland and forest establishment (Post and Kwon 2000; Guo and Gifford 2002; Zhang and others 2010a).

The Loess Plateau in China, with an area of 6.2×10^5 km^2, is well known as one of the most severely eroded areas in the world (Fu 1989). In order to control soil erosion in the Loess Plateau, the Chinese government has launched some major programmes. The “Grain for Green” project was one of the most ambitious programmes launched in this region. This project was initiated in 1999 in some local areas and expanded in 2000 to the whole plateau, with the goal of converting approximately 2.04×10^6 ha of croplands with slopes greater than 15° into woodland and grassland (Chen and others 2007). In this project, cropland is normally converted into grassland, shrub, and forest. The effects of this project on soil carbon in the Loess Plateau have been increasingly studied since the onset of the project (Fu and others 2000; Gong and others 2006; Chen and others 2007; Wei and others 2009). However, most of these studies were conducted at local sites, and soil carbon sequestration and controlling processes at a regional scale remain unclear. The main objectives of this study are to study and quantify the following: (1) the SOC sequestration potential of the “Grain for Green” project in Loess Plateau, (2) if there are differences in SOC sequestration among three types of restoration vegetation establishment (i.e., grassland, shrub, and forest), and (3) whether the effects of the perennial vegetation establishments on SOC accumulation are different among different climate zones.

Methods

Literature Review and Data Preparation

Our data were widely collected from the literatures concerning carbon change in soil following conversion from long-time cultivated cropland to forest, shrub, and grassland in the Loess Plateau. All of the studies that were reviewed were designed with a chronosequence sampling method. The sites reported from literature were widely distributed across the Loess Plateau (Fig. 1), concentrating

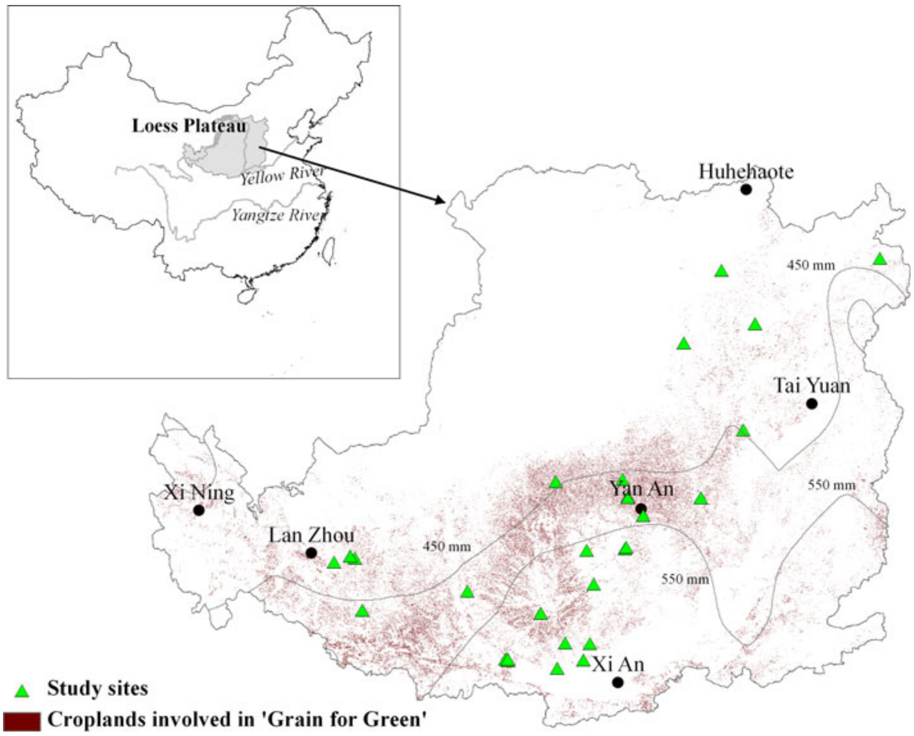

Fig. 1 Geographic locations of the study sites and croplands involved in the "Grain for Green" project in the Loess Plateau

mostly in the areas where the "Grain for Green" project was implemented. Reviewed studies could be organized into two categories: category one (27 studies) containing paired information of SOC or SOM content from both the control cropland and the converted land use, and category two (19 studies), which reported only the SOC or SOM content from the converted land use without information on control cropland. The missing SOC contents of the cropland in category two were found and matched with data from other reports at the same sites. The final database used for this research contained 172 observations (Appendix 1). The time since land use change ranged from 1 to 60 years. Additionally, long-term mean temperature, annual precipitation, and SOC change since land use transition at each site were included in the database.

In this study, we only considered SOC sequestration in the top 20 cm layer for two reasons. First, most of the studies (92%) only reported SOC or SOM change in the top 20 cm of soil. Second, studies have showed that there are significant differences in soil carbon only in topsoil, but not in subsoil, following land use change in the Loess Plateau (Wei and others 2009; Fu and others 2010).

Nevertheless, not all studies reported SOC changes in the top 20 cm layer. A few reported at different soil sample depths (e.g., 2 studies with 7 observations at 10 cm, 1 study with 1 observation at 15 cm, and 1 study with 3 observations at 40 cm). These data with different sample depths needed to be adjusted to the top 20 cm. In this study, using a 10-cm sample depth as an example, we assumed that there was no change in SOC density in the 10- to 20-cm layer between the conversion type and the corresponding cropland. In other words, the SOC density change examined in the top 10-cm layer was equal to the SOC density change in the whole top 20-cm layer. The other observations with different sample depths were adjusted similarly.

SOC Density and Change Estimation

Ellert and Bettany (1995) and Ellert and others (2006) recommended that the equivalent mass method (SOC density calculated based on a reference soil mass), taking the effect of soil bulk density change on soil carbon density into consideration, can be more accurate in detecting differences among different land use than the fixed-depth approach. However, the equivalent mass method was not used in this study to estimate SOC density change because the soil bulk density of different land use was not compared in many studies and was missing in some cases. So, we estimated and compared SOC density of different land use to a fixed depth (20 cm in this study) (see Eqs. 1 and 3). For the observations without soil bulk density, the soil bulk density of the same land use and soil series was used.

The SOC density of different land uses could be calculated as following:

$$SOCD = SOC \times BD \times H \times 10 \qquad (1)$$

where *SOCD* is SOC density of different land use (MgC/ha); *SOC* is soil organic carbon content (g/kg); *BD* is soil bulk density (g/cm^3), and H is thickness of soil (cm). If only soil organic matter content (SOM) was reported, SOC was calculated using Eq. 2.

$$SOC = SOM \times 0.58 \tag{2}$$

SOC density change following conversion from cropland was estimated by Eq. (3):

$$C_{seq} = SOCD_{other} - SOCD_{cropland} \tag{3}$$

where $SOCD_{other}$ and $SOCD_{cropland}$ are SOC densities of the converted land and corresponding cropland, respectively (MgC/ha), and C_{seq} is the SOC density change from cropland conversion into forest, shrub, or grassland (MgC/ha).

Estimation of the SOC Sequestration Potential for the "Grain for Green" Project in the Loess Plateau

The Loess Plateau can mainly be divided into three climate zones: northern Loess Plateau with precipitation below 450 mm, middle Loess Plateau with precipitation between 450 and 550 mm, and southern Loess Plateau with precipitation above 550 mm (Li and others 2008). It was suggested by Li and others (2008) that grassland and shrub should be the main restoration vegetation types in the northern Loess Plateau, that forest should be the primary conversion type in the southern Loess Plateau, and that in the middle Loess Plateau, grassland, shrub, and forest should be established. According to their suggestions (Li and others 2008), we assumed that the cropland involved in the "Grain for Green" project was converted into grassland and shrub in the northern Loess Plateau, forest, grassland, and shrub in the middle Loess Plateau, and forest in the southern Loess Plateau. SOC sequestration potential for the "Grain for Green" project in the Loess Plateau was estimated based on this assumption. In each of the three climate zones of the Loess Plateau, SOC sequestration potential was calculated by the average time–weighted rate of SOC change ($C_{time-weighted}$), and the area of cropland involved in this project in each subregion. The total SOC sequestration potential for the project in the entire Loess Plateau was the sum of the SOC sequestration potentials estimated in the three subregions.

Estimation of Average Time–Weighted Rate of SOC Change

The average rate of SOC change in each climate zone was calculated as a mean value that was weighted for time using the following equation described by Paul and others (2002).

$$C_{time-weighted} = \sum_{i=1}^{n} C_{seqi} / \sum_{i=1}^{n} age_i \tag{4}$$

where C_{seqi} and age_i are the change in SOC density and years since land use change (involving in grassland and shrub establishment in the northern Loess Plateau, forest, shrub and grassland establishment in the middle Loess Plateau, and forest plantation in the southern Loess Plateau) in each observation, respectively; n is number of the observations, which are 43, 55 and 33 in the northern, middle and southern Loess Plateau, respectively.

Estimation of Area of Cropland Involved in the Project

In the Loess Plateau, croplands with 15 degrees of slope or more were chosen for inclusion in the "Grain for Green" project (Uchida and others 2005; Chen and others 2007. The areas of cropland including criterion involved in this project in different climate zones of the Loess Plateau and in the whole Loess Plateau were obtained from overlaying a land-use map of the launch year of 2000 and a 90-m resolution digital elevation model (DEM). The land-use map was obtained using Landsat TM and ETM remote sensing images in 2000, and the output images were composed of 200 m × 200 m pixels. Land-cover could be divided into several types, including cropland.

Statistical Analysis

The restoration age has been found to play a significant role in SOC sequestration (Paul and other 2002; Zhang and others 2010a). A general linear model (GLM) was used to control for the influence of the restoration age by setting this variable as a covariate in the model according to Zhang (2002). Then, this model was used to compare the effects among grassland, shrub and forest and to compare the effects of the restoration vegetation types on SOC change among different climate zones. The main effects were compared by LSD method in GLM, and the significance threshold was set at 0.05. The variables and their transformations that were included in the GLM model are listed in Table 1. All analyses were performed using the GLM procedure of SPSS 11.0.

Results

Average Rate of SOC Change in Different Climate Zones and SOC Sequestration Potential of "Grain for Green" in the Loess Plateau

Under the "Grain for Green" project, 6.00×10^5, 9.76×10^5 and 4.54×10^5 ha of cropland with slopes greater than 15° were converted into perennial vegetation land in the northern, middle and southern Loess Plateau, respectively

Table 1 Variables of general linear model of SOC sequestration

Category	Variables	Units	Transformation for statistical analysis
Climate	Precipitation (northern Loess Plateau $\leq$ 450 mm; 450 mm < middle Loess Plateau < 550 mm and southern Loess Plateau $\geq$ 550 mm)	3 categories	
Management	Restoration age	years	none
	Conversion types: grassland, shrub and forest	3 categories	
SOC sequestration	SOC sequestration in top 20 cm	MgC/ha	$\ln(x - \min(x) + 10)$

Table 2 Average rates of SOC change in different climate zones and SOC sequestration potential of "Grain for Green" in Loess Plateau

Climate zone	Rate of SOC sequestration (Mg C/ha/year)	Land use conversion from cropland	Median of restoration age (year)	Area (ha)	SOC sequestration potential (TgC/year)	Number of observation
Northern LP	0.39	Grassland and shrub	10	6.00×10^5	0.234	43
Middle LP	0.29	Grassland, shrub and forest	20	9.76×10^5	0.283	55
Southern LP	0.43	Forest	20	4.54×10^5	0.195	33
Whole project	–	–	–	2.03×10^6	0.712	–

Northern LP indicates northern Loess Plateau with precipitation below 450 mm, Middle LP indicates middle Loess Plateau with precipitation between 450 mm and 550 mm, and Southern LP indicates southern Loess Plateau with precipitation above 550 mm. The SOC sequestration potential of whole project is the sum of the SOC sequestration potential in the different climate zones

Table 3 Proportion of the variances of SOC sequestration explained by the variables in GLM

Factors	Restoration age	Precipitation	Conversion type	Precipitation × conversion type
SOC sequestration	17.5**	0.8	1.1	9.2**

** Significant at 0.05 level

(Table 2). SOC in the top 20-cm layer increased at rates of 0.39 MgC/ha/year for 43 years, 0.29 MgC/ha/year for 60 years and 0.43 MgC/ha/year for 50 years after perennial vegetation land was established in the northern, middle and southern Loess Plateau, respectively (Table 2). Among the three climate zones, the SOC sequestration potential was found to be the highest in the middle Loess Plateau due to this geographical locale having the largest area of croplands in this subregion, whereas the SOC sequestration potential was lowest in the southern Loess Plateau, which has the smallest area of the corresponding croplands (Table 2). The total SOC sequestration potential of "Grain for Green" was estimated at about 0.712 TgC/year for 60 years with 2.03×10^6 ha cropland converted in the whole Loess Plateau (Table 2).

Effects of Impact Factors on SOC Sequestration

All of the variables that were examined explained 28.2% of the variation for SOC sequestration in GLM analysis (Table 3). Of the variables examined, restoration age explained the greatest proportion of the variation for soil carbon change (17.5%), but both the conversion type and precipitation explained a small proportion of the variation (Table 3). This result indicated that there was no difference in SOC sequestration among different climate zones and among different conversion types at the Loess Plateau scale. However, the significant effect of the interaction between precipitation and conversion type shown in Table 3 suggested that the effects of conversion type were significantly different among different climate zones. This was supported by the comparison of the effects of conversion type among different climate zones in the GLM (Fig. 2). Forest had a weaker effect on SOC accumulation in the northern Loess Plateau than in the other two zones (Fig. 2a), while grassland had a greater effect in the northern Loess Plateau (Fig. 2c). The effect of shrub on SOC sequestration was not found to be different among the three zones (Fig. 2b).

The comparison of the effects of different restoration types on SOC sequestration showed that there was no difference among grassland, shrub and forest in the northern Loess Plateau (Fig. 3c). However, soil carbon in the forest increased much more than in grassland or shrub in the middle Loess Plateau (Fig. 3b). In the southern Loess Plateau, forest had a stronger effect on SOC sequestration than grassland but had a non-significant effect compared to shrub (Fig. 3a).

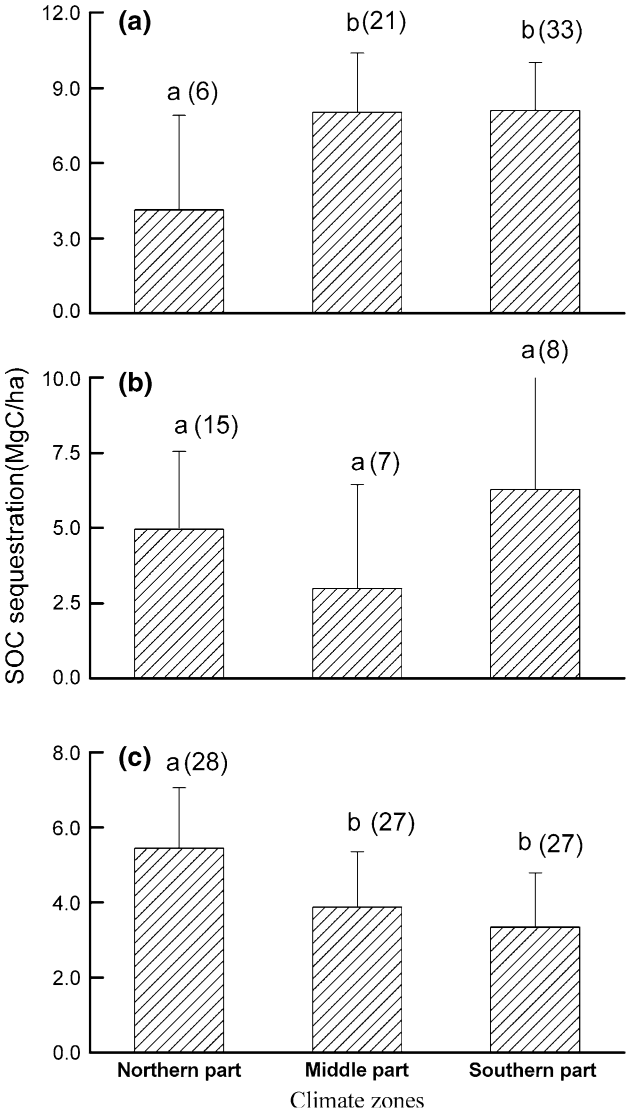

Fig. 2 Influence of different climate zones on SOC sequestration after cropland conversion into forest (**a**), shrub (**b**) and grassland (**c**). The error bars are the standard errors of the mean. A different letter means a difference significant at 0.05 level. The number of observations is indicated in parentheses. Northern part—northern Loess Plateau with precipitation below 450 mm; Middle part—middle Loess Plateau with precipitation between 450 mm and 550 mm; Southern part—southern Loess Plateau with precipitation above 550 mm

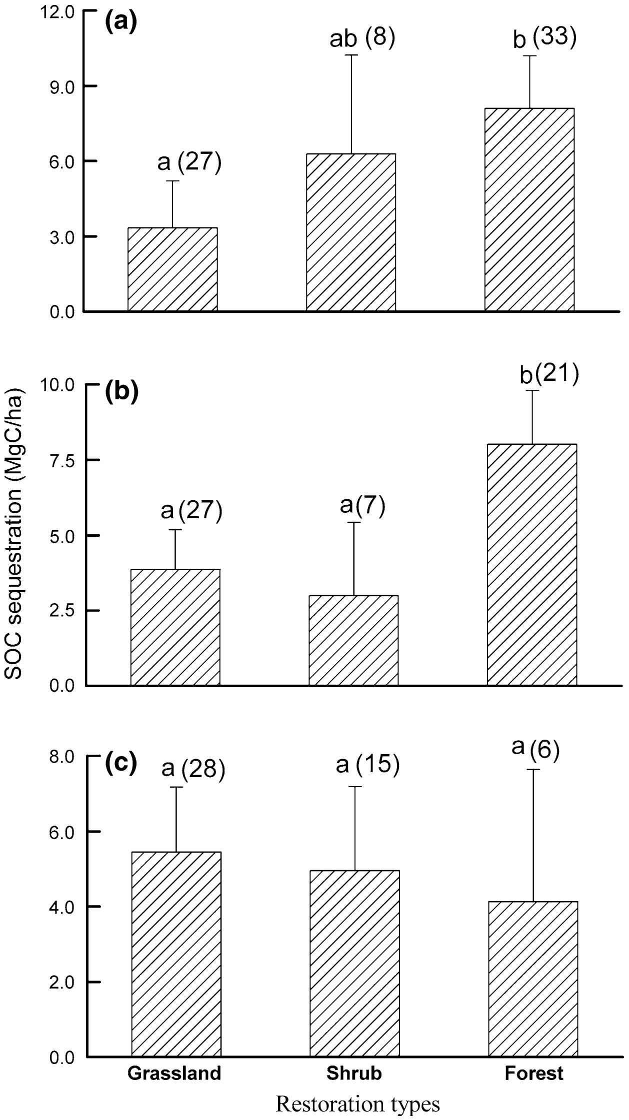

Fig. 3 Influence of different restoration type on SOC sequestration in southern Loess Plateau (**a**), middle Loess Plateau (**b**) and in northern Loess Plateau (**c**). The error bars are the standard errors of the mean. A different letter means a difference significant at 0.05 level. The number of observations is indicated in parentheses

Discussion

SOC Sequestration Potential of "Grain for Green" in Loess Plateau and Uncertainties

The SOC accumulation potential of the "Grain for Green" project in the Loess Plateau was 0.712 TgC/year (Table 2), comprising 6.1% of the total soil carbon sequestration for this project in the whole country, and the area involved in the Loess Plateau accounted for about 6.4% of the total area of this project (Zhang and others 2010a). These results indicated that the SOC sequestration rate (TgC/year/ha) of this project in the Loess Plateau was similar to the average rate of the whole project in China.

Chen and others (2007) found that SOC accumulated at about 17.37 MgC/ha in the top 40 cm of soil following land use change at the Anjiapo catchment, which has been located in the western part of the Loess Plateau for 29 years. This result has been scaled up to the overall "Grain for Green" project in the Loess Plateau by multiplying it by the area (2.04×10^6 ha, similar to our study). It was estimated that SOC storage increased by 35.6 TgC for this project over 29 years in the top 40 cm of soil (Chen and others 2007), which is approximately two times greater than our finding in the same time interval with about 20.6 TgC (data not shown). The difference between our study and that of Chen and others (2007) is partly due to the different soil sample depths. Furthermore, the error in their estimation may be greater than our study because they do not take the spacial heterogeneity of environmental factors (such as precipitation) into consideration.

Although we have provided the most accurate estimation of SOC sequestration potential for "Grain for Green" project across the entire Loess Plateau, there were some uncertainties in this study. First, some uncertainties may result from the fixed-depth method used in estimating SOC density and change in each observation. Some studies conducted at several sites in the Loess Plateau have found that the soil bulk density in cropland is greater than that of other transition types (Peng and other 2005; Zhang and others 2008). Therefore, the usage of the fixed-depth method may lessen the difference in SOC density change between the transition type and the corresponding cropland and then underestimate the SOC sequestration potential of the project, especially in the areas with high SOC concentration beneath the maximum sampling depth (e.g., 20 cm) (Van den Bygaart and Angers 2006). In contrast to the fixed-depth method, the equivalent mass method can reduce the error in estimating SOC change (Ellert and Bettany 1995; Ellent and others 2006; Van den Bygaart and Angers 2006). Therefore, it is necessary that we collect more data on soil bulk density and use the equivalent mass method to estimate SOC sequestration in the future to improve the estimation accuracy, especially in the southern and middle Loess Plateau due to the higher SOC in these two areas. Second, some error could also be due to the chronosequence method used in the studies that we reviewed. There are generally three types of methods used in calculating the SOC change, including repeated measurements on the same site, paired sites comparison and chronosequence; chronosequence has been suggested to cause the largest error (Murty and others 2002). Up to now, few studies have used the repeated measurements method or paired sites method in the Loess Plateau. More measurements conducted with these more accurate methods are needed to reduce the uncertainties in estimating SOC sequestration. Third, some uncertainties may be attributed to the uneven distribution of the observations with less observations collected in the southern Loess Plateau (Table 2) and the limited number of sites in a large study area (Falloon and others 2002; Lu and others 2009). More field measurements, especially in the southern Loess Plateau, are needed to reduce the uncertainties. Fourth, some uncertainties are introduced by the calculation of SOC sequestration with the average rate of SOC accumulation because the temporal pattern of SOC accumulation is found to be non-linear in many studies (e.g., Post and Kwon 2000; Paul and others 2002; Zhang and others 2010a). Additionally, the rate of SOC accumulation is normally greater in early conversion stage (Niu and Duiker 2006; Zhang and others 2010a). In this study, half of the observations collected were measured in the early period (Table 2), which can result in overestimation of SOC sequestration. In the future, more studies with longer measurement time are needed to reduce these uncertainties.

To summarize, most uncertainties are derived from limited data, which can be reduced by more field measurements conducted with higher accurate methods and longer measurement time added. However, such measurements are presently scarce. Thus, the calculation of SOC sequestration potential is a relatively reliable estimation based on current data.

Comparison of the Effects of Conversion Types on SOC Sequestration among Different Climate Zones

The SOC accumulation rate during afforestation in the northern Loess Plateau was lower than in the middle and southern Loess Plateau (Fig. 2a). This result is consistent with other findings that the soil carbon accumulation increases with increasing mean annual precipitation (e.g., Paul and others 2002). The decreased SOC accumulation in the northern Loess Plateau is due to more sandy soil, lower soil carbon input from aboveground and greater soil carbon loss from erosion. The soils in the northern Loess Plateau have more sand, and the sandier soils are found to accumulate less carbon than the soils with more clay (Post and Kwon 2000; Guo and Gifford 2002; Paul and others 2002; Laganière and others 2010). The aboveground biomass and productivity of forest are found to decrease sequentially from south to north across the Loess Plateau (Xiao 1990; Lu 1993). Thus, carbon input from aboveground litter in forest is lowest in the northern Loess Plateau. In addition, the extensive and intensive soil erosion in the northern Loess Plateau is suggested to explain in part the lower contents of SOC in Chinese Pine ecosystem in this subregion (Wei and others 2009).

Despite the aboveground biomass of forest in the middle Loess Plateau being lower than in the southern Loess Plateau, no difference in SOC accumulation between the southern and middle Loess Plateau was found (Fig. 2a). This result can be explained partly by the higher fine root biomass in forest ecosystem in middle Loess Plateau than in southern Loess Plateau (unpublished data). Fine roots have been suggested to play a significant role in SOC accumulation (Richter and others 1999; Rasse and others 2005; Bird and Torn 2006).

In contrast to forest plantation, grassland establishment had a greater effect on SOC sequestration in the northern

Loess Plateau than in the middle and southern Loess Plateau (Fig. 2c). This indicated that grassland should be recommended in the northern Loess Plateau to improve soil carbon sequestration potential. Soil erosion is claimed to be serious in early periods of grassland establishment from sloping cropland because of low vegetation cover (Lin and others 2007). Therefore, the higher carbon loss from erosion associated with higher precipitation in the middle and southern Loess Plateau at early conversion stage may in part contribute to the lower SOC accumulation in these two regions compared to the northern Loess Plateau. In addition, the temperature and precipitation were both higher in the middle and southern Loess Plateau compared to the northern Loess Plateau (Appendix 1), and these two climate factors are well known to have a positive relationship with SOC decomposition (Raich and Schlesinger 1992; Davidson and others 1998; Fang and others 2005). Thus, the higher loss of soil carbon from decomposition is another reason for lower SOC accumulation during grassland establishment in the middle and southern Loess Plateau.

Precipitation was a significant factor that influenced the change in soil carbon during grassland and forest establishment from cropland in the Loess Plateau as shown above, but it did not contribute to restoring SOC stocks following shrub plantation (Fig. 2b). In other words, shrub had a similar effect on SOC accumulation across the Loess Plateau.

Comparison Among Grassland, Shrub, and Forest

Compared to grassland, forest increased SOC sequestration in the middle and northern Loess Plateau (Fig. 3a, b). Our finding is also supported by other evidence from the Loess Plateau (Wang and others 2001; Gong and others 2006). This condition is attributed to more soil carbon gain from aboveground litter and roots and less soil carbon loss from erosion during forest plantation compared to grassland establishment. It has been observed in some stations in the Loess Plateau that carbon input into soil from aboveground vegetation and roots is higher in forest than in grassland (Fan and others 2006; Wei and Shangguan 2006; Guo and others 2009; Zhang and others 2009a). Additionally, the soil microbial biomass in forest has been found to be higher than in grassland in the Loess Plateau (Xue and others 2009), which is beneficial to sequester soil carbon through improved soil aggregate stability (Caravaca and others 2002) and increased nutrient cycling in forest. Soil erosion is suggested to be serious in early periods following grassland establishment (Lin and others 2007). On the other hand, soil carbon loss from erosion may be far lower during forest plantation because site preparation before afforestation plays a significant role in erosion control (Jiao and others 2002; Cai and others 2009). In the drier northern Loess Plateau, however, SOC accumulation was found to be higher in grassland than in forest, although the difference was not significant ($P = 0.174$) (Fig. 3c). This result is due to the notable decrease in soil carbon accumulation in forest and a significant increase in SOC sequestration in grassland in the northern Loess Plateau (Fig. 2a, 2c). At an entire Loess Plateau scale, there was no difference in SOC sequestration between grassland and forest as shown in GLM analysis (Table 3). At a larger scale, the average rates of SOC accumulation have also been found to be similar between grassland and forest in China (Zhang and others 2010a) and globally (Post and Kwon 2000).

At local sites, studies have found increases (Gong and others 2006; Chen and others 2007; Fu and others 2010), decreases (Lv and Zheng 2009; Wei and others 2009) and no difference (Wang and others 2001; Hu and others 2009) in SOC accumulation in shrub compared with forest. Also, compared to grassland, the effects of shrub on SOC accumulation are different at a local scale. For example, some studies show that shrub can accumulate more carbon into soil than grassland (Gong and others 2006; Chen and others 2007; Fu and others 2010), but other studies report that there is no difference (Wang and others 2001). However, at a whole Loess Plateau scale, we found that there was no significant difference between shrub and forest or grassland (Table 3).

Conclusion and Management Implication

The initial goal of the "Grain for Green" project was to control soil erosion in the Loess Plateau; meanwhile, this project is also playing a significant role in soil carbon sequestration. The SOC sequestration of the "Grain for Green" project in the Loess Plateau could reach 0.712 TgC/year base on recent data collected. Although China does not have any commitment for reducing emission of greenhouse gas for the present under the Kyoto Protocol, attention should still be paid to the significant role of the "Grain for Green" project in carbon sequestration.

As far as restoring SOC stocks for the "Grain for Green" project in the Loess Plateau, the different types of restoration vegetation should be established in different climate zones: grassland and shrub establishment are recommended in northern Loess Plateau, and forest has a greater effect in middle and southern Loess Plateau. Additionally, the plantation cost and adaptability of forest also should been taken into consideration.

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Appendix 1

See Table 4.

Experimental Data of SOC Sequestration in Loess Plateau

Sites (County/ Province)	Longitude/ Latitude	Temperature (°C)	Precipitation (mm)	Restoration types	Restoration age (years)	SOC sequestration (MgC/ha)	Reference
Heshui, Gansu	108.50°, 36.06°	7.5	575	Grassland	4	−2.97	Zhang and others (2006)
Ansai, Shaanxi	109.25°, 36.76°	8.8	505	Grassland	30	8.68	Dai and others (2008)
				Forest	30	7.84	
				Shrub	30	6.76	
				Forest	30	8.29	
Yongshou, Shaanxi	108.08°, 34.82°	10.8	601	Grassland	20	7.65	Zhang and others (2003)
				Shrub	20	6.05	
				Forest	20	1.61	
Yongshou, Shaanxi	107.93°, 34.48°	10.8	601	Shrub	5	1.50	Li and others (1998)
				Forest	33	6.50	
Qianyang, Shaanxi	107.06°, 34.62°	10.8	653	Forest	30	8.90	Zhang and others (2008)
				Forest	20	6.16	
				Forest	5	5.49	
				Forest	8	2.17	
Yanan, Shaanxi	110.52°, 36.70°	9.4	535	Forest	15	9.32	Fu and others (2000)
				Grassland	15	2.52	
Yanan, Shaanxi	110.52°, 36.70°	9.8	558	Grassland	25	6.55	Bai and others (2005)
				Forest	25	8.82	
				Shrub	25	−3.02	
Ansai, Shaanxi	109.25°, 36.76°	8.8	485	Grassland	25	6.55	Bai and others (2005)
				Forest	25	5.04	
				Shrub	25	0.76	
Wuqi, Shaanxi	108.00°, 37.00°	7.8	483	Grassland	25	11.59	Bai and others (2005)
				Forest	25	5.04	
				Shrub	25	1.51	
Pengyang, Ningxia	106.43°, 35.55°	7.6	475	Grassland	25	10.96	Wang and others (2009a)
				Forest	25	7.59	
Changwu, Shaanxi	107.68°, 35.23°	9.1	584	Grassland	30	10.43	Liu and others (2005)
				Forest	30	2.30	
				Shrub	30	10.30	
				Forest	30	10.30	
				Forest	30	10.22	
				Forest	50	18.67	
Wuqi, Shaanxi	108.00°, 37.00°	7.8	483	Grassland	6	1.66	Jiao and others (2006)
				Grassland	20	−0.68	
				Grassland	40	9.98	
				Shrub	4	1.01	
				Shrub	18	2.02	
				Forest	33	3.02	
				Forest	60	6.55	
Yongshou, Shaanxi	107.93°, 34.48°	10.8	601	Forest	40	32.50	Zhao and others (2008)
Shenmu, Shaanxi	110.37°, 38.80°	8.4	437	Forest	28	0.30	Wei and others (2009)
				Shrub	28	2.30	
				Grassland	28	0.70	

Table 4 continued

Sites (County/ Province)	Longitude/ Latitude	Temperature (°C)	Precipitation (mm)	Restoration types	Restoration age (years)	SOC sequestration (MgC/ha)	Reference
Dingxi, Gansu	104.63°, 35.30°	7	427	Forest	30	5.82	Chen and others (2007)
				Shrub	30	14.27	
				Grassland	5	1.61	
				Forest	30	4.01	
Chunhua, Shaanxi	108.50°, 34.80°	9.2	600	Forest	23	8.60	Li and Pang (2010)
				Forest	7	17.08	
Fuxian, Shaanxi	109.18°, 36.08°	9	577	Grassland	2	−5.20	Li and others (2005)
				Grassland	4	1.00	
				Grassland	14	6.00	
				Grassland	34	10.80	
Yuzhong, Gansu	104.50°, 36.00°	6.5	395	Grassland	7	17.08	Guo and others (2003)
				Shrub	30	8.66	
Yanan, Shaanxi	109.50°, 36.50°	9.8	558	Grassland	13	10.30	Ma and others (2007)
				Shrub	9	10.98	
				Shrub	20	17.82	
				Forest	18	4.61	
				Forest	12	−1.96	
Yuzhong, Gansu	104.14°, 35.95°	6.2	328	Grassland	20	0.54	Li and others (2009)
Yuzhong, Gansu	104.14°, 35.95°	6.2	328	Shrub	10	2.38	Wang and others (2007a)
				Forest	20	5.40	
				Grassland	5	3.67	
Heshui, Gansu	108.60°, 35.60°	7.4	575	Forest	12	21.93	Wang and others (2009b)
				Forest	20	14.03	
				Forest	32	10.73	
Qianyang, Shaanxi	107.10°, 34.60°	10	627	Forest	8	7.01	Zhang and others (2009a)
Yanan, Shaanxi	109.50°, 36.50°	9.8	558	Grassland	4	−0.21	Liu and others others (2007)
				Grassland	8	3.50	
				Grassland	16	2.88	
				Grassland	29	3.50	
				Grassland	55	4.94	
Ansai, Shaanxi	109.25°, 36.76°	8.8	505	Forest	5	7.89	Xue and others (2005)
				Forest	10	10.37	
				Forest	15	5.18	
				Forest	20	13.07	
				Forest	25	11.04	
				Forest	30	24.79	
				Forest	43	23.44	
				Grassland	5	3.16	
				Grassland	6	0.00	
				Grassland	8	4.51	
				Grassland	10	0.68	
				Grassland	14	1.35	
				Grassland	22	2.48	
				Grassland	42	10.37	
				Grassland	50	7.21	

Table 4 continued

Sites (County/ Province)	Longitude/ Latitude	Temperature (°C)	Precipitation (mm)	Restoration types	Restoration age (years)	SOC sequestration (MgC/ha)	Reference
Ansai, Shaanxi	109.25°, 36.75°	8.8	549	Grassland	1	3.00	Luo and others (2003)
				Grassland	2	−0.96	
				Grassland	3	4.39	
				Grassland	5	5.03	
				Grassland	8	0.61	
				Grassland	11	5.47	
Wuzai, Shanxi	111.66°, 39.00°	5	400	Shrub	5	1.65	Ji and others (2007)
				Shrub	10	1.86	
				Shrub	20	3.55	
				Shrub	30	3.86	
Yongshou, Shaanxi		10	611	Forest	35	16.03	Wang and others (2006)
Fuxian, Shaanxi	109.16°, 36.06°	9	576	Grassland	1	−3.61	Lv and Zheng (2009)
				Grassland	5	−0.85	
				Grassland	10	10.32	
				Grassland	20	9.47	
				Grassland	30	19.61	
				Grassland	40	0.77	
				Grassland	50	6.97	
Qianyang, Shaanxi	107.10°, 34.62°	10.9	677	Forest	5	7.83	Wang and others (2007b)
				Forest	26	23.13	
Shenmu, Shaanxi	110.37°, 38.80°	8.4	437	Grassland	5	0.10	Li and others (2007)
				Grassland	20	1.80	
				Shrub	30	2.10	
Qianyang, Shaanxi	107.10°, 34.62°	10.9	627	Forest	8	6.52	Zhang and others (2009b)
				Forest	8	−0.38	
Qianyang, Shaanxi	107.10°, 34.62°	10.9	627	Forest	26	7.52	Zhang and others (2010b)
Guangling, Shanxi	114.00°,39.75°	7	410	Grassland	6	5.37	Xiao and others (2009)
Changwu, Shaanxi	107.68°, 35.23°	9.1	584	Grassland	18	3.11	Yang and Rong (2007)
				Shrub	16	9.05	
				Forest	19	7.71	
				Forest	18	8.65	
				Forest	20	6.94	
				Forest	18	3.11	
Linyou, Shaanxi	108.38°, 34.58°	9.2	640	Forest	10	4.26	Han and Han (2005)
Linyou, Shaanxi	108.38°, 34.58°	9.2	640	Forest	22	5.15	Han and others (2007)
				Forest	22	8.24	
				Shrub	22	4.07	
Yuzhong, Gansu	104.42°, 36.03°	6.2	328	Grassland	3	2.22	Jia and others (2006)
				Grassland	5	6.22	
				Grassland	6	6.80	
				Grassland	9	5.14	
				Grassland	10	7.11	
				Grassland	13	7.30	
				Grassland	14	7.67	
				Grassland	26	12.01	

Table 4 continued

Sites (County/ Province)	Longitude/ Latitude	Temperature (°C)	Precipitation (mm)	Restoration types	Restoration age (years)	SOC sequestration (MgC/ha)	Reference
Wuzai, Shanxi	111.66°, 39.00°	5	400	Grassland	3	3.66	Wang and others (2007c)
				Shrub	30	−0.46	
				Forest	30	2.19	
Ansai, Shaanxi	109.17°, 37.00°	8.8	505	Grassland	4	0.24	Wen and others (2005)
				Grassland	11	0.94	
				Grassland	19	2.12	
				Grassland	27	4.96	
				Grassland	45	6.14	
Yanan, Shaanxi	109.50°, 36.50°	9.8	558	Grassland	4	−1.65	Wen and others (2007)
				Grassland	16	−1.24	
				Grassland	20	0.00	
				Grassland	25	0.62	
				Grassland	43	7.21	
Zhungeer, Neimenggu	111.12°, 39.75°	6.2	369	Shrub	25	0.44	Huang and others (2005)
				Forest	25	7.98	
Yuzhong, Gansu	104.42°,36.03°	6.2	328	Grassland	1	2.48	Jia and others (2007)
				Grassland	2	2.53	
				Grassland	3	7.88	
				Grassland	9	11.69	
				Grassland	13	13.41	
Yuzhong, Gansu	104.42°, 36.03°	6.2	328	Shrub	6	6.16	Guo and others (2009)
				Shrub	18	6.70	
				Shrub	26	9.94	
Yuzhong, Gansu	104.42°, 36.03°	6.5	320	Grassland	2	3.34	Jiang and others (2009)
				Grassland	7	4.67	
				Grassland	11	5.80	
				Grassland	20	7.13	
				Grassland	43	11.98	
Yancun, Shanxi	111.33°, 37.58°	8.7	500	Forest	21	5.58	Jin and others (2007)
				Forest	21	9.70	
				Shrub	21	8.32	
Dingxi, Gansu	104.63°, 35.30°	7	427	Grassland	3	2.84	Gong and others (2006)
				Shrub	25	19.41	
Yanan, Shaanxi	110.52°, 36.70°	9.8	535	Forest	5	1.26	Hu and others (2009)
				Forest	15	4.50	
				Forest	25	11.26	
				Shrub	5	1.88	
				Forest	5	0.44	

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