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Chinese Grain for Green Program led to highly increased soil organic carbon levels: A meta-analysis

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The Grain for Green Program (GGP), initiated in 1999, is the largest ecological restoration project in central and western China. Here, for the first time, we performed a meta-analysis and found that the GGP largely increased the soil organic carbon (SOC). The SOC was increased by 48.1%, 25.4%, and 25.5% at soil depths of 0–20 cm, 20–40 cm, and 40–60 cm, respectively. Moreover, this carbon accumulation has significantly increased over time since GGP implementation. The carbon accumulation showed a significantly more active response to the GGP in the top 20 cm of soil than in the deeper soil layers. Conversion of cropland to forest could lead to significantly greater SOC accumulation than would the conversion of cropland to grassland. Conversion from cropland to woodland could lead to greater SOC accumulation than would the conversion to either shrubland or orchard. Our results suggest that the GGP implementation caused SOC to accumulate and that there remains a large potential for further accumulation of carbon in the soil, which will help to mitigate climate change in the near future.

S oil organic carbon (SOC) accounts for more than half of the carbon storage in the soil carbon pool of the terrestrial ecosystem and is an important contributor to the variation of atmospheric CO_2 concentrations. The conversion of natural vegetation to cropland during the past two centuries is thought to have contributed greatly to increasing atmospheric CO_2 concentrations[1–3], and afforestation in cropland and wasteland may lead to the accumulation of carbon. Thus, afforestation has often been proposed as an effective means of mitigating climate change[4–6].

The Grain for Green Program (GGP)[7], also known as the Conversion of Cropland to Forest and Grassland Program or the Sloping Land Conversion Program[8], was initiated by the Chinese government in 1999. The GGP is the largest ecological restoration project in China and is closely related to land use and cover change (LUCC). The GGP involves the conversion of steep-sloped (greater than 25 degrees) and degraded cropland and barren land into forest and grassland with the intent of reducing soil erosion, enhancing biodiversity, and conserving natural resources. This program has been implemented in 25 provinces, municipalities, and autonomous regions located in central and western China, and these areas include 82% of the total land area of China[7,9] (Fig. 1). The primary areas targeted by the GGP were the upper and middle reaches of the Yellow River and Yangtze River. In these areas, steep slopes can cause serious soil erosion. By the end of 2012, the GGP had converted 9.06 million ha of cropland to forest and had converted 0.64 million ha of cropland to grassland[9].

Large-scale LUCC under the GGP will inevitably alter the soil carbon storage in the terrestrial ecosystems of China. Many individual studies have investigated changes in SOC levels under the GGP at different sites and found that GGP had either positive or negative effects on SOC accumulation at the stand level or on a regional scale[10–12]. However, the magnitude and direction of the change in SOC remains poorly understood. Previously reported results have been variable and even contradictory and have not been comprehensively and quantitatively synthesized, which limits our understanding of the true role of the GGP in the carbon cycle of terrestrial ecosystems. Meta-analysis is a powerful statistical method that compares and integrates results from multiple studies. This approach has been widely used to evaluate the ecological effects of afforestation[13], tillage management[14], and ecological restoration[15]. For example, Guo and Gifford[2] estimated the effects of land use change on soil carbon stocks based on a meta-analysis of 74 publications from 16 countries. Laganière et al.[16] reported the effects of afforestation in cropland, pasture, and natural grassland on SOC stocks based on a meta-analysis of 33
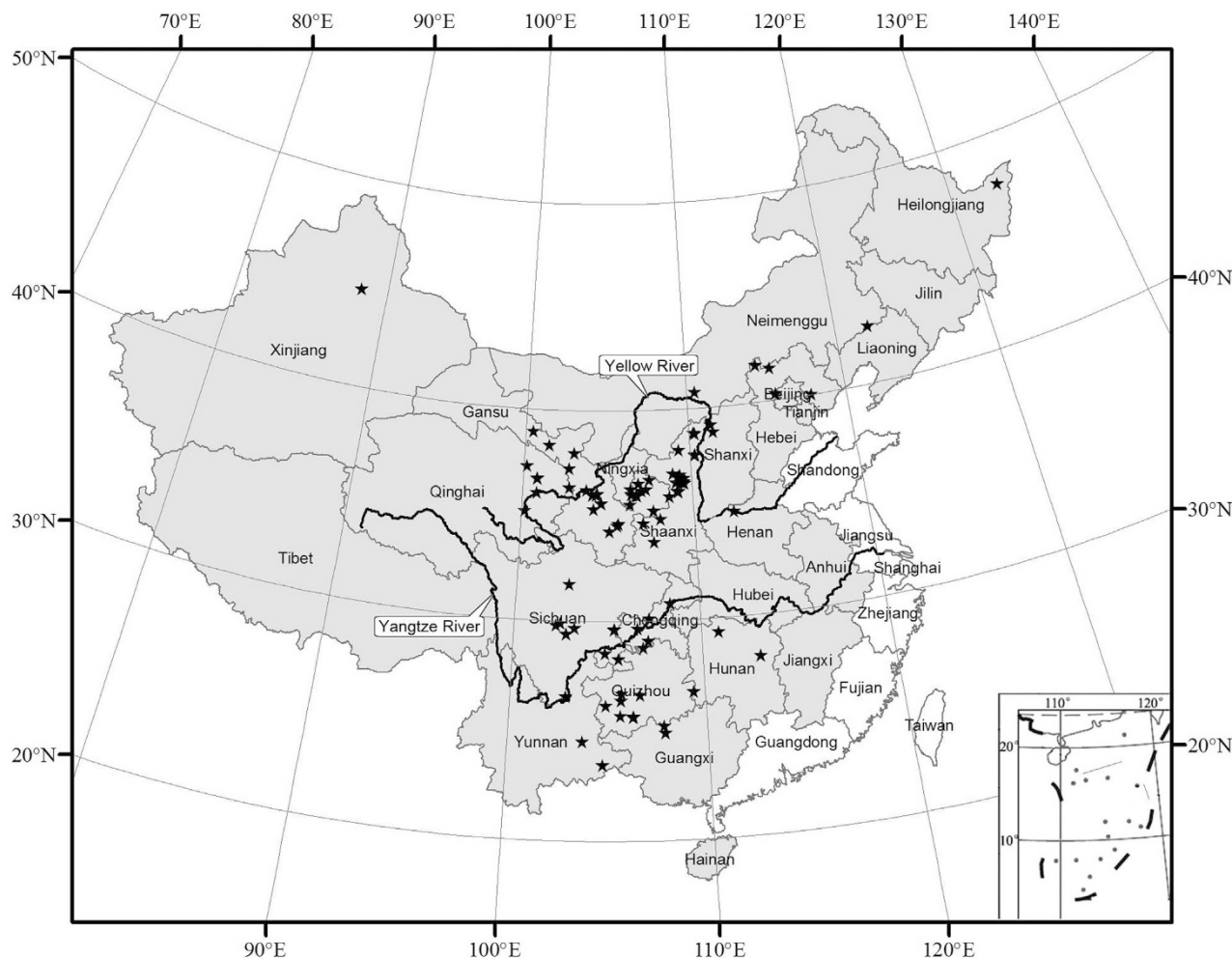
Figure 1 | Site distribution of studies on the Grain for Green Program that were included in the meta-analysis. The gray area represents the conversion of cropland to forest and grassland. The map of China was obtained from a public and open website affiliated with the State Bureau of Surveying and Mapping (SBSM): http://219.238.166.215/mcp/Default.html.

publications. Don *et al.*[17] used meta-analysis to estimate the impact of tropical land-use change on SOC stocks. In a meta-analysis study, Li *et al.*[13] evaluated the dynamics of soil carbon and nitrogen stocks following afforestation. However, most of these global-scale synthesis studies did not include studies on the effects of the GGP on SOC in China, mainly because most studies of the GGP have been reported and published in the Chinese literature, which makes them less accessible to the international community and lead to uncertainties due to incomplete data sources. To our knowledge, a meta-analysis has not been performed to examine the effects of the GGP on SOC. Given the large area affected by the GGP, a comprehensive investigation of the effects of the GGP on SOC could improve our understanding of LUCC effects on SOC at a region scale and may provide benchmark data and scientifically sound information for forest managers and policymakers in China. We conducted a meta-analysis by synthesizing previous studies conducted in the GGP area. This allowed us to investigate whether the directions and magnitudes of the GGP effects on SOC differ based on the following variables: 1) conversion type (forest or grassland), 2) plantation type (woodland, shrubland, orchard, or bamboo) for the Conversion of Cropland to Forest (CCF), 3) restoration approach (artificial grassland (AG) or natural restoration grassland (NRG)) for the Conversion of Cropland to Grassland (CCG), and 4) conversion period (i.e., time since conversion). In this report, we present our analysis and discuss the possible determinants of SOC variation as

well as the potential effects of the GGP on carbon accumulation in Chinese terrestrial ecosystems.

Results

Studies on the effects of the GGP on SOC at a depth of 0–20 cm included 411 observations from 104 papers, of which 247 were related to CCF and 164 were related to CCG. Studies at a soil depth of 20–40 cm included 134 observations from 43 papers, of which 96 were related to CCF and 38 were related to CCG. Studies at a soil depth of 40–60 cm included 46 observations from 14 papers, all of which were related to CCF. Several observations at a soil depth of 40–60 cm for CCG did not include statistical analyses due to limited data.

General effects of the GGP on the SOC at different soil depths. The SOC content at a depth of 0–20 cm increased by 48.1% in response to the GGP; this change was significantly greater than the increases observed at soil depths of 20–40 cm and 40–60 cm (Fig. 2). The SOC content at a depth of 0–20 cm increased by 55.6% under CCF and by 36.9% under CCG, and these increases were also significantly greater than at soil depths of 20–40 cm and 40–60 cm. The increase in SOC was not significantly different between the 20–40 cm and 40–60 cm soil layers under GGP and CCG. The response ratios of the SOC were significantly higher under CCF than CCG at depths of 0–20 cm and 20–40 cm ($P < 0.05$) (Fig. 2).
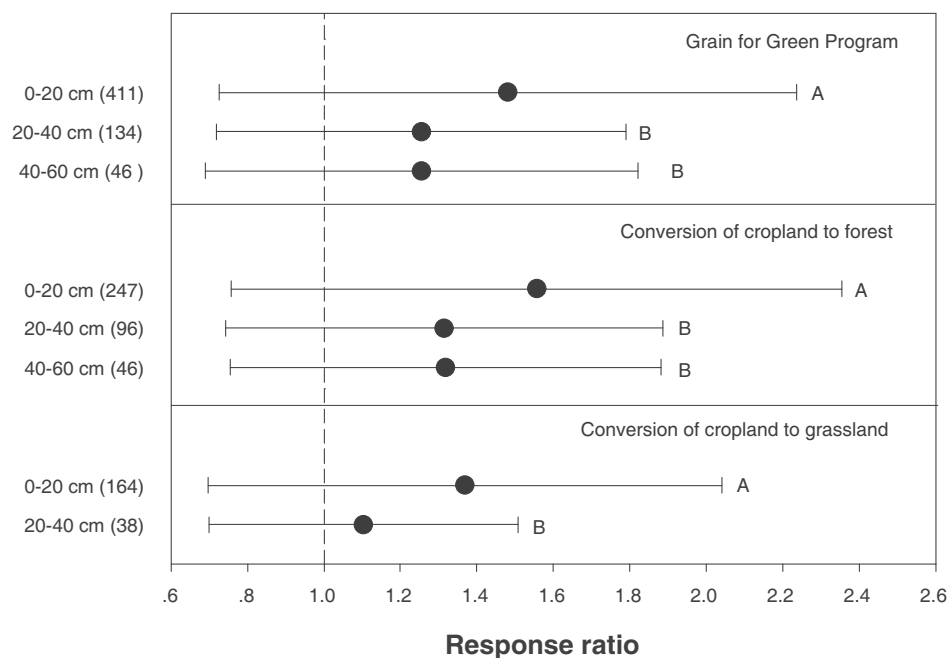
Figure 2 | Untransformed response ratios pertaining to the effects of the Grain for Green Program on soil organic carbon contents at different soil depths. Dots with error bars denote the overall mean response ratio and the 95% CI. Sampling depths (0–20 cm, 20–40 cm, and 40–60 cm) are indicated. Capital letters to the right of the bars indicate statistically significant differences between soil layers at the P < 0.05 level.

Effects of CCF on the SOC. In the 0–20 cm soil layer under CCF (Fig. 3a), the SOC content increased by 68.6% in the woodland, which was significantly greater than the increases observed in shrubland (43.7%) and orchards (30.6%). The SOC content increased by 55.6% in bamboo forests. The SOC content showed a greater increase for a longer period of time under CCF. Specifically, 16 yrs after conversion, CCF showed significantly positive effects on the SOC ($P < 0.05$). The SOC gradually increased by 68.1%, 96.6%, and 135.7% during the 16–20 yr, 21–30 yr, and >30 yr periods of CCF, respectively.

The SOC content also increased in the 20–40 cm soil layer under CCF (Fig. 3b). The SOC increased by 10.3% in orchards and by 38.9% in bamboo forests, although these increases were not significantly different between the plantation types. Generally, the SOC also showed an increasing trend with increasing duration after CCF. The SOC content increased significantly during the 11–15-yr and >30-yr periods after CCF ($P < 0.05$).

In the 40–60-cm soil layer under CCF (Fig. 3c), the greatest SOC increase occurred in bamboo forests (52.8%) followed by woodland (44.9% and 9.6%). The smallest increase was observed in shrubland (1.9%). The SOC did show a consistent increase with the duration after CCF. However, the SOC significantly increased by 73.8%, 49.4%, and 78.3% during the 0–5-yr, 11–15-yr, and 21–30-yr periods after CCF ($P < 0.05$), respectively.

Effects of CCG on the SOC. In the 0–20-cm soil layer under CCG (Fig. 4a), the SOC content increased by 42.3% and 21.3% in NRG and AG, respectively, although there were no significant difference between the two restoration approaches. Generally, the SOC content increased with an increasing duration after CCG, and this increase became significant 20 yrs after CCG ($P < 0.05$).

In the 20–40-cm soil layer under CCG (Fig. 4b), the SOC content increased by 14.4% and 4.7% in NRG and AG, respectively, and no significant difference between the two restoration types was observed. The SOC gradually increased with the duration after CCG and was significantly increased after 11 yrs of CCG ($P < 0.05$).

Factors affecting the SOC under GGP. The statistical analysis of the between-group heterogeneity (Q_b) showed that the type of cropland conversion (CCF/CCG) had significant effects on the SOC at depths of 0–20 cm and 20–40 cm ($P < 0.05$, Table 1). After CCF, both the plantation type ($P < 0.05$) and conversion period ($P < 0.001$) had significant effects on the SOC in the top 20 cm of soil, whereas these effects were not significant at a depth of 20–40 cm. The SOC at a depth of 40–60 cm was also significantly influenced by the conversion period ($P < 0.001$) but not the plantation type. After CCG, the conversion period significantly affected the SOC at depths of 0–20 cm and 20–40 cm ($P < 0.05$), although the restoration approach did not differ significantly. Pearson correlation analysis showed that the response ratios of the SOC to GGP did not exhibit any significant correlation with the mean annual temperature (MAT) or mean annual precipitation (MAP) (Table 2). Significant negative relationships were observed between the response ratios of the SOC to the GGP in the three soil layers and to the initial SOC content in cropland (control plot). The response ratios of the SOC at depths of 0–20 cm and 20–40 cm for CCF also showed significant negative correlations with the initial SOC content in cropland, whereas such correlations were not observed for CCG.

Discussion

The effects of the GGP on SOC. SOC stocks are the result of a dynamic balance between carbon input from plant litter and carbon output due to organic matter decomposition by soil microbes. The conversion of cropland to plantation or grassland may increase the soil carbon input in several ways: by influencing the net primary productivity (NPP)[18]; by enhancing the stability of SOC and reducing soil carbon output by decreasing the weathering and microbial breakdown[17,19,20], which would prevent soil erosion[21,22]; and by altering soil biological and chemical processes[16,19] in ways that contribute to the accumulation of SOC. Guo and Gifford[2] reported that SOC stocks significantly increased by 18% and 19% after the conversion of cropland to plantation and pasture, respectively. Don *et al.*[17] also demonstrated that SOC stocks increased by 29% after agricultural
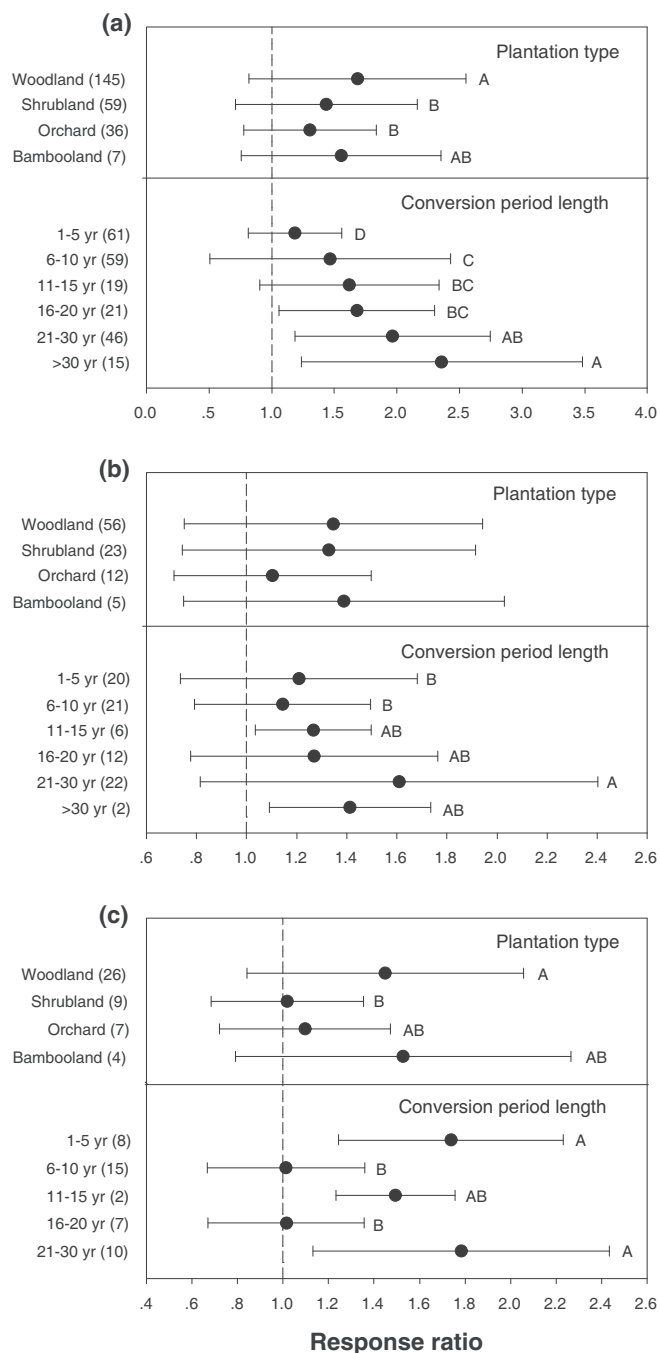
Figure 3 | Untransformed response ratios pertaining to the effects of the conversion of cropland to forest on soil organic carbon contents at depths of 0–20 cm (a), 20–40 cm (b), and 40–60 cm (c). Dots with error bars denote the overall mean response ratio and 95% CI. Capital letters to the right of the bars indicate statistically significant differences based on the plantation type or conversion period at the p < 0.05 level.

land was afforested and by 26% after cropland conversion into grassland. For the GGP in China, our study showed a higher rate of increase (55.6% and 36.9% in the top 20 cm of soil for CCF and CCG, respectively) than the rate reported by Guo and Gifford[2], indicating that the GGP in China has caused strong SOC accumulation. Moreover, the SOC accumulation rates were significantly higher under CCF than under CCG at depths of 0–20 cm and 20–40 cm (P < 0.05), which implies that CCF is a more efficient way to accumulate carbon in soil than is CCG. This may occur because forest soils receive more carbon input from

aboveground litter and belowground roots but experience less carbon output due to erosion than does grassland[10].

Effects of the plantation type on the SOC. The plantation type created after afforestation can also greatly affect SOC accumulation by affecting carbon inputs such as litter and affecting carbon loss by soil respiration and leaching[23,24]. For example, previous studies found that pine plantations significantly decreased the soil carbon stocks, whereas the planting of broadleaf trees had little effect on soil carbon, most likely because pine roots reduced the carbon input into the soil[2,25]. Shi et al.[26] found that trees had a greater capacity than shrubs to increase the SOC stock in the top 20 cm of soil in afforested croplands, whereas this capacity was reversed in the deep soil layer (below 20 cm). The authors speculated that this trend occurred because 90% of the shrubs used in cropland restoration are N-fixing species, which facilitate carbon accumulation in agricultural soil. Such shrubs allocate more of their photosynthetic production into the deep soil layer compared to trees. In the current meta-analysis, the plantation type was shown to significantly affect the SOC accumulation in the top 20 cm of soil (P < 0.05). The highest response ratio was observed for afforestation in woodland, and the lowest response ratio was observed in orchards. This may be due in part to the extensive organic matter input into the soil from the large above-ground biomass in woodland. In orchards, frequent human disturbances such as fertilization and fruit picking may affect the organic matter input. Our results imply that the conversion from cropland to woodland could be considered a priority if afforestation conditions allow for this conversion type.

Effects of the CCG restoration approach on SOC. Artificial grassland is associated with a low extent of SOC accumulation and high costs. Thus, we suggest that a natural restoration approach should be given priority in CCG from the perspective of enhancing soil carbon accumulation.

SOC variation with soil depth. The SOC of topsoil is more susceptible to land use changes and other perturbations as compared to the deep soil[27]. Therefore, the SOC accumulation varies with the soil depth after afforestation[13,17]. This variation has received little attention in previous reviews[12,16,26]. Our analysis revealed that the response ratios of SOC under both CCF and CCG were significantly higher in the top 20 cm of soil than at soil depths of 20–40 cm and 40–60 cm. Guo and Gifford[2] also found that carbon accumulation declined with soil depth after the conversion of cropland to pasture. Our findings indicate that carbon accumulation is more responsive to the GGP in the top soil layer than in the deeper soil layers (below 20 cm).

Determinants of SOC variation. SOC variation results from an imbalance between carbon input and output. After conversion from cropland to plantation or grassland, the aboveground biomass gradually becomes large, resulting in a high input of organic matter such as litter and below-ground biomass into the soil. This causes the soil temperature to decrease and creates high water-holding capacity and low SOC decomposition rates[16,26,28]. These changes facilitate SOC accumulation. In the early stage of afforestation, SOC accumulation may be not significant due to the low productivity of the new forest and strong carbon loss due to soil disturbance. Li et al.[13] reported that significant carbon stock increases occurred 30 yrs after afforestation. Shi et al.[26] also found that stand age was the main factor controlling SOC changes due to the afforestation of agricultural soil. Our results show that the GGP conversion period significantly affects the rate of soil carbon accumulation, especially for the top 20 cm of soil. SOC accumulation gradually increased with increasing conversion time, although the increase only became significant after 16–20 yrs of conversion (Figs. 3, 4). The GGP has been ongoing for approximately 14 yrs
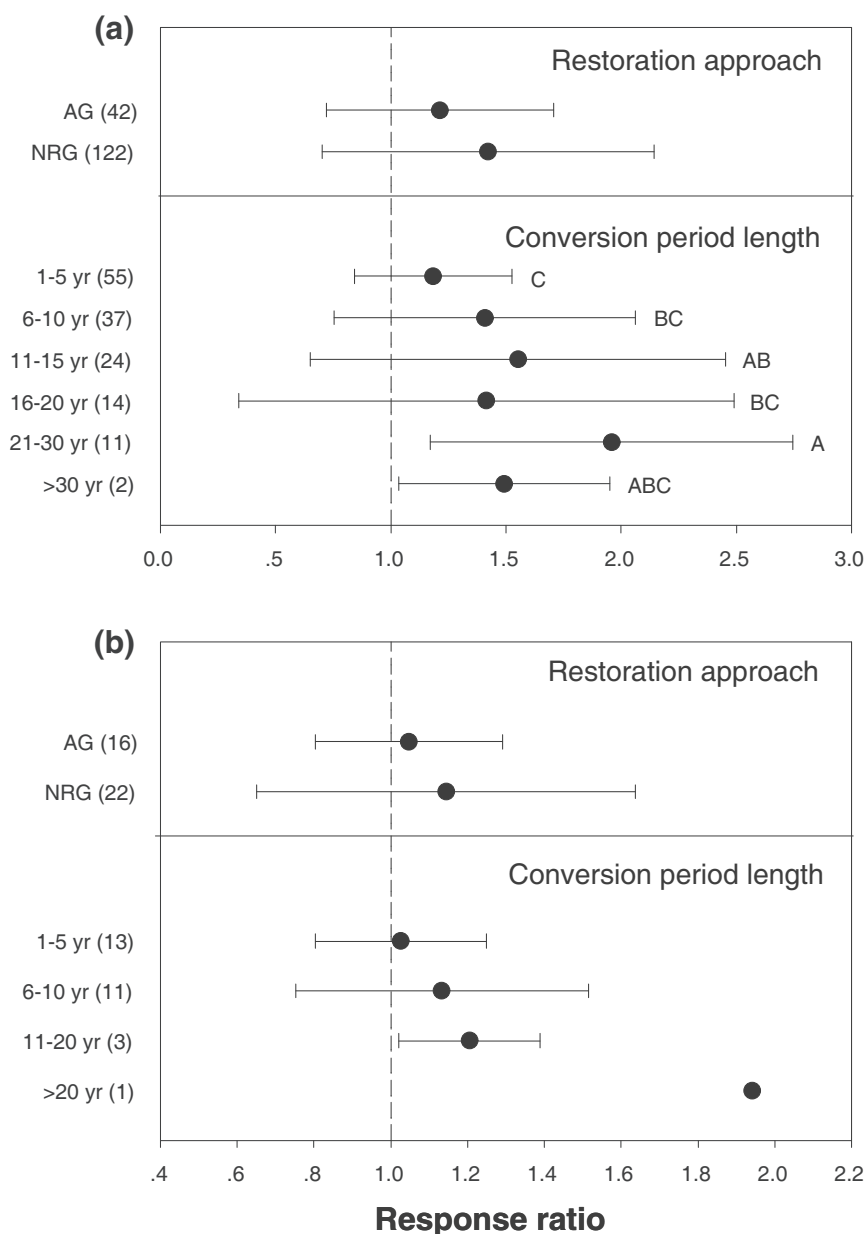
Figure 4 | Untransformed response ratios pertaining to the effects of the conversion of cropland to grassland on soil organic carbon content at depths of 0–20 cm (a) and 20–40 cm (b). Dots with error bars denote the overall mean response ratio and 95% CI. Capital letters to the right of the bars indicate statistically significant differences based on the restoration approach or conversion period at the p < 0.05 level.

since being initiated in 1999. Based on these results, we argue that the SOC stock under the GGP will markedly increase over the next few decades and that the GGP has considerable potential to lead to additional carbon accumulation in soil in the future.

The initial SOC content prior to afforestation also affects SOC accumulation. Shi et al.[26] reported that SOC change rates at depths of 0–20 cm and 20–40 cm after the afforestation of cropland were significantly negatively correlated with the initial C content in each soil layer ($P < 0.05$), which is consistent with our findings (Table 2). This effect may be explained by the concept that a higher initial SOC can be more easily reduced by disturbances to the soil structure during forest planting[26].

Climate influences the productivity of an ecosystem and affects the decomposition of organic matter and C leaching. These processes in turn affect SOC accumulation[2,13]. Shi et al.[26] found that the relative SOC change in the topsoil (0–20 cm) after afforestation was sensitive to both MAP and MAT ($P < 0.05$). Laganière et al.[16] concluded that

climatic factors had smaller effects on SOC accumulation than did other factors, such as the type of tree species that was planted. However, our analysis did not detect a significant relationship between the SOC response ratio to GGP and either the MAP or MAT, which is supported by the recent study of Deng et al.[29]. One possible reason for this observation is that most sites involved in the current study are located in arid and semiarid regions, especially the Loess Plateau of China, having a consistent climate with low MAP and MAT (Supplementary Table S1). The cold, dry climate may weaken the effects of climate factors on the SOC.

Uncertainty. The GGP includes 25 provinces, municipalities, and autonomous regions. Our study involved 591 observations from 104 studies in 16 provinces covering the key areas of the GGP. The lack of observations from several provinces may weaken the certainty of the results to some extent. As the first meta-analysis of the Chinese GGP, our findings provide a new, comprehensive, and quantitative

Table 1 | Effects of the Grain for Green Program on between-group heterogeneity (Q_b) in relation to the soil organic carbon response ratio

Soil layer	Conversion type	Categorical variable	Q_b	P-value	F
0–20 cm	Total	**CCF/CCG**	3.438	**0.014**	6.107
	CCF	**Plantation type**	2.218	**0.014**	3.598
		Conversion period	5.259	**0.00000007**	9.126
	CCG	Restoration approach	1.374	0.081	3.073
		Conversion period	1.311	**0.016**	2.91
20–40 cm	Total	**CCF/CCG**	1.21	**0.04**	4.306
	CCF	Plantation type	0.209	0.597	0.631
		Conversion period	0.558	0.11	1.869
	CCG	Restoration approach	0.088	0.472	0.528
		Conversion period	0.271	**0.047**	3.071
40–60 cm	CCF	Plantation type	0.591	0.132	1.977
		Conversion period	1.403	**0.0004**	6.53

CCF: Conversion of cropland to forest; CCG: conversion of cropland to grassland.

understanding of the potential role of the GGP in carbon sequestration for terrestrial ecosystems as well as climate change mitigation.

Conclusions

The GGP is the largest ecological restoration project in China and has had significant positive effects on SOC accumulation. The SOC has increased by 48.1%, 25.4%, and 25.5% at soil depths of 0–20 cm, 20–40 cm, and 40–60 cm, respectively. The conversion of cropland to forest is more efficient regarding the accumulating SOC than the conversion of cropland to grassland. Conversion from cropland to woodland leads to greater SOC accumulation than does conversion to either shrubland or orchard. The time since the implementation of conversion measures is positively correlated with the SOC accumulation. The response of carbon accumulation to GGP was greater in the top soil layer than in the deeper soil layers. The GGP plays an important role in SOC accumulation in terrestrial ecosystems and has great potential to mitigate the effects of climate change in the near future.

Methods

Data selection. Data were extracted from peer-reviewed publications that reported the SOC or soil organic matter (SOM) contents in both GGP plots and control plots (i.e., cropland). The relevant publications were identified via a keyword search using the terms "conversion of cropland to forest and grassland", "grain for green program", "slope land conversion program", "land use and cover change", and "vegetation restoration". These terms were used to query the Web of Science and the China Knowledge Resource Integrated Database. Any study lacking replication in its experimental design was excluded from the meta-analysis. If an article only reported the effect of the GGP on SOM, the SOC value was calculated by multiplying the SOM value by a conversion coefficient of 0.58[2,12]. To conduct a comprehensive analysis, a total of 104 publications containing 591 observations (Fig. 1; Supplementary Table S1) were selected from 857 papers. Based on the SOC sampling depths, the 591 observations were divided into three categories (soil layers): 0–20 cm, 20–40 cm, and 40–60 cm.

To better understand the factors that regulate the direction and magnitude of the SOC response to the GGP, we subdivided the observations for each soil layer based on the conversion type (conversion to forest or grassland), plantation type (woodland, shrubland, orchard, and bamboo) under CCF, restoration approach (artificial grassland or natural restoration grassland) under CCG, and conversion period (time since the conversion). Relevant climate data were also collected: mean annual temperature (MAT), mean annual precipitation (MAP), and life zone (temperate and subtropical).

Meta-analysis. The effect size for each investigation was calculated as the response ratio r = xe/xc, where xe is the mean SOC in GGP plots, and xc is the mean SOC in the associated control plots (i.e., cropland).

As is typical in meta-analyses, most of the articles only reported mean values for treatment and control plots without reporting standard deviations or standard error values. To maximize the number of observations in the studies assembled for this analysis, we used an unweighted meta-analysis as described in previous studies[2,30,31]. The mean effect size for each categorical subdivision was calculated, and a bias-corrected 95% confidence interval (CI) was ascertained by applying a bootstrapping procedure using METAWIN 2.0[32]. The effect of GGP on the SOC within a categorical subdivision was considered significant at P < 0.05 if the 95% CIs did not include 1[33].

The total heterogeneity among groups (Q_t) was partitioned into within-group heterogeneity (Q_w) and between-group heterogeneity (Q_b). The Q_b for each

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

Conversion type	Soil layer	SOC$_{in}$	MAT	MAP	N
Total	0–20 cm	**−0.171****	0.046	−0.020	411
	20–40 cm	**−0.205***	−0.037	−0.057	134
	40–60 cm	**−0.294***	0.290	0.315	59
CCF	0–20 cm	**−0.212****	−0.020	−0.116	247
	20–40 cm	**−0.220***	−0.111	−0.088	96
	40–60 cm	−0.278	0.270	0.277	46
CCG	0–20 cm	−0.136	0.088	0.089	164
	20–40 cm	−0.112	−0.129	−0.184	38
	40–60 cm	−0.293	−0.082	−0.024	13

CCF: Conversion of cropland to forest; CCG: conversion of cropland to grassland; SOC$_{in}$: initial soil organic carbon content in cropland; MAT: mean annual temperature; MAP: mean annual precipitation; N: number of samples.
*p < 0.05; **p < 0.01.

categorical variable was determined for the response variable. A significant Q_b value indicated that the effect size was different between different categorical subdivisions. The Pearson correlations between the response ratio of the SOC and various other factors were determined using SPSS software (version 13.0, SPSS Inc., Chicago, Illinois, United States of America) with Microsoft Windows.

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Author contributions

X.S. and C.P. designed the study. X.S. performed the data collection and analysis. X.S., C.P., G.Z., H.J. and W.W. interpreted the results and wrote the paper.

Additional information

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