Received: 19 August 2019 | Revised: 22 April 2020 | Accepted: 29 April 2020
DOI: 10.1002/ldr.3644

RESEARCH ARTICLE

WILEY

Land-use conversion changes deep soil organic carbon stock in the Chinese Loess Plateau

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Funding information
National Key Research and Development Program of China, Grant/Award Numbers: 2017YF0504600, 2017YFC0506503; National Natural Science Foundation of China, Grant/Award Number: 41771318

Abstract

Land-use change is a key factor driving changes in soil organic carbon (SOC) sequestration worldwide. However, the changes in deep (>100 cm depth) SOC stock following land-use conversion have not been fully elucidated. In this study, to determine the changes in deep SOC stock (to a depth of 400 cm) resulting from conversion of cropland to woodland, shrubland and grassland on the Chinese Loess Plateau, 469 observations from peer-reviewed publications and original measured data were synthesised. The results were as follows: (a) SOC stock increased significantly at 0–100 and 100–200 cm layers regardless of land-use conversion types. (b) Carbon loss occurred in the 200–400 cm layers due to land-use conversion. (c) Changes in SOC stock varied with restoration age, except for conversion of cropland to grassland. Specifically, SOC stock increased with restoration age in the upper 200 cm layers, whereas that in the 200–400 cm layers first increased and then decreased in the middle to later stages under conversion to woodland and shrubland. (d) Initial SOC stock and rainfall zones had significant effects on the changes of deep SOC stock. (e) Furthermore, an accumulation of 1 Mg ha^{-1} in the upper 100 cm was associated with an approximately 0.45 Mg ha^{-1} increase in the 100–400 cm soil layers. These results indicate that land-use conversion, particularly conversion of cropland to woodland, changes deep (>100 cm) SOC stock, and restoration age should be taken into consideration when assessing deep carbon sequestration.

KEYWORDS
deep soil organic carbon, Grain for Green Programme, land-use conversion, Rhizosphere priming effect, soil water consumption

1 | INTRODUCTION

Soils comprise the largest terrestrial carbon pool, containing approximately 1,500 Pg of carbon (Jobbágy & Jackson, 2000). However, this estimate accounts for only the upper 100 cm of the soil profile. Jobbágy and Jackson (2000) concluded that incorporating the second and third metres of the soil profile would increase the estimated soil carbon pool by 842 Pg, and Köchy, Hiederer, and Freibauer (2015) more recently estimated that including all layers deeper than 100 cm would increase the global soil organic carbon (SOC) stock to almost 3,000 Pg. Land-use conversion, one of the most common determinants of SOC, strongly influences the terrestrial carbon cycle by changing SOC sequestration, carbon turnover, soil carbon loss and vegetation reservoirs (DeGryze et al., 2004; Post & Kwon, 2000; Xiao et al., 2018). However, there has been a paucity of research investigating how land-use conversion, for example, converting cropland to woodland, shrubland or grassland, may affect deep SOC sequestration (>100 cm), although there is a large amount of SOC stored in deep soils.

The majority of studies on SOC change do not sample to even 100 cm, and a sampling depth of less than 20 cm is much more common (Wade et al., 2019). The long residence times of deep SOC have been used to support the assumption that deeper SOC sequestration is either negligible or resistant to change (Chabbi, Kogel-Knabner, & Rumpel, 2009; Kaiser, Eusterhues, Rumpel, Guggenberger, & Kogel-Knabner, 2002). However, deep soils have unique C and nutrient cycles (de Graaff, Jastrow, Gillette, Johns, & Wullschleger, 2014; Fontaine et al., 2007) that are likely to respond differently to global change than those of surface soils (Bernal et al., 2016; Guenet, Danger, Abbadie, & Lacroix, 2010; Harper & Tibbett, 2013; Mobley et al., 2015). Recent studies suggest that changes in deep SOC may be more sensitive to change than the changes in the shallow layer (Dietzen et al., 2017; Shahzad et al., 2018). Bernal et al. (2016) concluded that deep SOC pools (~300 cm) might be more vulnerable to environmental or anthropogenic change than previously thought, potentially influencing estimates of net CO_2 exchange between land and the atmosphere. Furthermore, Shahzad et al. (2018) found that the vulnerability of deep SOC to microbial mineralisation was comparable to that of surface SOC since a similar priming effect/root biomass ratio was found along the soil profile. Despite this new paradigm for understanding the stabilisation of SOC, deep soil studies are still uncommon because of the expenses and time associated with deep sampling (Gao, Meng, & Zhao, 2017).

A large number of studies have shown that land-use conversion induces changes in SOC within the 0–100 cm soil layer (L. Deng, Liu, & Shangguan, 2014; Shi, Zhang, Zhang, Yu, & Ding, 2013), but there is evidence that deeper sampling can actually change the conclusions of some research on net carbon accumulation or loss (Dietzen et al., 2017; Harrison, Footen, & Strahm, 2011). An improved understanding of deep soil processes and quantification of subsurface SOC stock changes are required to predict the extent to which land-use conversion may induce the mineralisation of the previously stable deep SOC stock or increase the SOC stock in deep layers, especially in arid and semiarid regions.

The stability of deep SOC pools can change in response to a wide variety of perturbations, including deep root penetration (Hamer and Marschner, 2002; Fontaine et al., 2003; Waldrop and Firestone, 2004; Ewing et al., 2006; Schmidt et al., 2011; Bernal et al., 2016). Root structure and function are closely associated with plant carbon assimilation, partitioning and release into soils (Warren et al., 2015) via root exudation, mycorrhizal associations and root tissue mortality, which are probably the main deep SOC sources in arid regions due to the low rates of SOC translocation from surface soils (Gao et al., 2017). Furthermore, climatic and land-use changes such as conversion of cropland to land with deeply rooted plants are modifying plant rooting depths (Gao et al., 2017), which can reach more than 1,000 cm, especially in regions with thick soils, such as the Chinese Loess Plateau, Brazilian Amazonia and Mississippi floodplains (Y. Q. Wang et al., 2015; Z. Q. Wang, Liu, Liu, & Zhang, 2009). In these soils, deep roots likely play an important role in determining the magnitude and vertical distribution of SOC. Rasse, Rumpel, and Dignac (2005) showed that the incorporation of carbon into the soil was much greater due to plant roots than due to aboveground litter. Davidson et al. (2011) reported that although root inputs of SOC to deep soils (0–1,100 cm) were small with respect to the carbon dynamics of the aboveground vegetation (woodland), the deep rooting behaviour clearly affected the SOC profiles. Therefore, the contribution of root inputs to SOC can greatly influence both the total amount and vertical distribution of SOC over a long timescale (Rumpel & Kogel-Knabner, 2011).

However, plant roots not only contribute to the changes of SOC stock but also accelerate the decomposition of soil organic matter (SOM) through related physical and biological mechanisms (Guenet et al., 2018). For example, roots can break soil aggregates and increase soil oxygen diffusion rates (Mueller, Jensen, & Megonigal, 2016) and the supply of fresh, relatively labile organic compounds deep in the soil profile through root turnover or exudation of sugars, all of which can stimulate soil microbial community activity (Bernal et al., 2016; de Graaff et al., 2014; Fontaine et al., 2007). Microbial growth requires nutrients such as nitrogen, which microbes can actively mineralise from SOM through exoenzyme production when growth is N limited (Fontaine et al., 2007). Increased microbial mineralisation of SOM in response to an increase in the supply of labile organic inputs is a phenomenon known as 'priming' (Shahzad et al., 2018), which is common in plant–soil systems subject to organic input or substrate changes (Kuzyakov, Friedel, & Stahr, 2000). In addition, a recent study (Jiao et al., 2018) revealed that larger archaeal and fungal communities, which are strongly related to multi-nutrient cycling in the soil and play major roles in carbon turnover, were found in a deep soil profile (0–300 cm) in revegetated soils. Furthermore, the severe depletion of deep soil water induced by extensive consumption in revegetated soils may influence the changes of SOC stock by affecting root growth (Su & Shangguan, 2019; Tuo et al., 2018; Y. Q. Wang et al., 2015). All these factors may increase uncertainty in deep SOC stock changes. However, to the best of our knowledge, few studies have investigated deep SOC stock and its associated changes induced by land-use conversion.

Land-use conversion on the Chinese Loess Plateau has changed substantially since the 'Grain for Green' Programme was implemented. Usually, cropland with a slope greater than 25° was converted into perennial vegetation because slope cropland in this region suffers severe soil erosion, low input of organic materials and few conservation tillage practices, which resulted in low soil quality and grain yield. Although the initial goal of the 'Grain for Green' Programme was to control soil erosion on the Loess Plateau, it has been instrumental in increasing both the rate and overall quantity of SOC sequestered in the soil. L. Deng, Shangguan, and Sweeney (2014) and R. Chang, Fu, Liu, and Liu (2011) investigated the changes in SOC stock in the uppermost 20 cm under different land-use conversion types in this area and reported that land-use conversion changed the rate of surface SOC sequestration. However, the fate of deep SOC stock (>100 cm) and its change have not been investigated thus far.

The aims of this study were to (a) quantify the changes in deep SOC stock under different land-use conversion types; (b) analyse the temporal changes in deep SOC stock with restoration age and

(c) identify the factors affecting the changes of deep SOC stock. We hypothesised that land-use conversion would change deep SOC stock (>100 cm), especially conversion of cropland to land with deeply rooted vegetation, for example, woodland or shrubland.

2 | METHOD AND MATERIALS

2.1 | Data compilation

2.1.1 | Compilation of data from peer-reviewed publications

The database used in this study consisted of two parts: data extracted from peer-reviewed publications and our original measured data. All of the available peer-reviewed publications during 2010–2019 concerning changes in SOC stock were collected. Literature searches were performed using online databases http://www.webofknowledge.com/ (Web of Science) and http://www.cnki.net/ (China National Knowledge Infrastructure). These publications dealt with soils from areas with land-use conversion from cropland to woodland, shrubland and grassland during the 'Grain for Green' Programme in China. In this study, we assume that cropland practices do not affect the deep SOC (>100 cm) due to shallow crop root distribution, shallow ploughing and fertilising in this region, and experiments from the same watershed, but different plots, were assumed independent. As a result, we spent more time to avoid data duplication between works published by the same team. Moreover, sample collection by different scholars or at different periods in the same watershed can be considered to be spatially independent. The following criteria were used to select publications for analysis:

- SOC stocks were provided or could be calculated based on SOC or SOM content, bulk density (BD) and soil depth;
- There were data for both the afforested sites (LUn) and the slope cropland (LU0); the experiment used a paired-site, chronosequence or retrospective design and had similar soil conditions for both LUn and LU0;
- The number of years since cropland conversion was either provided or could be directly derived;
- Location and annual average precipitation (mm) were clearly stated;
- Adequate replication and uniform soils were used (studies were excluded if the experiments were not adequately replicated or if the paired sites or sites in a chronological sequence were confounded by different soil types);
- Only afforestation of the first rotation was considered, and data for the 0–100 cm, 100–200 cm, 200–300 cm and 300–400 cm soil layers were extracted.

The raw data were either obtained from tables or extracted by digitising graphs using the GETDATA GPRAPH DIGITIZER (ver. 2.24, Russian Federation). For each paper, the following information was compiled: sources of data, location (longitude and latitude), climate data (mean annual temperature and mean annual precipitation), current land use (grassland after cropland abandonment, planted shrubland and woodland), years since land-use conversion, soil depth and SOC in the four layers at a 0–400 cm depth. In studies with many replicates, data for plots of the same age, edaphic conditions and land use were pooled. Where a particular chronological sequence or retrospective study included observations recorded over a number of years after planting, plants of different ages were taken as different and independent units for the analysis.

2.1.2 | Compilation of original measured data

Original measured data were collected in the Zhifanggou watershed (C. Zhang, Liu, Xue, & Wang, 2016) and Ziwuling Forest area (An et al., 2008) in Ansai and Fu Counties of Shaanxi Province, respectively (Figure 1). Land use in both sites experienced dramatic changes due to the 'Grain for Green' Programme, and a great deal of croplands were converted to grassland, shrubland and woodland. When sampling at each site, stands of the three typical revegetation types (i.e., grassland, shrubland and woodland) were selected, and nearby slope cropland stands were chosen for comparison. The slope gradients and aspects of the selected stands were similar to each other. All of the grassland, shrubland and woodland sites were converted from long-term cultivated cropland, and they had similar histories and management practices before revegetation. The restoration ages of grassland, shrubland and woodland were 10 or more years, 18–42 years and 10–35 years, respectively, which were determined from the local farmers and government. At each sampling site, three plots (20 m * 20 m for woodland, 10 m * 10 m for shrubland and 1 m * 1 m for grassland) were established in the stands of the three revegetation types, and a detailed vegetation survey was conducted in each plot.

Soil samples from the Zhifanggou watershed were collected in July 2011 by digging 400 cm profiles at 20 cm intervals from 0 to 200 cm and at 40 cm intervals from 200 to 400 cm, whereas samples from the Ziwuling Forest area were collected in August 2014 at 20 cm intervals from the 0–200 cm profile. After removing the ground litter, soil samples were collected from three random points in each plot and then mixed to form one soil sample from each soil layer at these two sites. Finally, laboratory analysis was carried out to determine SOC by the potassium dichromate volumetric method, and BD was determined by drying the material at 105°C to a constant mass and weighing.

In total, the final dataset included 469 observations, 115 of which were from our original measured data.

2.2 | Calculation of SOC stock

For those studies in which BD had not been measured, we used the empirical relationship between SOC and BD (L. Deng, Liu, & Shangguan, 2014; Guo & Gifford, 2002):

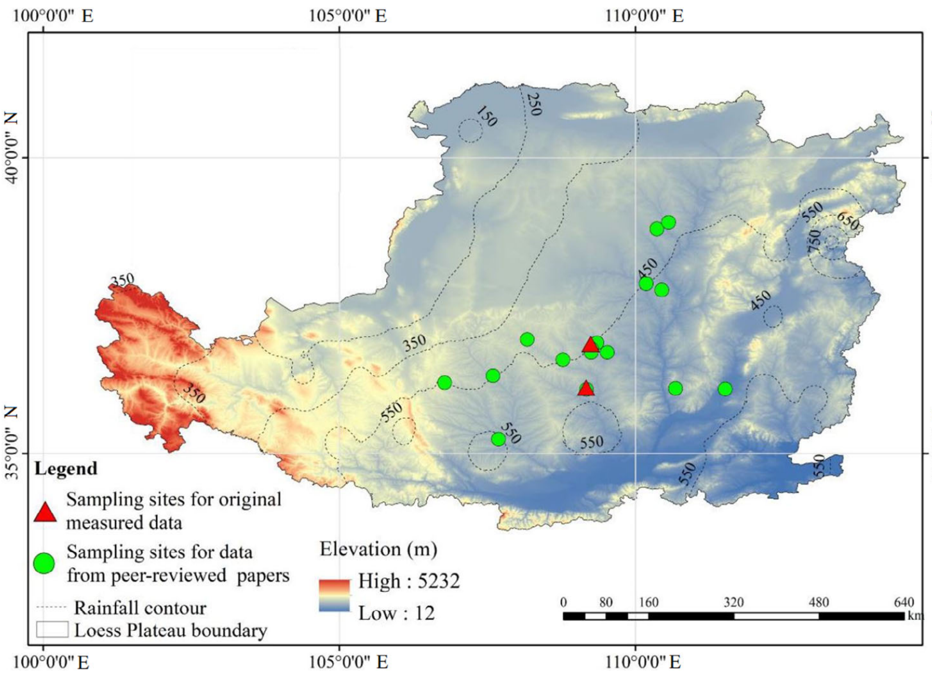

FIGURE 1 Distribution of sampling sites in the dataset [Colour figure can be viewed at wileyonlinelibrary.com]

$$\mathrm{BD} = -0.1229 \times \ln(\mathrm{SOC}) + 1.2901\ (\text{for SOC} < 6\%), \tag{1}$$

$$\mathrm{BD} = 1.3774 \times e^{-0.0413\mathrm{SOC}}\ (\text{for SOC} > 6\%). \tag{2}$$

We did not adjust the reported data to a common BD but used mass-corrected SOC stocks. Not adjusting for an equivalent BD could result in only slight bias in the estimation of changes in SOC stocks.

The SOC stock was calculated using the following equation:

$$\text{SOC stock} = \frac{\mathrm{SOC} \times \mathrm{BD} \times \mathrm{D}}{10} \tag{3}$$

where SOC stock is the SOC stock (Mg ha^{-1}); SOC is soil organic carbon (g kg^{-1}); BD is soil BD (g cm^{-3}) and D is thickness (cm).

2.3 | Meta-analysis

The size of the effect in each investigation was calculated as the response ratio which was defined as the change degree in SOC stock after the cropland conversion:

$r = LU_n/LU_0 - 1$, where LU_n is the SOC stock under current land use and LU_0 is the SOC stock under cropland, the same as the initial SOC stock. As is typical in meta-analysis, most of the published papers reported mean values for treatment and control plots but not standard deviations or standard errors. To maximise the number of observations included in the present analysis, we used unweighted meta-analysis, as described in earlier studies (L. Deng, Yan, Zhang, & Shangguan, 2016; Su & Shangguan, 2019). The mean response size for each categorical subdivision was quantified, and a 95% confidence interval (CI) was calculated by using the R. A method reported earlier and it was also used to calculate the 95% CIs of the mean SOC stocks, as shown in Equations (4) and (5):

$$S_{\mathrm{Etotal}} = \sqrt{\frac{V_s}{N}}, \tag{4}$$

$$95\%\ \mathrm{CI} = 1.96 \times SE_{\mathrm{total}}, \tag{5}$$

where SE_{total} denotes the standard error of the response size for soil moisture, and Vs and N are the variances of response size for SOC stock and the number of observations, respectively. In this study, the 95% CI did not include zero, and the grouping factors were considered significantly different from one another if their 95% CIs did not overlap.

2.4 | Data analysis

The Kruskal-Wallis rank sum test, performed by the *kruskal.test* function in R, was used to test the effect of rainfall zone in different soil layers. Differences were evaluated at $p < .05$. This method is equivalent to single-factor analysis of variance but is used when only a few individuals are included in at least one of the samples, and the data are not normally distributed.

Broken-line models were used to detect the breakpoints of SOC sequestration with restoration age. Broken-line models are regression models where the relationships between the response and one or more explanatory variables are piecewise and linear, namely, represented by two or more straight lines connected at unknown values; these values are usually referred to as breakpoints, change points or even join points. The R package SEGMENTED was used to fit a broken-line model (Muggeo, 2008).

To test the significance of the breakpoints, the package SEGMENTED was employed to perform the Davies (1987) test with the R function *davies test*. The function tests for a nonzero difference in the slope parameters of a segmented relationship. Specifically, the null hypothesis is

$$H0: \beta = 0,$$

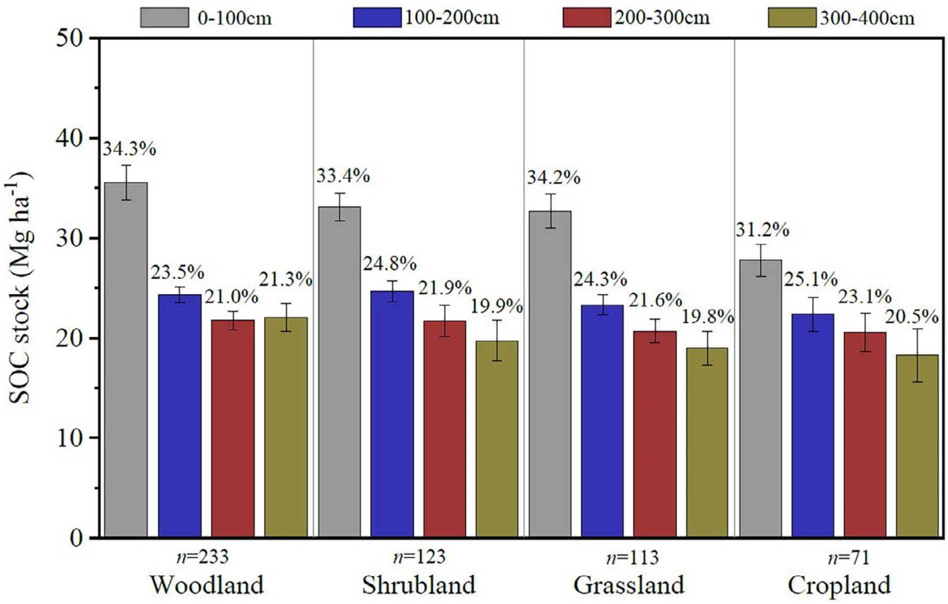

FIGURE 2 Proportions of the SOC stock in each layer relative to the SOC stock in the 0–400 cm layer. Note: The error bars represent standard errors for the SOC stock in each layer; bar graphs illustrate the SOC stock in each soil layer; and percentages above the bars are the proportions of the SOC stock in a particular 100 cm layer relative to the SOC stock in the 0–400 cm layer. SOC, soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

where β is the difference in slopes, that is, the coefficient of the segmented function. The hypothesis of interest (β = 0) corresponds to no breakpoint.

In addition, the logarithmic transformation was used in the Figure 5 to transform the nonlinearity between the initial SOC stock (previous cropland SOC stock) and changes of SOC stock into linearity. To perform the logarithmic transformation, all the response size value was added 1 because the value range was −1 to 1. Adding 1 will not change their original slope except the value of intercept. In this study, we mainly focused on the slope rather than the intercept.

3 | RESULTS

3.1 | Deep SOC stock in the 0–400 cm profile

The patterns of SOC stock proportions in the 0–100 cm, 100–200 cm, 200–300 cm and 300–400 cm layers were similar among the land-use types (Figure 2). The SOC stock decreased gradually with soil depth. In the 0–100 cm layer, the SOC stocks of woodland, shrubland, grassland and cropland were 35.56, 33.10, 32.70 and 27.77 Mg ha^{-1}, respectively. The corresponding values in the 0–400 cm layer were 103.7, 99.2, 95.63 and 89 Mg ha^{-1} (Figure 2). The SOC stocks in the 0–400 cm layer were approximately 2.9, 3.0, 2.9 and 3.2 times higher than those in the 0–100 cm layer in woodland, shrubland, grassland and cropland, respectively. Overall, the deep soil layer (>100 cm) contained more than 60% of the total SOC stock of the whole 400 cm profile (Figure 2).

3.2 | Changes in deep SOC stock due to land-use conversion

When land was converted to perennial vegetation, the SOC stock in the 0–400 cm layer increased significantly (p < .05), irrespective of the type of vegetation (woodland, shrubland or grassland) (Figure 3a–c). Overall, SOC stock increased significantly by 15.97% (Figure 3d). Across the soil profile, the increase in SOC stock was greater in the shallower layers than in the deeper layers (Figure 3). In the case of conversion to woodland, the increase in the deep layer (200–300 cm and 300–400 cm) was not significant, whereas that in the subsoil (100–200 cm) was significant (Figure 3a). In the case of conversion to shrubland, the pattern of change was similar to that in the case of conversion to woodland except that the largest increase occurred in the upper 100 cm layer, with a nonsignificant increase at 100–200 cm (Figure 3b). In the case of conversion to grassland, the increase was significant only in the top layer (0–100 cm, Figure 3c). However, a significant decrease in SOC stock (p < .05) in the 300–400 cm layer occurred under conversion to shrubland (−14.42%) (Figure 3b) and grassland (−10.23%) (Figure 3c) when all the data were combined and only land-use conversion type was considered. The SOC stock in the 200–400 cm layer changed slightly under conversion to woodland (Figure 3a).

3.3 | Factors affecting deep SOC sequestration

3.3.1 | Restoration age

The regression analysis indicated that the effect of restoration age on the changes of SOC stock varied among land-use types and soil layers (Figure 4). SOC stock changes under conversion to grassland showed no significant trends in any soil layers (Figure 4g–i). In the case of conversion to woodland, changes of SOC stock were significantly and positively correlated with age in the 0–100 cm and 100–200 cm layers (Figure 4a,b). In the case of conversion to shrubland, SOC stock significantly increased with age in the 0–100 cm layer, but the increase with age was not significant in the 100–200 cm layer (Figure 4d,e). Moreover, breakpoints were detected in the deeper layers (200–400 cm) in both woodland and shrubland (Figure 4c,f). The Davies test suggested

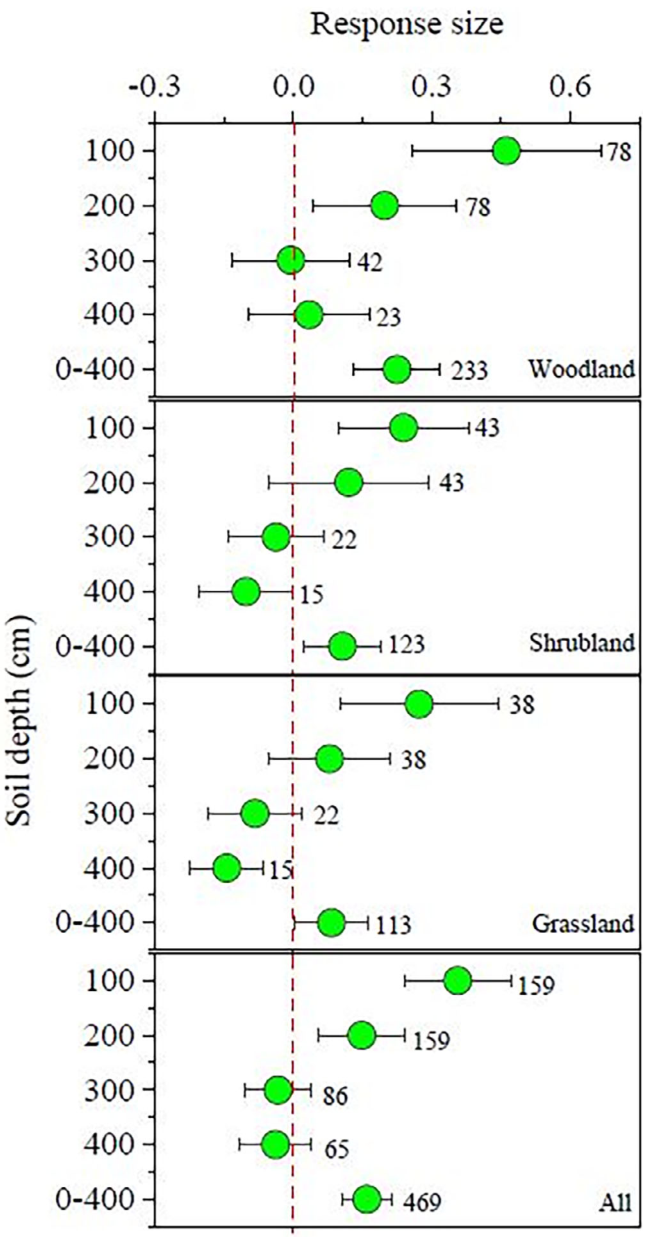

FIGURE 3 The impact of vegetation restoration under the 'Grain for Green' Programme with different vegetation types (grassland, shrubland, and woodland) on the changes of soil organic carbon stock in different soil layers on the Loess Plateau. Note: Dots with error bars denote the overall mean values and the 95% confidence interval, and the numbers of observations are shown to the right of the error bars. The dashed line indicates $x = 0$ [Colour figure can be viewed at wileyonlinelibrary.com]

that the breakpoint for woodland was significant ($p < .05$) which indicated that deeper SOC stock (200–400 cm) initially increased and then decreased at 25 year (Figure 4c,f).

3.3.2 | Initial SOC stock and rainfall zones

Changes in SOC stock were negatively and significantly influenced by initial SOC stock under different land-use conversion types and in different soil layers (Figure 5) (except for the 200–400 cm layers in shrubland, $p > .05$). Overall, the initial SOC stock in the 100–200 cm layer explained more variation in SOC stock changes ($R^2 = 0.52–0.62$, Figure 5b,e,h) than did that in the 0–100 cm ($R^2 = 0.21–0.37$, Figure 5a,d,g) and 200–400 cm ($R^2 = 0.03–0.34$, Figure 5c, f, i) layers.

Furthermore, the sensitivity (slope value) of SOC stock changes to initial SOC stock also differed among different soil depths and land-use types. For example, the value of sensitivity in the 0–100 cm (Figure 5a,d,g) and 100–200 cm layer (Figure 5b,e,h) was similar, with the lowest sensitivity in the 200–400 cm layers (Figure 5c,f,i). In addition, the sensitivity under conversion to woodland (Figure 5a–c) was higher than that under conversion to shrubland (Figure 5d–f) and grassland (Figure 5g–i).

Combining all the land-use conversion types, the Kruskal test showed significant effects of rainfall zone on the changes in SOC stock in the 100–200 cm ($p < .01$) and 200–400 cm ($p < .001$) soil layers (Table 1); for the upper soil layer (0–100 cm), rainfall zone had no significant effects on SOC stock changes ($p > .05$) (Table 1). For the whole profile, there were significant effects of rainfall zone on the changes of SOC stock.

4 | DISCUSSION

4.1 | SOC stock in deep soil layers

A considerable SOC stock was found in deep (>100 cm) soil layers in this study (Figure 2). Similar results were also found (Figure S1 and Table S1) in the central African tropical forest (Wade et al., 2019), on the Chinese Loess Plateau (Gao et al., 2017; Liu, Shao, & Wang, 2011), in the Brazilian rainforest (Sommer, Denich, & Vlek, 2000) and in southwestern Australia (Harper & Tibbett, 2013). It seems that there is a large proportion of deep SOC stock around the world. Such a considerable SOC stock in deep soil layers may be disturbed by the human activities and climate changes, for example, construction, global warming and revegetation with deep-rooted plants. However, most inventory studies have generally limited the measurements of SOC to the upper 100 cm layer (R. Chang et al., 2011), and this is also the standard depth used for the global carbon budget (Lal, 2018). Although applying the results in this study to the estimation of global carbon budget would result in biased estimates, deep soil has the potential to sequester more carbon in the future, and this part of carbon was previously overlooked. Results showed that a large amount of SOC is indeed stored below 100 cm, from >30% (100–200 cm) to >90% (100–2,100 cm) (Figure S1), while the global carbon budget only uses 0–100 cm, and this may be not suitable which underestimates global carbon stocks. Furthermore, our results indicated that planted vegetation (especially planted woodland) will increase deep SOC stock, which may provide a reference for other regions with similar backgrounds around the world, for example, the Brazilian Amazonia and Mississippi floodplain, and so forth. (Y. Q. Wang et al., 2015). However, compared to SOC sequestration

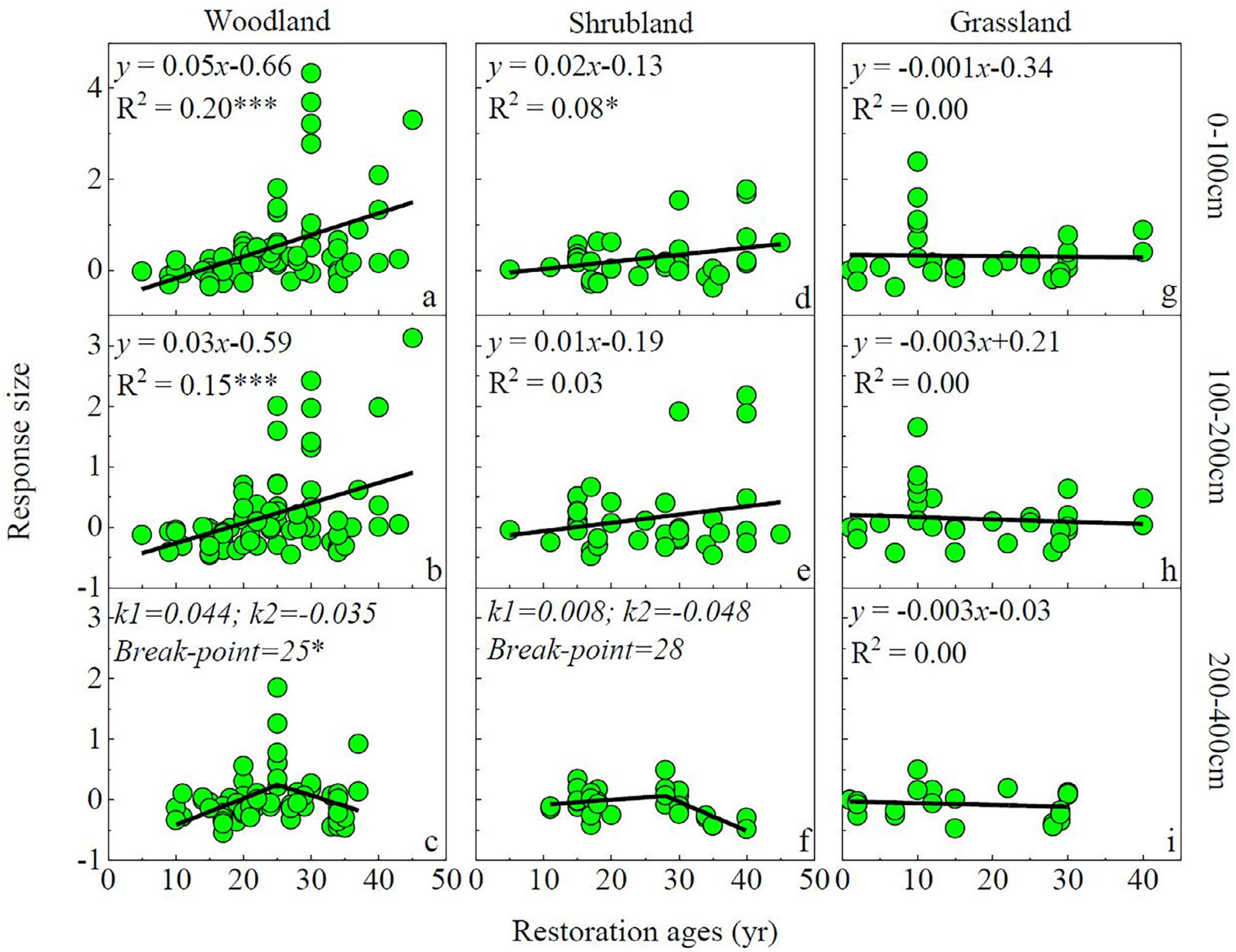

FIGURE 4 The changes in soil organic carbon stock in the 0–100 cm, 100–200 cm and 200–400 cm layers with restoration age for different land-use conversion types. Note: "***," "**" and "*," means the significant level at 0.001, 0.01 and 0.05, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

in shallow layers, data in deep soils are still quite few because of the expenses, time associated with deep sampling and therefore deep SOC especially its long-term monitoring was urgently needed.

4.2 | Effects of land-use conversion on the changes of deep SOC stock

Converting cropland into perennial vegetation leads to SOC accumulation in the shallow layer (<100 cm) by increasing SOC derived from the new vegetation, thereby simultaneously decreasing SOC loss due to decomposition and erosion (R. Chang et al., 2011; Guo & Gifford, 2002; Laganiare, Angers, & Para, 2010).

Our synthesis also revealed that a significant increase in SOC stock occurred in the 0–100 cm layer (Figure 3), with the land-use conversion types ranking in terms of response size as follows: woodland (46.17%) > grassland (27.28%) > shrubland (23.9%). Woodland always benefitted more than grassland and shrubland in terms of carbon sequestration due to the well-developed root system in this type of land (Gao et al., 2017; Y. Q. Wang et al., 2015). However, changes of SOC stock under conversion to grassland were greater than that under conversion to shrubland. This finding is consistent with that of Y. Q. Wang, Han, Jin, Zhang, and Fang (2016). Grassland in arid and semiarid regions is characterised by extensive root systems in shallow layers (Tate & Ross, 1997), efficient accumulation of biomass via photosynthesis, longer growing seasons due to earlier and later seasonal growing periods and the allocation of plant resources. The last factor is related to the net primary production of grassland plants, which is probably more efficient than that of shrubs (Y. Q. Wang et al., 2016; Y. Q. Wang et al., 2015).

In the 100–200 cm layer, there was a significant increase in SOC stock in woodland (19.8%) and a nonsignificant increase in shrubland (12.03%) and grassland (7.86%) (Figure 3a–c). This result indicates that this layer contributes substantially to SOC stock, especially under conversion of cropland to woodland. The thick loess is widely distributed on the Chinese Loess Plateau, in which the thickness can be up to

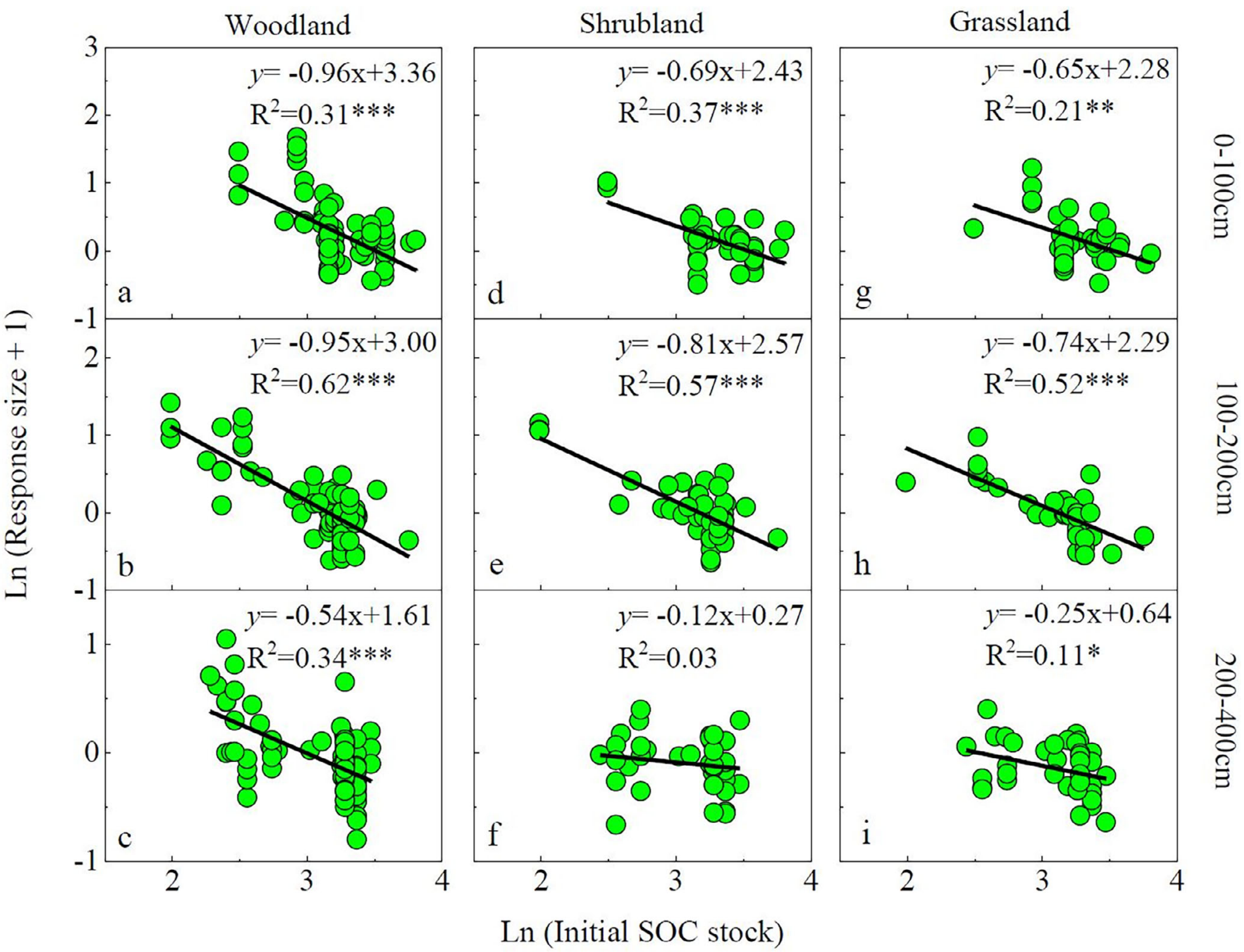

FIGURE 5 Changes in SOC stock in the 0–100 cm, 100–200 cm and 200–400 cm layers with initial SOC stock for different land-use conversion types. SOC, soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Results of the Kruskal tests between different rainfall zones

	0–100 cm		100–200 cm		200–400 cm		0–400 cm	
Source	Chi square	Sig	Chi square	Sig	Chi square	Sig	Chi square	Sig
Rainfall zone	1.36	Ns	9.47	**	22.19	***	30.97	***

Note: Rainfall zone <450 mm, 450–550 mm and >550 mm; significant at **p* < .05, ***p* < .01 and ****p* < .001.

30–80 m on average. Due to limited precipitation and a thick soil profile, woodland, shrubland and grassland have developed root systems in deeper layers (Gao, Li, Zhao, Ma, & Wu, 2018), which contributed to an increase in SOC stock in the 100–200 cm layer (Figure 3d). In addition, woodland had a developed root system and fine root biomass, which greatly increased SOC (Gao et al., 2017).

Unexpectedly, different degrees of SOC loss occurred at 200–300 cm and 300–400 cm under conversion to shrubland and grassland, in which the decrease at 300–400 cm reached a significant level (Figure 3). In addition, changes of SOC stock in these layers were approximately zero under conversion to woodland (Figure 3a). Carbon loss in revegetated soils has been found in several cases (L. Deng, Liu, & Shangguan, 2014; L. Deng, Shangguan, & Sweeney, 2014; Paul, Polglase, Nyakuengama, & Khanna, 2002), where it was induced by soil erosion or a lack of fertilisation in the early years, but the studies focused mainly on surface soil (<100 cm); therefore, these studies may not interpret the carbon loss in the view of deep soil layers (>100 cm). Historically, deep SOC has been viewed as functionally inert, presumably because of its protection from microbial decomposition via organomineral associations or its existence as recalcitrant chemical structures (Torn, Trumbore, Chadwick, Vitousek, & Hendricks, 1997). However, recent studies have suggested that root penetration can induce a rhizosphere priming effect (RPE), which may consequently lead to the loss of SOC (Bernal et al., 2016; Fontaine et al., 2007; Shahzad et al., 2018), and deep SOC would be more vulnerable than the SOC in surface soil (Bernal et al., 2016; Shahzad et al., 2019).

On the Chinese Loess Plateau, crops with shallow roots (approximately 50 cm), for example, millet and wheat, are generally planted on sloped cropland. After the implementation of the 'Grain for Green' Programme, deeply rooted trees, for example, *Robinia pseudoacacia* and *Caragana microphylla*, were widely planted, and the roots of these plants can penetrate to depths greater than 1,000 cm (Gao et al., 2018; Y. Q. Wang et al., 2015). Even grassland plants can extend their roots to a maximum depth of 500 cm (Gao et al., 2017). Fresh carbon input (above- and belowground) contributes to SOC sequestration but also accelerates the decomposition of SOM via biological priming mechanisms (Guenet et al., 2018). However, carbon loss in deeper layers will not continue for a long time because plant roots accumulate (H. J. Li, 2019) and carbon loss decreases with restoration age (Figure 4c, f). In addition, deep soil layers exhibit large accumulated SOC stocks but low SOC contents, resulting in an unsaturated state of mineral surfaces. The specific surface area of fine mineral particles plays an important role in the formation of mineral-organic associations, which represents one of the main mechanisms regulating SOC stabilisation (Wiesmeier et al., 2019). The incorporation of SOC-rich material, dead tissues or exudates into deep soils with a highly undersaturated mineral surface area could therefore provide an opportunity to sequester SOC by slowing the decomposition and enhancing the stabilisation of new SOC. Furthermore, in our study, there was a significant ($p < .001$) linear relationship between 0–100 and 100–400 cm changes of SOC stock following cropland conversion (Figure 6). It indicates that an accumulation of 1 Mg ha^{-1} in the upper 100 cm was associated with an approximately 0.45 Mg ha^{-1} increase in the 100–400 cm soil layers. This finding further confirms our hypothesis that land-use conversion changes SOC sequestration in deep soil layers (>100 cm) and that the deep soil layer exhibits a high potential to sequester more carbon. More importantly, this finding can be used to collaborate deep soil studies with surface soil studies, and the proportion of the change in SOC stocks after land-use conversion between 0–100 and 100–400 cm layers can be applied to scale up surface soil studies to deep soil studies.

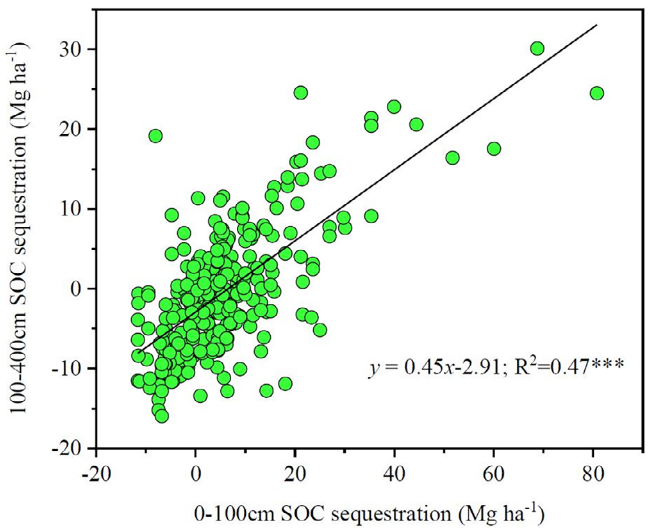

FIGURE 6 Relationship between 0–100 and 100–400 cm soil organic carbon stock changes following cropland conversion [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | The effects of restoration age, initial SOC stock and climatic conditions on the changes of deep SOC stock

4.3.1 | Restoration age

Restoration age is suggested to be an important factor to consider when estimating SOC stock after cropland conversion (L. Deng, Liu, & Shangguan, 2014). With time, there is an increase in the quantity of carbon inputs, accompanied by a new microclimatic regime and enhanced organic matter protection that promoted SOC accumulation (Laganiare et al., 2010). Previous studies on the temporal patterns of SOC stock changes following cropland conversion have been reported in a number of field studies: (a) increases (L. Deng, Wang, Chen, Shangguan, & Sweeney, 2013), (b) decreases (Kirschbaum, Guo, & Gifford, 2008), (c) no change (Sartori, Lal, Ebinger, & Eaton, 2007) and (d) an initial decrease in SOC during the early stage, followed by a gradual return of SOC stocks to cropland levels and then an increase to net carbon gains (Ritter, 2007). However, the temporal changes mentioned above were mainly based on shallow layers (<100 cm). Few studies have considered the changes in deep soil layers (>100 cm) due to the expense and time associated with deep sampling.

Our results showed that restoration age had stronger positive effects on SOC sequestration after cropland conversion at 0–100 cm than at 100–200 cm (Figure 4) due to the larger number of roots in the first meter and quickly improved soil quality. However, the relationship between deeper (200–400 cm) SOC stock changes and restoration age varied when cropland was converted into grassland, shrubland and woodland (Figure 4). In the case of conversion to woodland, a breakpoint (age = 25 years) was detected. SOC stock increased before 25 years and then decreased thereafter. This difference could be attributed to a change in soil water content (Feng, Zhao, Fu, Ding, & Wang, 2017; Lu, Fu, Jin, & Chang, 2014; C. Wang et al., 2017). Tuo et al. (2018) and Y. Q. Wang et al. (2015) reported that deep SOC stock was positively correlated with soil water content. It indicates that there was a synergic relationship between them. At the early stage (5–10 years), woodland on the Loess Plateau usually grows fast, as soil water is sufficient (Chen, Huang, Gong, Fu, & Huang, 2007); however, the growth rate of woodland can decrease greatly when soil water is depleted during the intermediate stage (20 years) (Liang et al., 2018). Severe soil water depletion induced by extensive consumption may further constrain fine root development, which is a main carbon source. In the case of conversion to shrubland, a trend similar to that for conversion to woodland (but not significantly similar) was observed (Figure 4), whereas the year in the breakpoint was 28. There are two possible reasons for the change in deep SOC stock in shrubland: (a) Shrubland on the Loess Plateau will gradually degrade after 10–15 years. Then, the growth of shrubland will be limited, especially that of the old shrubs. (b) Excessive deep soil water consumption will also limit the growth of shrubland (Feng et al., 2017). Here, we show that deep SOC stock changes with restoration age and deeper SOC stock (200–400 cm) does not increase linearly with restoration age, in contrast to the SOC sequestration in shallow layers (0–200 cm), due to the limitation of soil water and root growth. It is essential to understand deep SOC stock changes. However, long-term site monitoring and many more related data may be necessary.

4.3.2 | Initial SOC stock

Initial SOC stock (previous cropland SOC stock) is a main factor affecting the changes of SOC stock after cropland conversion (L. Deng, Liu, & Shangguan, 2014). In previous studies, the relationship between SOC stock changes and initial SOC stock was described as linear on the basis of linear regression or Pearson correlation analysis (L. Deng, Liu, & Shangguan, 2014; L. Deng, Shangguan, & Sweeney, 2014). Here, we showed that the effects of initial SOC stock on SOC stock changes can be well represented by a logarithmic function rather than a simple linear correlation (Figure 5). This indicated that the effects of initial SOC stock on the changes of SOC stock may decrease gradually with the increase of initial SOC stock.

Furthermore, our results showed that the negative effects of initial SOC stock on the changes of SOC stock were various among different land-use conversion types and depths (Figure 5). For example, the sensitivity of SOC stock change to initial SOC stock in the 200–400 cm layer was much lower than the first two meters. K. Zhang, Dang, Tan, Cheng, and Zhang (2010) suggested that the higher initial SOC displayed a lower rate of SOC accumulation and attributed this result to the different rates of decomposition in soils with various nutrient conditions. This is supported by Vesterdal, Ritter, and Gundersen (2002) who inferred that slower rates of decomposition might make SOC stock increase faster in more nutrient-poor soils following afforestation. In addition, the lower carbon saturation in deep soil layers also contributed to the faster carbon increase (Castellano, Mueller, Olk, Sawyer, & Six, 2015). However, the implication of this view point must consider different depths, because previous studies on this topic were focused mainly on the surface soils. From a perspective of deeper soil layers (>200 cm), the effects of initial SOC stock on SOC stock changes may be offset by higher SOC mineralisation induced by RPE (Bernal et al., 2016). The effects in the first two meters showed similar trends, and the initial SOC stock could explain more variations of SOC stock changes in the second meter (Figure 5). This may be partly due to the less disturbance compared to the first meter (L. Deng, Liu, & Shangguan, 2014). Moreover, higher sensitivity to initial SOC stock was found under woodland in three depths than shrubland and grassland. This may be due to the penetration depth and the fine root biomass. More fine root biomass and deeper penetration under planted woodland may make the SOC increase faster in similar poor nutrient soils compared to that under shrubland and grassland (Gao et al., 2018; Vesterdal et al., 2002). Here we tried to explain the phenomenon in a viewpoint of deep soil layers; nevertheless, the relationship between initial SOC stock and SOC stock changes varies among spatial scales, soil layers, rainfall zones, restoration ages and levels of other factors (L. Deng, Liu, & Shangguan, 2014; L. Deng, Shangguan, & Sweeney, 2014). Specifically, other related data (such as soil pH, BD and soil texture) that influenced the carbon and nutrient cycle, particularly in deep layers, could not be found in collected papers; therefore, we could not carry out an analysis on the contribution to the change of deep SOC stock. Therefore, more effective factors should be included.

4.3.3 | Climate

Due to the lack of sufficient sequences of rainfall and temperature in the peer-reviewed papers on deep carbon, multiple regression analysis could not be performed instead of Kruskal analysis. Our results primarily revealed that climatic conditions have a strong effect on the changes of deep SOC stock (Table 1). Climate may affect SOC sequestration via the biotic processes associated with both the productivity of vegetation and the decomposition of organic matter (D. Li, Niu, & Luo, 2012). For shallower layers, Berthrong, Jobbagy, and Jackson (2009) reported that the effects of afforestation on SOC were significantly related to annual mean precipitation. However, Laganiare et al. (2010) found that SOC stock was not significantly correlated with annual average temperature or precipitation, which was similar to the finding of L. Deng, Liu, and Shangguan (2014). However, deep soils (>100 cm) have unique carbon and nutrient cycles (de Graaff et al., 2014; Fontaine et al., 2007) that are likely to respond differently to global change than surface soils (Harper & Tibbett, 2013; Mobley et al., 2015). The dynamics of deep SOC pools have been understudied, leaving their response to environmental change poorly understood (Jobbágy & Jackson, 2000).

5 | IMPLICATIONS FOR MANAGEMENT

Here we show that land-use conversion changes deep SOC stock (>100 cm). SOC stock changes in the 100–200 cm soil layer showed similar pace with that in 0–100 cm soil layer, and we suggest that land-use conversion, especially converting cropland to woodland, may increase SOC stock greatly not only in the first metre but also the second metre which was previously overlooked.

In the deeper soil layers (200–400 cm), changes in SOC stock showed significant responses to land-use conversion with restoration age, and there was an increasing trend, although carbon loss occurred when considering only land-use type. This finding implies that deep soil layers may be able to sequester more carbon at longer time scales. However, deeply rooted plants sequester carbon at the cost of water, which limits further carbon increases. Researchers have proposed that converting cropland to natural grassland would be a good way to reduce water consumption in arid and semiarid regions. Nevertheless, the recovery of plant communities and SOC stocks appears to be slow in semiarid environments without revegetation efforts along with appropriate field management, although post-agricultural soils have a high potential for carbon sequestration (X. F. Chang et al., 2017). As a result, appropriate measures should be adopted to increase carbon sequestration under lower water consumption. Gao et al. (2018) suggested that mixed tree/shrub plantations could effectively sequester carbon and lower water consumption in arid and semiarid regions. Furthermore, woodland thinning practices are the main forestry measure used to increase tree growth by reducing stand tree density and competition for resources (Martín-Benito, Del Río, Heinrich, Helle, & Cañellas, 2010) and fostering carbon sequestration, but the contribution of thinning intensity should be considered (Dietzen et al., 2017; Kim, Kim, Han, Lee, & Son, 2018). In addition, because rainfall zone plays a vital role not only in shallow and deep carbon sequestration but also in soil water consumption in revegetated soils (R. Chang et al., 2011; Su & Shangguan, 2019; C. Wang et al., 2017), further proof of whether conversion of cropland to land with deeply rooted plants or natural grassland is needed when the aim is to increase the total carbon sequestration in the whole profile should be sought.

ACKNOWLEDGEMENTS

This research was financially supported by the National Key Research and Development Program of China (nos. 2017YFC0506503 and 2017YF0504600) and the National Natural Science Foundation of China (no. 41771318). We give many thanks to Hu Zhenhong and two anonymous reviewers, who provided many suggestions for revising this paper.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Li B-B, Li P-P, Yang X-M, Xiao H-B, Xu M-X, Liu G-B. Land-use conversion changes deep soil organic carbon stock in the Chinese Loess Plateau. *Land Degrad Dev*. 2020;1–13. https://doi.org/10.1002/ldr.3644