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Effects of artificial restoration on vertical distribution of soil carbon storage following revegetation in a semiarid grassland of North China

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Abstract

Artificial restoration is an important strategy to restore plant communities and soil nutrients in degraded grassland ecosystems. Despite that research has been extensive on the impacts of vegetation restoration on soil carbon storage, little work has been tried to examine the impacts of artificial restoration on the vertical distribution of soil organic carbon (SOC) storage following revegetation in grassland ecosystems. In this paper, the responses of plant species diversity, litter biomass (LB), aboveground biomass (AGB), the relative biomass of three dominant plant species, and the belowground biomass (BGB) were quantified under five different restoration regimes (natural recovery, harrowing, harrowing plus fertilization, harrowing plus irrigation, harrowing plus fertilization and irrigation), to explore the direct and indirect effects of artificial restoration, mediated by changes in the plant properties following revegetation, on SOC storage in *Leymus chinensis* steppe, North China. We found that artificial restoration greatly facilitated the recovery of *Leymus chinensis* but lowered the plant diversity. Irrigation treatment, particularly harrowing plus irrigation, was associated with both higher BGB and LB, which had positive effects on SOC storage at the 30–60 cm soil layer when compared with natural restoration. In addition, artificial restoration had positive but not significant effects on SOC storage in the surface soil layer (0–10 cm) mediated directly by changes in BGB, while it exerted negative indirect effects on SOC storage at the 10–30 cm soil layer through low level of plant species diversity. The loss of two dominant species (*Stipa krylovii* and *Cleistogenes squarrosa*) could greatly impact SOC storage not only due to lowered species diversity but also the reduced quality of litter input into soil. It is therefore proposed that maintaining high levels of plant species diversity could help sustain higher soil carbon storage through producing high-quality root and litter. Our findings from the 9-year restoration experiment suggested that natural restoration is a sustainable grassland restoration regime to conserve both plant diversity and soil nutrients over short timescales in semi-arid grasslands in North China. In the long term, SOC storage can be

substantially enhanced by artificial restoration, especially under treatments that include irrigation.

KEYWORDS
aboveground biomass, belowground biomass, litter biomass, natural restoration, plant species diversity

1 | INTRODUCTION

Grasslands represent the largest carbon reservoir in terrestrial ecosystems and play an essential role in mitigating climate change (Chen et al., 2018). China has been among the countries suffering from serious degradation resulting from human activity and climate change (Liu et al., 2011; Ma et al., 2014). In the last few decades, a considerable effort has been made to combat grassland degradation, and the beneficial effects of certain vegetation restoration strategies have been widely reported (Baoyin & Li, 2009; Wang et al., 2022; Zhang et al., 2000). Natural restoration and artificial restoration have a long history of utilization and they are still the main restoration strategies in grassland (Deng et al., 2018; Zhu et al., 2021). Theoretical and experimental studies suggested that vegetation restoration is an important practice to improve SOC storage in degraded grasslands by altering land cover (Huang et al., 2022; Lu et al., 2018). Although some success has been achieved, many uncertainties still remain such as whether vegetation restoration can improve soil carbon storage, especially at short timescales. Numerous field studies have linked increased SOC storage to higher above- and belowground litter C input following vegetation restoration (Huang et al., 2022; Kalinina et al., 2013). However, so far as we know, studies have primarily focused on natural restoration (Bai et al., 2020; Yu et al., 2019), while the impacts of artificial restoration have been mostly overlooked (Baoyin & Li, 2009; Yang et al., 2020).

Artificial restoration can be used in seriously degraded grassland that needs to be quickly restored as an important practice in grassland restoration (Kang et al., 2018). However, the efficacy of artificial restoration for increasing SOC sequestration has been questioned in recent studies. For example, some researchers have shown that artificial restoration has the potential to promote SOC sequestration through altering the quantity and quality of plant inputs to the soil, as well as accelerating microbial N mineralization and rhizosphere processes (De Deyn et al., 2011; Zhang et al., 2021). Some researchers have argued that artificial restoration has poor stability, weak resistance, and low biodiversity, which has negative impacts the soil C storage (Abdalla et al., 2018; Huang et al., 2022). The effects of artificial restoration on SOC sequestration may vary with the response patterns of vegetation, climate condition, restoration type, restoration age, and soil depth (Zhang et al., 2021; Zhu et al., 2021). It is therefore important to understand the effects of artificial restoration on SOC sequestration is crucial for establishing sustainable land-use management regimes.

Grassland restoration is a complex dynamic process, which could affect SOC storage in multiple ways (Liu et al., 2011). These potential effects may alter the resource inputs into the soil by changing the plant diversity and plant community structure (Chen et al., 2018). The dominant plant species in semiarid grasslands, such as perennial rhizomatous grasses and perennial bunchgrasses, represent typical plant functional groups that play a key role in ecosystem function because of their distinct traits (Wang et al., 2022). Previous studies have shown that dominant plant species, directly and indirectly, affect the SOC storage through altering microbial N mineralization and rhizosphere processes (Deng & Shangguan, 2017; Dong et al., 2022). The potential impacts of dominant plant species on SOC storage may also be related to above- and belowground litter input, which varies under different grassland restoration strategies (Huang et al., 2022). Although an increasing number of studies have established litter input to be a major factor controlling SOC storage (Dong et al., 2022; Huang et al., 2022), however, the potential effects of dominant plant species on above- and belowground litter input have been largely neglected. To date, it is still unknown how SOC storage is impacted by the dominant plant species, and whether the above- and belowground litter input are altered by dominant plant species following artificial restoration. Therefore, further research is needed to better understand the mediating impacts of dominant plant species on SOC storage under artificial restoration (Chen et al., 2022; Chen, Wang, & Baoyin, 2021).

Grassland restoration can also influence SOC storage by altering the soil's physical properties such as pH, moisture, temperature, and aggregate stability (Dong et al., 2022; Huang et al., 2022). It has been recognized that soil disturbance (e.g., harrowing, shallow plowing) substantially alters SOC storage through improving soil physical characteristics, which in turn influences the grassland primary productivity and ecosystem functionality (Yang et al., 2020). However, short-term practices involving soil disturbance have been often reported to slow down the restoration of soil quality relative to natural recovery in grassland ecosystems (Chen, Xu, et al., 2021). Research to date, however, has only addressed the potential for C sequestration in the topsoil profile under harrowing and shallow plowing, with few reports conducted on the effects of more artificial restoration management type on the vertical distribution of SOC storage (Yang et al., 2019). Recent studies have proposed the application of organic fertilizers as one of the best practices for improving SOC storage (Cooper et al., 2020; Liang et al., 2021), which subsequently increases plant productivity (Zhang et al., 2020). However, some concerns remain on the impact of organic fertilizer return, which may lower the SOC storage under certain climate conditions, soil quality and response patterns of vegetation (Liang et al., 2021). Irrigation has been widely accepted as an important agricultural practice to enhance plant productivity, however, whether irrigation enhances SOC storage during grassland restoration remains unclear. Although an increasing number of studies have established the restoration management type to be a major factor controlling SOC storage (Huang et al., 2022; Zhu et al., 2021), the combined effects of different restoration management types on the vertical distribution of SOC storage remain lucrative.

Given the important role of SOC storage in ecosystem services and functionality, quantifying its response to artificial restoration could provide essential information to improve global carbon cycling and ecosystem management. Therefore, a nine-year grassland restoration experiment was carried out in the present study (regimes: natural recovery, harrowing, harrowing plus fertilization, harrowing plus irrigation, harrowing plus fertilization and irrigation) in *L. chinensis* steppe. We hypothesized that: (1) artificial restoration affects the SOC storage by altering the plant community composition; (2) such impacts vary with soil depth through changing the above- and belowground litter inputs; and (3) the impacts of natural restoration on SOC storage are more beneficial than those of artificial restoration.

2 | MATERIALS AND METHODS

2.1 | Study site

The restoration experiment was conducted over a nine-year period (2012–2020) in a degraded *Leymus chinensis* steppe located in the Inner Mongolia Plateau of China (41°30′–46°45′ N, 110°50′–119°58′ E, 1101 m a.s.l.). The area belonged to a temperate semiarid continental climate, where the daily mean air temperature is 3.7°C, and the annual mean precipitation is 320 mm, respectively (2012–2020). Chestnut soil (Calcic-Orthic Aridisol) is the main soil type. In this region, *Leymus chinensis* (perennial rhizomatous grass) is the main constructive species, *Stipa krylovii* (perennial tall bunchgrasses) and *Cleistogenes squarrosa* (perennial short bunchgrasses) are the dominant plant species, and these three species are responsible for more than 80% of cover.

2.2 | Experimental design

We adopted a randomized block design for the field study, which was set up in 2012 with five restoration treatments in four replicates, creating a total of 20 plots of 15 m × 50 m. The five treatment regimes were as follows: NR (the control, natural restoration; fenced the degraded grassland from the beginning of 2012), HA (harrowing; cut the plant roots in June 2012 and May 2013 using a sod breaker at 12 cm depth), HF (harrowing+fertilization; 4500 kg ha^{-1} of sheep manure was applied at 30 days after harrowing in 2012), HI (harrowing+irrigation; drip irrigation was applied after harrowing annually to ensure that the top 20 cm soil layer was thoroughly wetted), and HFI (harrowing+fertilization+irrigation; HA, HF and HFI were simultaneously applied) (Figure 1a).

2.3 | Vegetation and soil sampling

Samples of aboveground live plants were collected from two 1 × 1 m quadrants in each plot, and all vegetation was cut to ground level in

FIGURE 1 Photographs of restored grassland in the current study, which was conducted in the degraded *Leymus chinensis* steppe, Inner Mongolia, North China. (a) Restoration processes; and (b) Restoration effectiveness. [Colour figure can be viewed at wileyonlinelibrary.com]

late August from 2012 to 2020. The upright vegetation was oven-dried and weighed to calculate the plant's aboveground biomass (AGB). The litter samples were collected from two 1 × 1 m quadrants in each plot, then oven-dried and weighed to calculate the total litter biomass (LB). Root sample was collected from 0–10 cm, 10–20 cm, 20–30 cm, and 30–60 cm depth layers using a 7 cm diameter root auger, then washed, oven-dried and weighed to calculate the below-ground biomass (BGB). The Shannon-Wiener index was used to calculate the plant species diversity.

The soil samples were taken at 0–10, 10–20, 20–30, and 30–60 cm depth layers using two soil cores (5 cm in diameter) in each quadrat in late August of 2020. SOC concentration for each depth layer were determined using the potassium dichromate oxidation method. Soil bulk density (BD; g cm^{-3}) for each soil layer was determined using the volumetric ring method (three replicates).

2.4 | Calculation of SOC storage

The SOC storage (SOCs; Mg ha^{-1}) was calculated using the following equation:

$$\mathrm{SOCs} = 0.1 \times \mathrm{SOC_i} \times \mathrm{D_i} \times \mathrm{BD_i}$$

Where: the parameter 0.1 is the unit conversion factor, SOC_i denotes the SOC concentration (g kg^{-1}), D_i is soil layer thickness (cm), and BD_i is soil bulk density for layer *i*.

2.5 | Statistical analysis

ANOVA was utilized to compare the variations of plant properties (PD, AGB, BGB, and LB) and the SOC concentration and storage between different treatments ($p < 0.05$). Pearson correlation was used to calculate the relationships between the PD, AGB, BGB, LB, and SOC storage for each soil depth. The RDA was conducted to evaluate the relative contribution of plant properties to the SOC storage for each soil depth. Stepwise regression analysis was employed to detect the main factors driving the changes in SOC storage for each soil depth. Linear regression was conducted to investigate the relationship between SOC storage, the relative biomass of the three dominant plant species, BGB, and LB using R software (version 3.6.3). SEM was carried out to explore the direct or indirect effects of vegetation restoration on SOC storage using AMOS (version 24). Based on current knowledge, the theoretical model was assumed that: (i) restoration treatment could directly influence the SOC storage; (ii) restoration treatment could indirectly affect the SOC storage by changing plant diversity; (iii) restoration treatment could indirectly affect the SOC storage by changing plant productivity; (iv) restoration treatment could indirectly affect the SOC storage by changing the above- and belowground litter inputs. The treatment variable was created by assigning the value 1 to the control treatment, 2 to the harrowing treatment, 3 to the harrowing plus fertilization treatment, 4 to the harrowing plus irrigation treatment, and 5 to the harrowing plus fertilization and irrigation treatment. Good model fits were determined using the root mean square error of approximation (0 ≤ RMSEA ≤0.08) and the non-significant chi-square (χ^2) test ($0.05 \le p \le 1.00$, $\chi^2/df < 3$), based on low akaike value (AIC) and high comparative fit index (CFI >0.90).

3 | RESULTS

3.1 | Restoration of plant community

The plant species diversity decreased significantly under HA and HI compared with NR ($p < 0.05$; Figures 1b and 2a). The irrigation activity during vegetation restoration (HI and HFI) had positive effects on AGB and LB ($p < 0.05$; Figure 2b, c). The LB and *L. chinensis* biomass increased significantly under artificial restoration regimes compared with NR ($p < 0.05$; Fig Figures 1b and 2c,d). On the contrary, the relative biomass of *C. squarrosa* and *S. krylovii* exhibited a decreasing trend after 9 years of artificial restoration compared with NR ($p < 0.05$; Figures 1b and 2d–f). Besides, BGB increased significantly under artificial restoration across the 0–60 cm depths when compared with NR after 9 years of restoration ($p < 0.05$; Figure 3a). The irrigation treatment (HI and HFI) yielded the greatest amount of BGB over other treatments in the 0–10 and 30–60 cm soil layers ($p < 0.05$; Figure 3a, b).

3.2 | Changes in SOC storage following vegetation restoration

SOC storage barely changed at the top 20 cm depth after nine-year period of artificial restoration treatment ($p < 0.05$; Figure 3c). Among the five restoration practices, HA resulted in the smallest change in SOC storage at the 20–60 cm layer; HF and HI led to lower SOC storage at the 20–30 cm layer; while HI achieved higher SOC storage at 30–60 cm soil depth (Figure 3c, d).

3.3 | Relationships between plant properties and SOC storage

The results of Pearson correlation analysis, stepwise regression analysis and regression analysis showed that the SOC storage had a significant positive relationship with BGB at the topsoil (0–10 cm) layer, a positive correlation with plant diversity and the biomass of *S. krylovii* and *C. squarrosa* at top 30 cm depth, and a positive correlation with LB and BGB at subsoil (30–60 cm) depth ($p < 0.05$; Figures 4 and 5; Table 1). However, SOC storage had a significant negative relationship with *L. chinensis* biomass at 10–30 cm depth ($p < 0.05$; Figures 4 and 5). The SEM results showed that the restoration treatments could influence SOC storage by directly altering the BGB at top 10 cm depth ($p < 0.001$; Figure 6a). For 10–30 cm soil depth, plant diversity

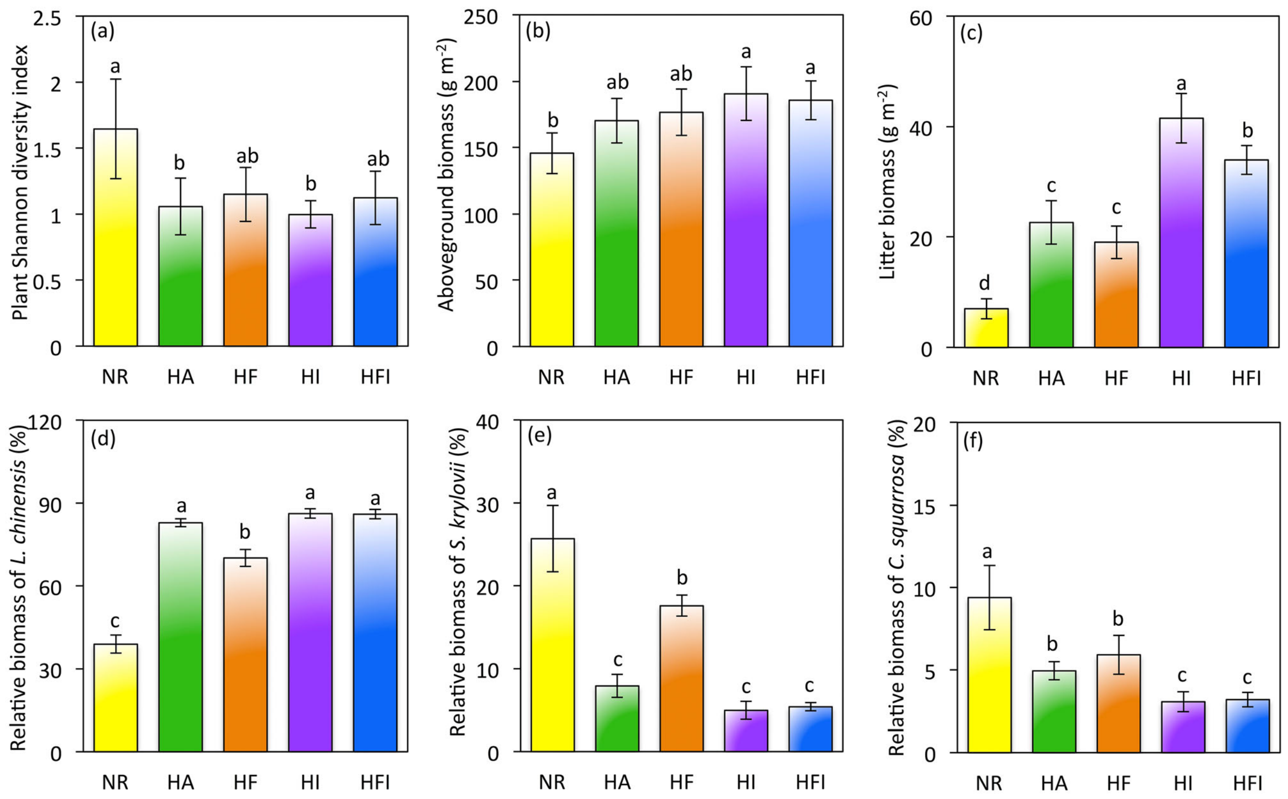

FIGURE 2 Effects of artificial restoration regimes on plant species diversity (a), plant aboveground biomass (b), litter biomass (c), and relative biomass of three dominant species (d–f) in *Leymus chinensis* steppe, North China. Different letters mean significant differences among the five restoration treatments ($p < 0.05$). NR, restoration; HA, harrowing; HF, harrowing plus fertilization; HI, harrowing plus irrigation; HFI, harrowing plus fertilization and irrigation. [Colour figure can be viewed at wileyonlinelibrary.com]

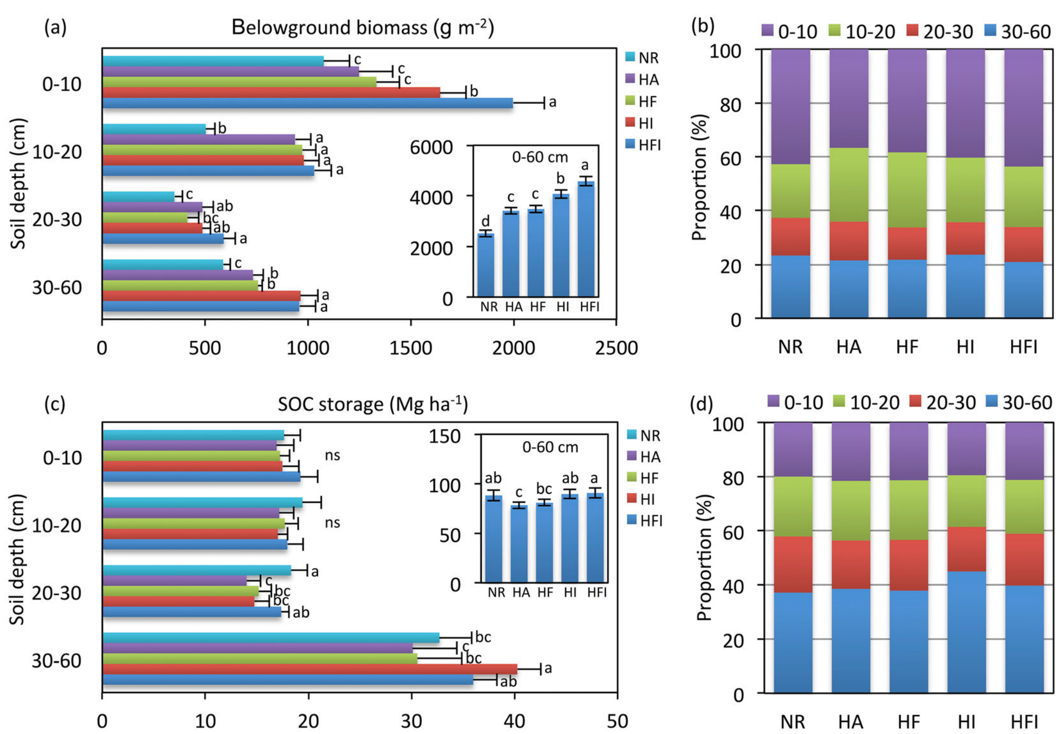

FIGURE 3 Effects of artificial restoration regimes on plant belowground biomass (a, b) and SOC storage (c, d) at different soil layers. Different letters mean significant differences among the five restoration treatments ($p < 0.05$). The ns or same letters mean no significant differences among the five restoration treatments ($p > 0.05$). NR, natural restoration; HA, harrowing; HF, harrowing plus fertilization; HI, harrowing plus irrigation; HFI, harrowing plus fertilization and irrigation. [Colour figure can be viewed at wileyonlinelibrary.com]

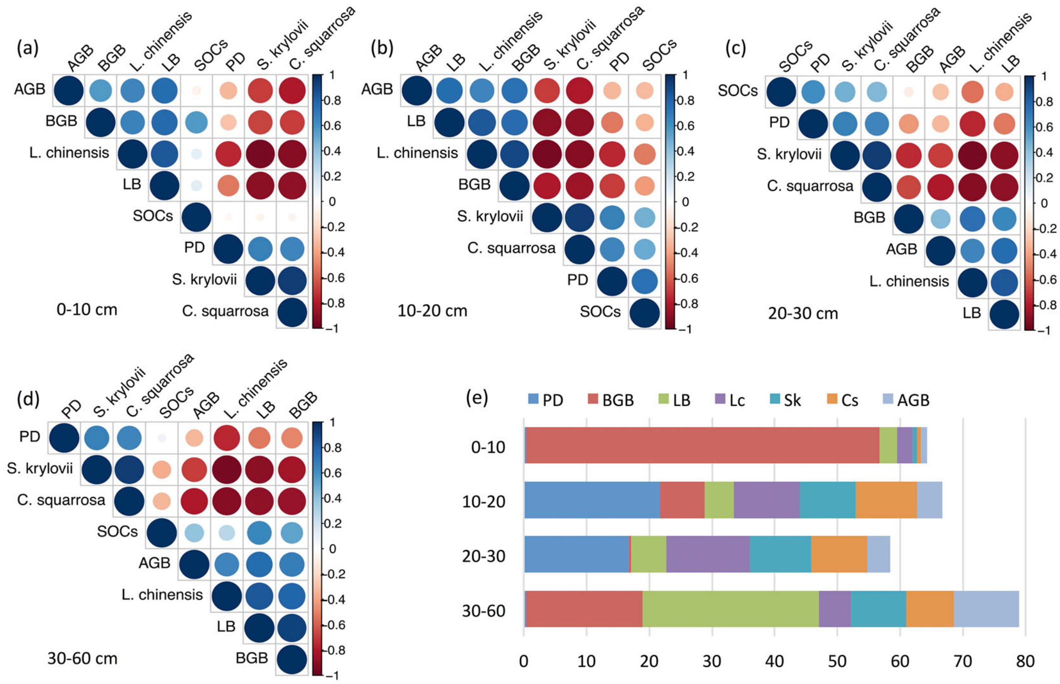

FIGURE 4 Results of Pearson's correlation analysis between plant properties and SOC storage at 0–10 cm (a), 10–20 cm (b), 20–30 cm (c), and 30–60 cm (d) soil depths and the relative contribution of plant properties on SOC storage at different soil depths (e) for artificial restoration treatments. AGB, plant aboveground biomass; Lc, relative biomass of *Leymus chinensis*; Sk, relative biomass of *Stipa krylovii*; Cs, relative biomass of *Cleistogenes squarrosa*; LB, litter biomass; PD, plant species diversity; BGB, plant belowground biomass; SOCs, SOC storage. [Colour figure can be viewed at wileyonlinelibrary.com]

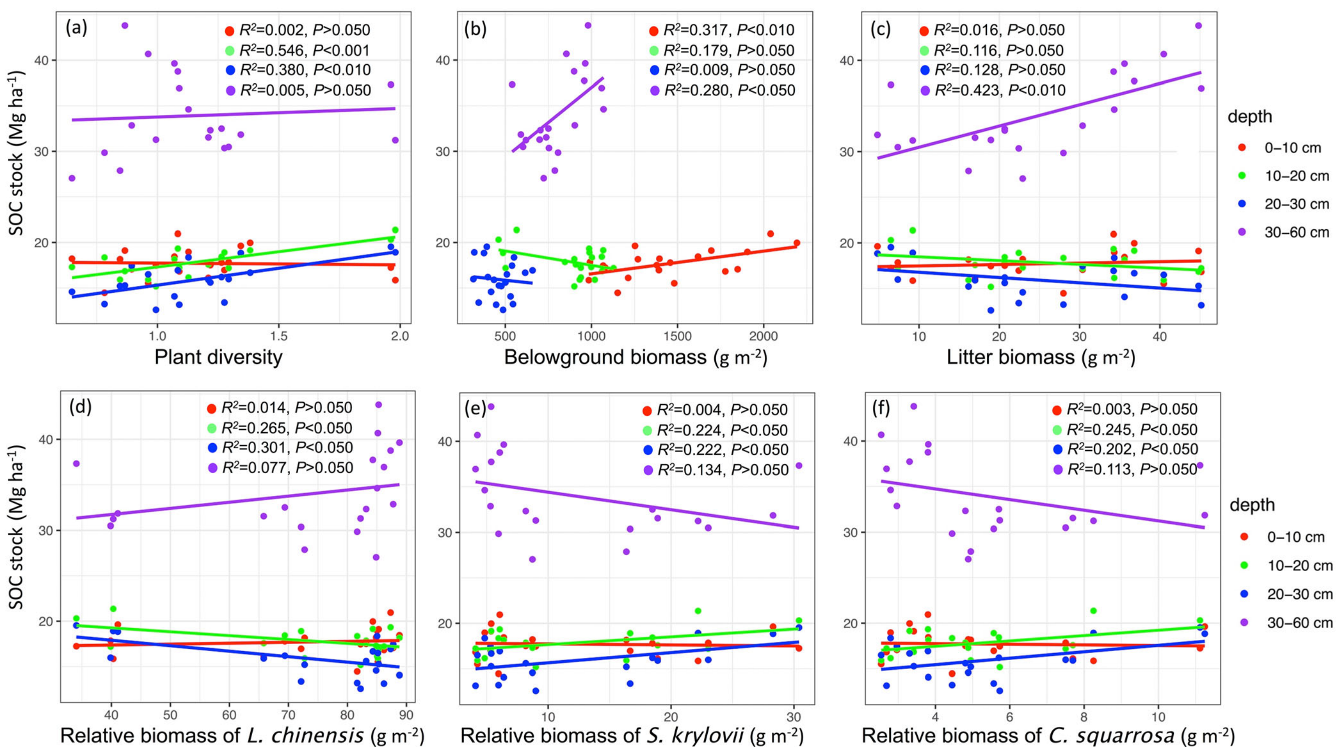

FIGURE 5 Regression analysis shows the relationships between the plant properties and SOC storage at 0–10, 10–20, 20–30, and 30–60 cm soil depths for artificial restoration treatments. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Stepwise regression to detect the driving factors (plant properties) determining the changes in SOC storage for each soil depth following grassland restoration

Soil depth	Models	*p*	R^2
0–10 cm	SOCs = 10.837 + 2.891BGB	<0.050	0.317
10–20 cm	SOCs = 15.956 + 4.649PD	<0.001	0.546
20–30 cm	SOCs = 8.569 + 2.891PD	<0.010	0.380
30–60 cm	SOCs = 10.837 + 2.891LB	<0.010	0.422

Abbreviations: BGB, plant belowground biomass; LB, litter biomass; PD, plant species diversity; SOCs, SOC storage.

could indirectly and positively influence SOC storage through increasing the biomass of *L. chinensis* but decreasing the biomass of *S. krylovii* and *C. squarrosa* in the plant community (Figure 6b, c). At 30–60 cm soil depth, LB could indirectly and positively influence SOC storage through increasing the AGB and BGB ($p < 0.001$; Figure 6d).

4 | DISCUSSION

Our study used a nine-year field experiment in semiarid grassland ecosystem to compare the direct effects of different artificial restoration regimes on SOC storage and their indirect effects mediated by the plant community characteristics. Based on the findings of this study, three generalizations are made.

First, our results indicated that artificial restoration had positive effects on SOC storage at 0–10 cm soil depth through directly changing the BGB. This suggested that the input of organic matter in the soil was mainly through root biomass in this soil layer. Artificial restoration resulted in a higher root biomass, but it did not lead to a significant increase in SOC storage at 0–10 cm soil depth when compared with natural restoration. This indicated that 9 years of artificial restoration had negligible effects on SOC storage at this soil depth, although it had greater positive effects on plant productivity. This finding is opposite to that of Zhang et al. (2000), who detected a higher SOC content in artificially restored grassland than in naturally recovered grassland. This may be because of the differences in root composition caused by the difference in plant community composition under different restoration types (Man et al., 2020). It has been shown that land use can directly affect root decomposition through influencing litter quality (Wang et al., 2015). *L. chinensis* litter has higher C: N ratio and slower decomposition rate and quality than *C. squarrosa* litter, which inhibits soil nitrification and N mineralization, resulting in reduced SOC storage (Man et al., 2020). In this study, harrowing could stimulate the vegetative reproduction of *L. chinensis* (perennial rhizomatous grass) through improving soil physical characteristics, but it also indirectly reduced the decomposition rate and quality of root litter (Wang et al., 2020). Therefore, although artificial restoration was beneficial to the recovery of *L. chinensis*, but it slowed the restoration of soil nutrients relative to natural recovery. The negative effects of *L. chinensis* biomass on SOC storage confirmed this speculation. In addition, we found that changes in the *L. chinensis* biomass led to parallel changes in AGB and LB, which had consistent negative effects on SOC storage at the top 10 cm soil depth. This indicated that higher plant production does not lead to greater carbon input in the topsoil. Our results agreed with the results of a previous study (Chen et al., 2018), suggesting that dominant plant species may be important drivers of belowground C input, thus supporting our first hypothesis.

Second, we found that artificial restoration regimes had direct and indirect negative impacts on SOC storage at 10–30 cm soil depth. These negative impacts were mainly dependent on the decrease in plant species diversity. Artificial restoration significantly improved the relative biomass of *L. chinensis* but decreased that of *C. squarrosa* and *S. krylovii*, and thus decreased the plant species diversity when compared with natural recovery. The loss of both dominant species would greatly impair ecosystem functions due to the loss of compensation capability. Our results agreed with the findings of a previous study (Liu et al., 2011). These results indicated that artificial restoration regimes significantly shaped the plant community composition by stimulating the recovery of dominant *L. chinensis* after grazing removal, and ultimately negatively affected the SOC storage. This confirmed previous results that natural recovery had better restoration effects on SOC storage than artificial restoration (Yang et al., 2020).

Generally, high-diversity plant communities tend to have higher belowground carbon inputs, thereby increasing the SOC storage through enhancing the diversity and activity of soil microbial communities (Chen et al., 2018). The overcompensatory growth of *L. chinensis* could elicit less diverse plant communities that probably led to the decreases in root exudates released into the surface soil (Liu et al., 2011), which in turn affected the SOC storage under artificial restoration (Wang et al., 2016). In addition, a lower SOC storage under artificial restoration may also be attributed to the increased carbon emission from soil to the atmosphere by accelerating soil respiration under soil disturbance (Yang et al., 2020). Furthermore, soil disturbance was shown to decrease the SOC stock through enhancing the exposure of soil organic matter during the tillage period, which could result in an increased decomposition rate of soil organic matter, and eventually decreased SOC storage (Abdalla et al., 2018; Huang et al., 2022). Our findings supported all of these observations and suggested that a nine-year period of artificial restoration is less conducive to the restoration of soil quality, which is a longer-term and slower process than that of the plant community, thereby supporting our third hypothesis.

Third, we found that artificial restoration had indirect positive effects on SOC storage at 30–60 cm soil depth through changes in LB and BGB. This finding indicated that input of organic matter in the subsoil was mainly through LB and BGB. The treatment that includes irrigation (HI and HFI) produced higher LB and BGB, resulting in increased SOC storage at 30–60 cm soil layer when compared with other treatments. Thus, irrigation had beneficial effects on SOC storage in the subsoil layer. These may be attributed to the increase in soil moisture caused by irrigation. It has been shown that the effects of soil moisture on litter decomposition rate were stronger than the effects of litter diversity or quality across different land use types

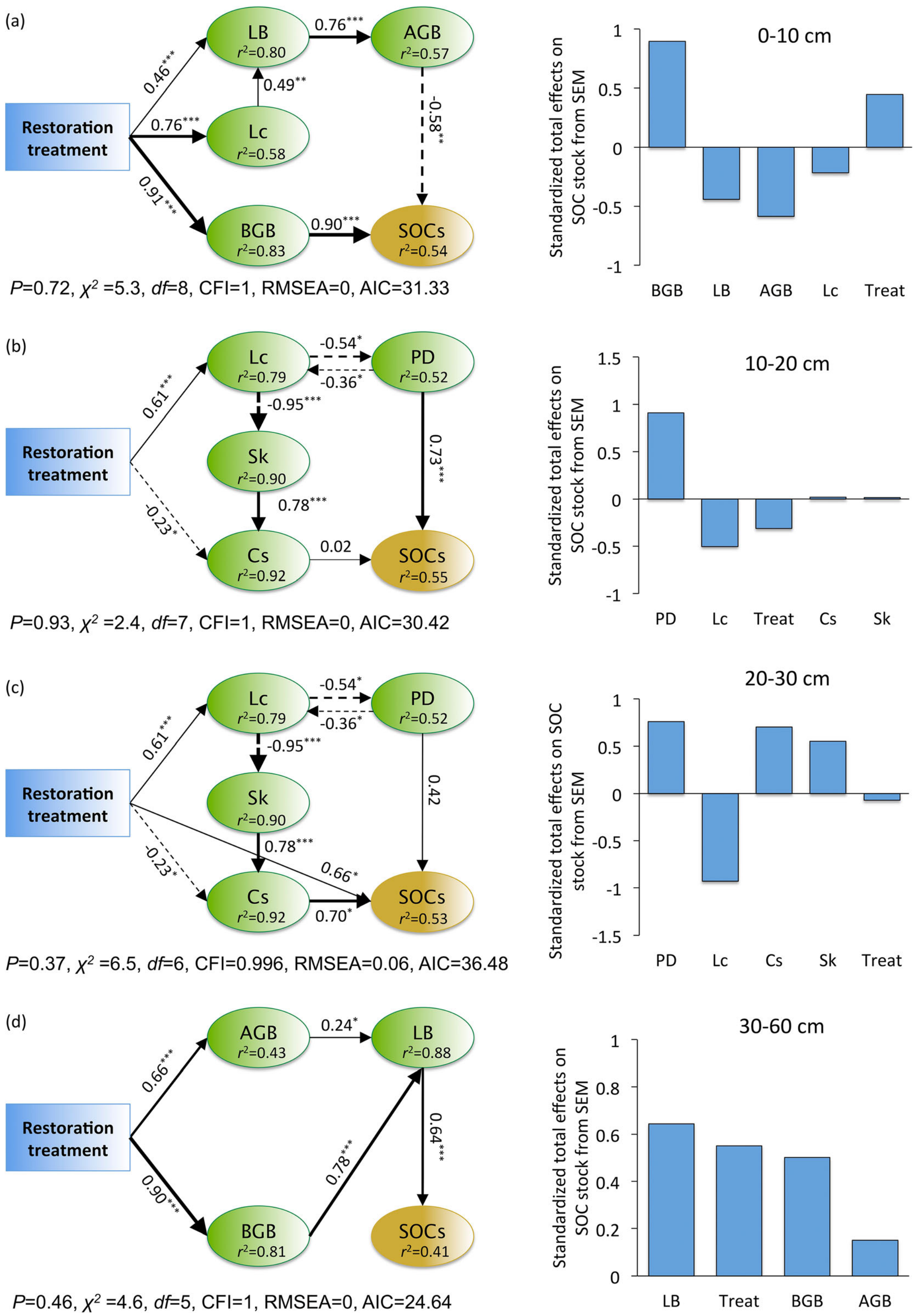

FIGURE 6 Structural equation model (SEM) showing the direct and indirect effects of artificial restoration on SOC storage at 0–10 cm (a), 10–20 cm (b), 20–30 cm (c), and 30–60 cm (d) soil depths. The solid arrows represent positive relationships, and the dashed arrows represent negative relationships, respectively. The width of arrow is proportional to the strength of the relationship, and the adjacent numbers on arrows represent standardized path coefficients. r^2 represent the proportion of variance explained by the model. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. AGB, plant aboveground biomass; Lc, relative biomass of *Leymus chinensis*; Sk, relative biomass of *Stipa krylovii*; Cs, relative biomass of *Cleistogenes squarrosa*; LB, litter biomass; PD, plant species diversity; BGB, plant belowground biomass; SOCs, SOC storage; Treat, restoration treatment. [Colour figure can be viewed at wileyonlinelibrary.com]

(Wang et al., 2020). In addition, irrigation may also increase the moisture content of litter, accelerating the decomposition of litter (Wang et al., 2015). These findings are agreed with many previous studies and indicate that moisture content is an important factor affecting above- and belowground litter C input into soil (Epstein et al., 2002; Wang et al., 2020). However, in the present study, fertilization seemed to have negligible effects on SOC storage when compared with natural restoration. This result could be due to the C losses associated with microbial respiration, which may offset the positive effect of organic fertilizer on SOC storage (Chen et al., 2018). For the soil C pool, the input of new organic matter can serve as a substrate for soil microbes, which will enhance the diversity and activity of soil microbial communities and subsequently stimulate the mineralization of old organic matter, resulting in reduced SOC storage (Liang et al., 2021). This finding is also corroborated by the results of Dong et al. (2022), who also detected a decreasing SOC content after the application of animal manure.

Furthermore, we found that artificial disturbance indirectly affected the LB through changes in AGB and BGB, which had consistent positive effects on SOC storage at the subsoil depth. This indicated that higher plant production (both above- and belowground) led to greater carbon input in the subsoil layer. Our results confirmed the results of the previous study (Chen et al., 2018), clearly demonstrating that both above- and below-ground litter C input are major drivers of SOC storage, which supports our second hypothesis.

5 | CONCLUSIONS

Nine years of artificial restoration had negative indirect effects on SOC storage at the 10–30 cm soil layer through low level of plant species diversity. Irrigation treatment, particularly harrowing plus irrigation had positive effects on SOC storage at the 30–60 cm soil layer when compared with natural restoration. The enhancement of litter and roots biomass is an indicator of soil quality evolution at deep soil layers, whereas the decline of plant species diversity, caused by the loss of two dominant species (*Stipa krylovii* and *Cleistogenes squarrosa*), is the main reason why the SOC storage of artificially restored grassland is lower than that of naturally restored grassland. Therefore, we propose that the natural restoration approach is more conducive to the restoration of soil quality, while the artificial restoration approach is more beneficial to the restoration of plant community. Our study highlights that SOC storage can be substantially enhanced by long-term artificial restoration, especially under irrigation treatment. In the short term, natural recovery should be given preference for the recovery of degraded *L. chinensis* steppes.

AUTHOR CONTRIBUTIONS

Lingling Chen: data curation, writing- reviewing and editing, funding acquisition. Jiahui Sun: methodology, investigation. Taogetao Baoyin: conceptualization, supervision, funding acquisition. All authors read and approved the final manuscript.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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