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The Coupling Interaction of Soil Water and Soil Organic Carbon after Vegetation Restoration on China's Loess Plateau

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Abstract: Soil water content (SWC) and soil organic carbon (SOC) are two important factors to consider when revegetation in degraded land of arid and semiarid areas. Knowing the response of SWC and SOC to vegetation restoration as well as their coupling interaction is important for sustainability of vegetation restoration. In this study, three common plantations of the same recovery years were selected on China's Loess Plateau, which included *Pinus sylvestris*, *Pinus tabuliformis* and *Populus simonii*, to evaluate the response of SWC and SOC to vegetation restoration as well as their interactions, and then revealed the influencing factors of SWC and SOC variations. Results showed that compared to the grassland, three plantations all exacerbated the deficit of deep soil water, but *Populus simonii* increased the SOC, while the rest all decreased the SOC. And tradeoff of *Populus simonii* had the lowest root mean squared error (RMSD). Therefore, *Populus simonii* was identified as representing a suitable revegetation technique for this region. There was strong interaction between SWC and SOC for shallow soil layers. Land use type (LUT) has an important effect on deep SOC variations, while SOC and soil texture for deep SWC variations. The results were helpful to the sustainable development of artificial forests in this region as well as other similar arid and semiarid areas.

Keywords: afforestation; deep soil profile; semi-arid area; soil water content; soil organic carbon

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1. Introduction

Vegetation restoration was considered to be an efficient measurement to control soil erosion, windbreak and sand fixation and soil carbon sequestration for degraded land [1–3], known as "Grain for Green", and "Three North Shelterbelt Development". However, in arid and semiarid area, unreasonable afforestation leads to the SWC deficits of deep soil layers [4–7], and then influences the sustainable development of artificial forests. Therefore, SWC is a key factor to be considered when vegetation is recovering in arid areas. In addition, SOC sequestration in terrestrial ecosystems has long been areas of great research effort, which was caused by their effects on climate change and the ecosystem[8]. And it is reported that revegetation is considered to be an effective approach to enhance soil C sequestration [9,10]. Therefore, understanding the response of SWC and SOM to vegetation restoration as well as their coupling relationship is of great significance for the sustainable development of vegetation restoration in arid regions [11].

At present, a lot of studies have been performed on the response of SWC and SOM as well as their coupling interactions to vegetation restoration in arid regions, mainly concentrating on different vegetation types, different restoration years and different succession stages [12–15]. For example, Yang et al. [12] evaluated the spatiotemporal variation of soil carbon storage and soil water storage to *R. pseudoacacia* forest, and found vegetation restoration increases carbon sequestration while depleting soil water, and stand density (SD) is a major contributor to the dynamics of SWS and SCS through its influence on vegetation, soil and litter characteristics. Chen (2022) [13] compared the SWC and SOC response of different plant community of arid area, found topography is the main factor affecting SWC and SOM in 100-200 cm, and soil texture is the stable driving factor affecting SWC and SOM in full profile (0-200 cm). Zhang and Shangguan [15] evaluated the response of SWC and SOC to a long-term vegetation succession (~150 a) and found the influence of soil physical factors on the interaction between SWC and SOC gradually weakened during vegetation succession. However, few studies have focused on the response of SWC and SOM to different vegetation types of the same age, which is of great significance for rational selection of tree species for vegetation restoration.

China's Loess Plateau is a typical arid and semi-arid region with the short water source. The vegetation cover in the area has been significantly improved since the China government launched several projects [1]. However, it is reported that there is significant soil water deficit after revegetation on the Loess Plateau [4,5]. Therefore, it is vital to investigate the response of SWC and SOC to vegetation recovery. In our study, the typical artificial forests of the similar recovery years are taken as the research object. The aims were (1) to investigate the vertical distributions of SOC and SWC as well as their coupling interaction of typical afforestation in China's Loess Plateau; (2) to assess the extent of the tradeoff between SWC and SOC; and (3) to quantify the relative contributions of various environmental factors to SWC and SOC.

2. Materials and Methods

2.1. Study Area

The study area was located in the Liudaogou Catchment of China's Loess Plateau (N 38°46′~38°51′; E 110°21′~110°23′) (Figure 1), and the area is 6.9 km^2. The area belongs to a moderate-temperate semiarid climate and the ecological environment is fragile. With the mean annual temperature being 8.4 °C, the mean annual precipitation is 437 mm. The precipitation varies on an annual and interannual scale and is mainly concentrated from June to September, occupying over 60% of the annual rainfall. The average annual potential evapotranspiration is 785 mm. The zonal soil types include eutric regosols, calcaric arenosols, calcaric regosols, and calcaric fluvisol. Vegetation cover has increased significantly since the use of the "Grain for Green" project in 1999.

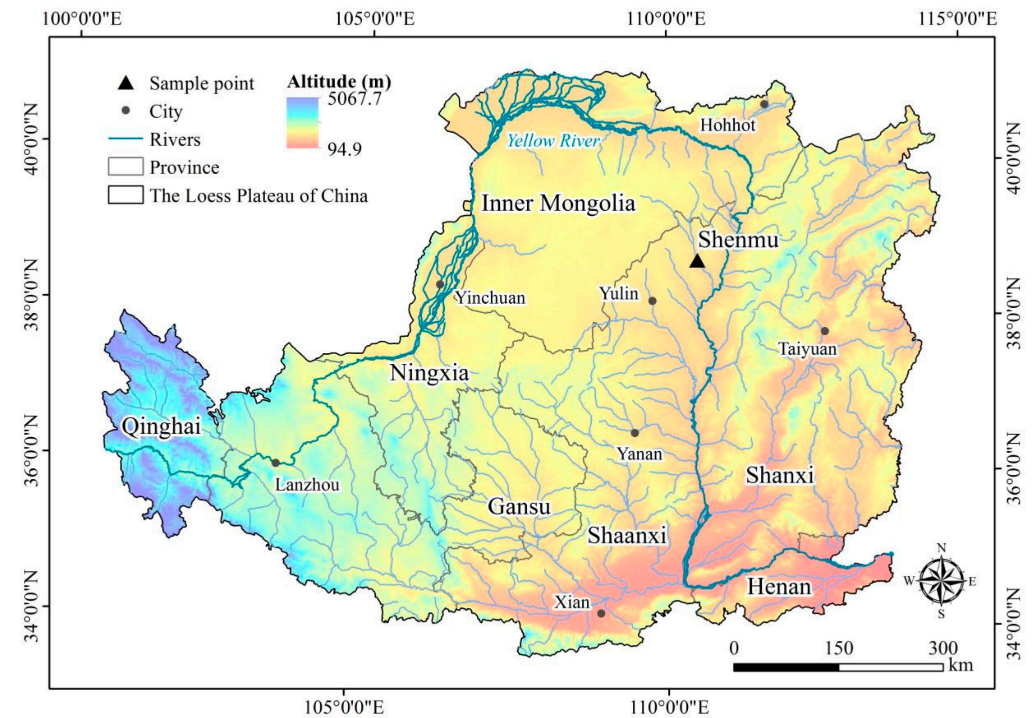

Figure 1. The location of sampling sites.

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The study area is located in the northern part of the Loess Plateau, which has suffered a lot of soil erosion. To select suitable tree species for soil and water conservation, three common plantation forests on the Loess Plateau were planted in the study area (*Pinus sylvestris*, *Pinus tabuliformis* and *Populus simonii*) since 1980s (before the "Grain for Green" of the Loess Plateau). The response of SWC and SOM to vegetation restoration was evaluated by selecting three kinds of planted forests using grassland as the control. The planting time and site conditions of the three plantations were consistent. It is of noted that the planting density of different plantations is different, which is caused by the different size and morphology of the plants when planting. In addition, this is common in similar studies to evaluate the suitability of planted forests [16,17]. Table 1 showed the basic information of three plantations.

Table 1. The basic information of different plantations.

VT	Altitude	Latitude	Longitude	TH	DBH	CD	Tree age	PD
Grassland	1510	37°31′28″	108°39′01″	/	/	/	/	/
Pinus sylvestris	1310	37°25′3″	108°58′5″	4.77	14.01	80	41	1.72 m × 1.68 m
Pinus tabuliformis	1520	37°25′53″	108°36′11″	10.33	15.5	85	41	6.48 m × 2 m
Populus simonii	1500	37°31′28″	108°39′01″	5.62	8.49	60	40	3.75 m × 1.94 m

VT: Vegetation type; TH: Tree height (m); DBH: Diameter of breast height (cm); CD, Canopy density; PD, Planting density;.

2.2. Field Sampling and Laboratory Analysis

A 15 km × 15 km plot of each plantations was selected to collect soil samples. Soil samples of SWC were collected from May to November of 2023. Soil anger (5 cm in diameter) was used to collect disturbed soil samples, and the sampling interval was 10 cm for 0-1 m, and 20 cm for 1-5 m. And three random holes were chosed to collect soil water samples for each sampling. Soil samples of SOC were collected in November in 2023. When soil samples of SWC were collected, a part of soil were stored in a plastic bag to measure SOC. And the sampling interval was the same as that of SWC.

To measure the SWC, a portion of each disturbed soil sample was oven-dried at 105 °C for 24 h. The rest soil samples were air-dried and sieved to 2 mm and were then adopted for analyzing the soil's physical and chemical properties. The soil SOC was identified by the potassium dichromate volumetric method. With the use of a Mastersizer 2000 (Marlven Instruments, Malvern, England), the soil particle composition was explored by laser diffraction.

2.3. Evaluation Indices

The soil water content deficit (SWCD, %) refers to the soil water content deficit compare to the control, which could be evaluated [18,19]:

$$SWCD_{i,j} = \frac{SWC_{i,j} - SWC_{0,j}}{SWC_{0,j}} \times 100\% \quad (1)$$

where $SWC_{i,j}$ and $SWC_{0,j}$ is the soil water content in the jth soil layer of the ith treatment and the control observations.

Soil organic carbon deficit (SOCD) is calculated followed by [19]:

$$SOCD_{i,j} = \frac{SOCD_{i,j} - SOCD_{i,j}}{SOCD_{cpi,j}} \times 100\% \quad (2)$$

where $SOCD_{i,j}$ and $SOCD_{0,j}$ is the soil organic content in the jth soil layer of the ith treatment and the control observations.

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2.4. Evaluation of Tradeoff

The root mean squared error (RMSE) was used to quantify the tradeoff of SWC and SOC, which was proved to be an effective index of balancing different ecosystem services (ES) [20,21] . It is noted it is necessary to standardize data of SWC and SOC to eliminate dimensional relationships between different variables. And the equation of ES standardization was followed:

$$ES_{std} = (ES_{obs} - ES_{min}) / (ES_{max} - ES_{min}) \quad (3)$$

Where ES_{std} represent the standardized value, ES_{obs} represent the observed value, ES_{max} represent the maximum value, ES_{min} represent the minimum value, respectively. In addition, the equation of RMSE was followed:

$$RMSE = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ES1_{(i)} - ES2_{(i)})^2} \quad (4)$$

Where $ES1_{(i)}$ is the normalized value of ES1, $ES2_{(i)}$ was the normalized value of ES2, n is the number of observations. And more details on trade-off analysis have been published in Su et al. (2021) and Feng et al. (2020).

2.5. statistical Analyses

The normality of data was assessed using the Kolmogorov-Smirnov test, and the variance homogeneity was determined using the Levene test. A one-way analysis of variance (ANOVA) was conducted to examine the differences in the SWC and the SOC content of different plantations. The significance level was defined to 0.05. All statistical analyses were performed in SPSS 22.0. Redundancy analysis (RDA) using CANOCO 5.0. was performed to decide the relative contributions of soil properties to SWC and SOC.

3. Results

3.1. Vertical Distributions of SWC of Different Plantations and SWCD

Figure 2 presents the vertical distributions (0-500 cm) of SWC of different plantations. It is noted vertical distributions of SWC were the mean value of different months. Obviously, SWC of different plantations had large variations for 0-1 m, explaining that SWC of 0-1 m was influenced by a lot of factors, including rainfall, solar radiation, litter and root, leading to big variations. Therefore, in this study, we mainly investigated the distribution trend of SWC between 1 and 5 m. From 1 to 5 m, Grassland and *Pinus tabuliformis* generally presented showed a stable trend. It is noted that SWC of the grassland increased significantly after 3.5 m. This indicated that SWC of 1-3.5 m was significantly consumed. *Pinus sylvestris* exhibited a gradual increasing trend. *Populus simonii* tended to decrease from 1 m to 2 m, and remained stable from 2 m to 5 m. Mean SWC of different plantations showed the following order: grassland (4.95%) > *Populus simonii* (4.49%) = *Pinus sylvestris* (4.49%) > *Pinus tabuliformis* (2.43%) (Table 2). SWC of *Pinus tabuliformis* was significantly lower than other plantations, and then consumed more SWC. The coefficient of variation (CV) values of different plantations were in the following order: *Populus simonii* (74.22%) > *Pinus sylvestris* (65.69%) > *Pinus tabuliformis* (47.19%) > Grassland (27.59%) (Table 2), which were consistent with other results [22], reporting that CV of grassland was significantly lower that of forests.

Table 2. Descriptive statistics of SWC and SOC for different plantations.

Plantations	Variables	Min	Max	Mean	SD	CV (%)
Grassland	SWC (%)	3.05	8.29	4.95	1.37	27.59
	SOC (g kg^{-1})	0.87	9.01	2.24	1.87	83.35
Pinus sylvestris	SWC (%)	1.69	13.91	4.49	2.95	65.69

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	SOC (g kg-1)	0.9	8.18	1.91	1.85	96.81
Pinus tabuliformis	SWC (%)	1.07	5.62	2.44	1.15	47.19
	SOC (g kg-1)	0.83	5.86	1.65	1.24	75.16
Populus simonii	SWC (%)	1.51	14	4.49	3.33	74.22
	SOC (g kg-1)	0.79	8.16	2.41	1.92	79.53

Min: minimum; Max: Maximum; SD: standard deviation; CV: Coefficient of variation.

Compared to control (grassland), the total SWCD of different plantations was -14% (*Pinus sylvestris*), -51% (*Pinus tabuliformis*) and -13% (*Populus simonii*), respectively (Figure 3). The SWCD of *Pinus tabuliformis* was the largest while the lowest for Populus simonii. To detailly understand the DSWS of different plantations, we performed the SWCD of different depths (Figure 2). SWCD of *Pinus sylvestris* showed a decreased trend, and SWCD was the highest for 100-200 cm (33%), indicating that SWC of 100-200 cm was widely used by *Pinus sylvestris*. SWCD of *Populus simonii* and *Pinus tabuliformis* presented an increased trend, indicating that SWC of deep soil layer was used widely by *Populus simonii* and Pinus *tabuliformis*, and may exceed 500 cm.

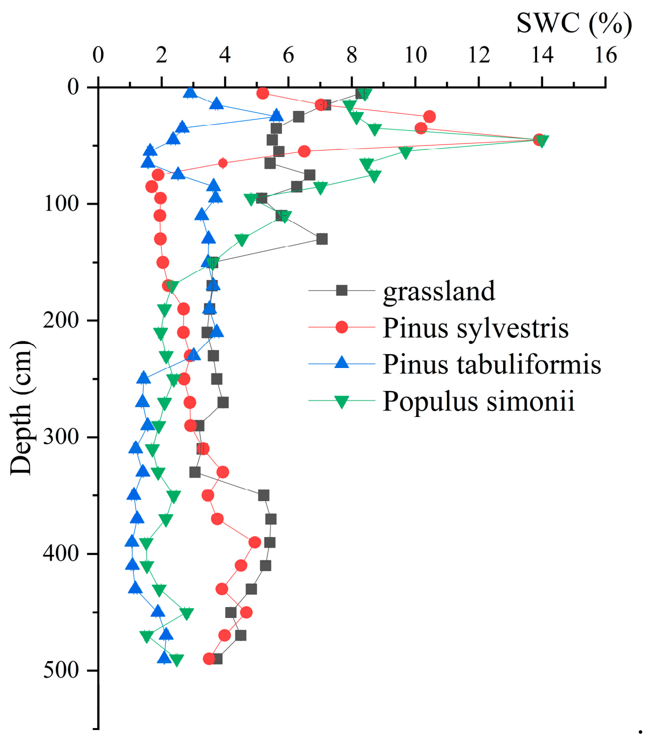

Figure 2. Vertical distributions of soil water content (SWC) for different plantations.

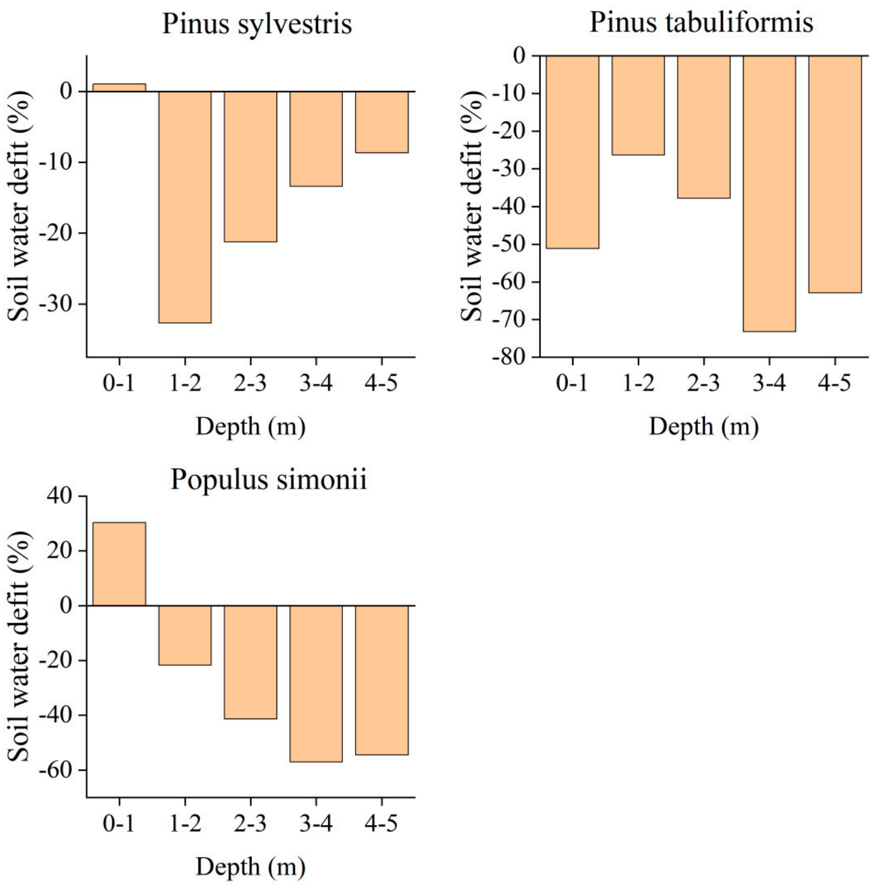

Figure 3. Soil water content deficit of different plantations for different soil depths.

3.2. Vertical Distributions of SOC Content and SOCD

With the increase of depth, the SOC content of all plantations decreased first and then remained stable (Figure 4). It is a consensus that the impact of afforestation on SOC mainly concentrates on the shallow soil layer, especially for 0-100 cm, while there is no obvious difference for the deep soil layer [12,13,23]. Mean SOC of different plantations showed the following order: *Populus simonii* (2.41 g kg^{-1}) > grassland (2.24 g kg^{-1}) > *Pinus sylvestris* (1.91 g kg^{-1}) > *Pinus tabuliformis* (1.65 g kg^{-1}), respectively. In addition, the coefficient of variation (CV) values of SOC of different plantations were in the following order: *Pinus sylvestris* (96.81%) > Grassland (83.35%) > *Populus simonii* > (79.53%) > *Pinus tabuliformis* (75.16%). Compared to grassland, the SOCC of different plantations was -15% (Pinus sylvestris), -26% (*Pinus tabuliformis*) and 8% (*Populus simonii*) (Figure 5), indicating that *Populus simonii* stored SOC content, while *Pinus sylvestris* and *Pinus tabuliformis* consumed SOC content, and the depth of store or consumption was mainly 0-150 cm. With the increase of depth, SOCD of plantations all presented a decreased trend. Moreover, it was also explained that the difference of different plantations was mainly focused on the shallow layers (0-100 cm), while there existed no obvious difference for the deep layers, resulting in the decrease trend of SOCD.

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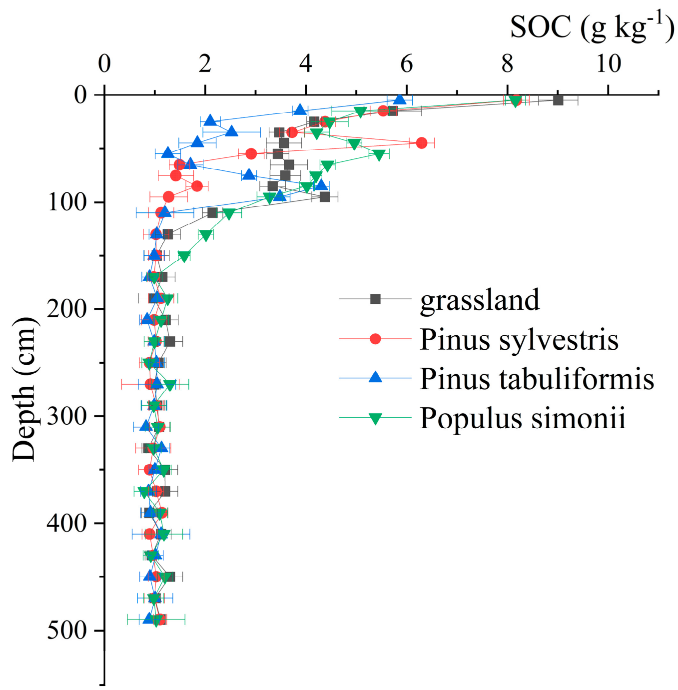

Figure 4. Vertical distributions of soil organic content (SOC) for different plantations.

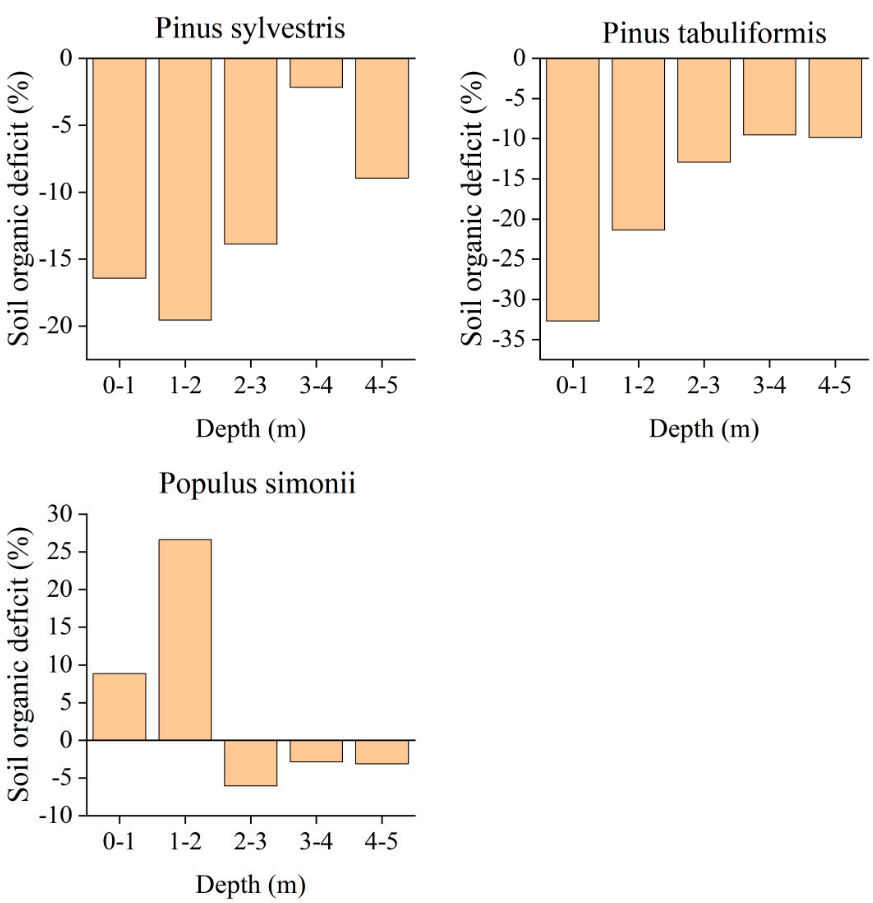

Figure 5. Soil organic carbon content deficit of different plantations for different soil depths.

3.3. Tradeoff between SWC and SOC

The benefits of SWC were all higher than that of SOC for all vegetation types (Figure 6). In addition, the order of RMSE value were *Pinus tabuliformis* (0.31) > grassland (0.26) > *Pinus sylvestris* (0.20) > *Populus simonii* (0.13), respectively, indicating *Populus simonii* may be a good choice from the perspective of water-carbon tradeoff relationship.

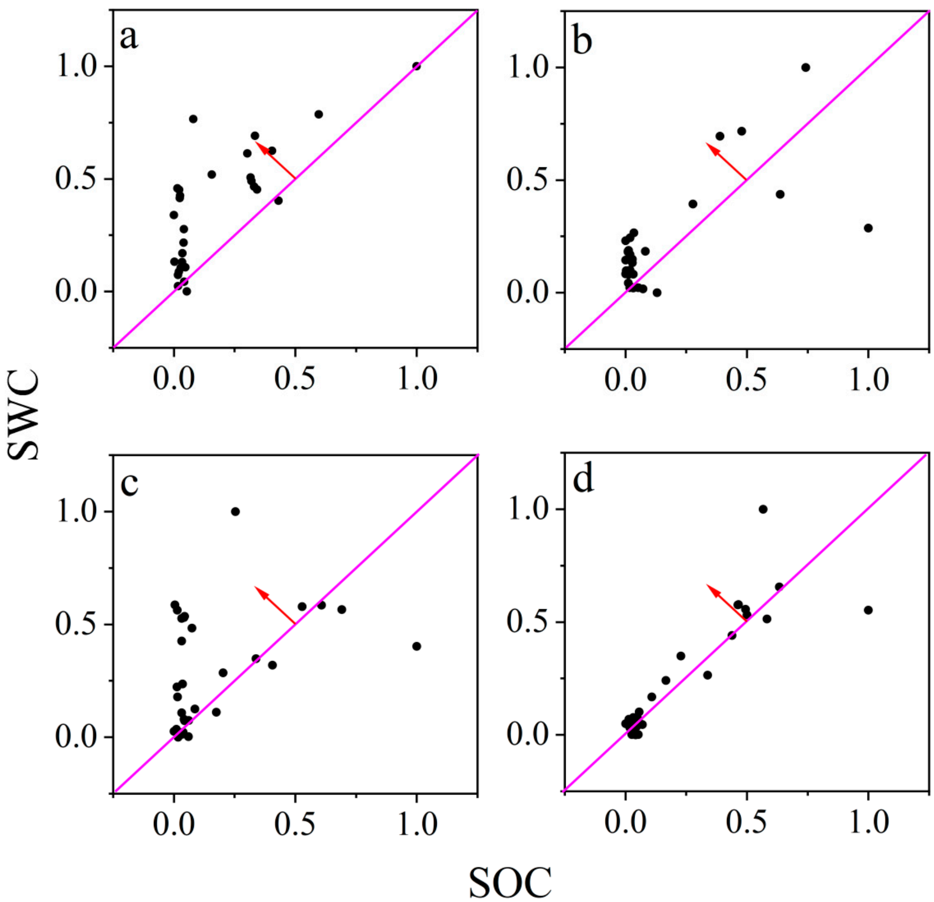

Figure 6. The tradeoff between SOC and SWC. (a, Grassland; b, *Pinus sylvestris*; c, *Pinus tabuliformis*; d, *Populus simonii*. And the direction of red arrow represent higher benefit for SWC/SOC.

3.4. Influences of Environmental Factors on SWC and SOC

To further show the influencing factors of environmental factors (soil texture and land use type) on SWC and SOM, The redundancy analysis was conducted in this study (Figure 7). In general, SOC, LUT and soil texture explained 45.75%, 19.38% and 34.87% of SWC variations, respectively. SOC and soil texture were the main influencing factors for SWC variation of 0-5 m. For SOC variations, SWC, LUT and soil texture accounted for 37.24%, 47.60% and 15.17% of SOC variation for 0-5 m, suggesting the importance of SWC and LUT to SWC variation. However, the main influencing factors of different depth were different for SOC variations, namely SWC for 0-2 m, while LUT for 2-5 m.

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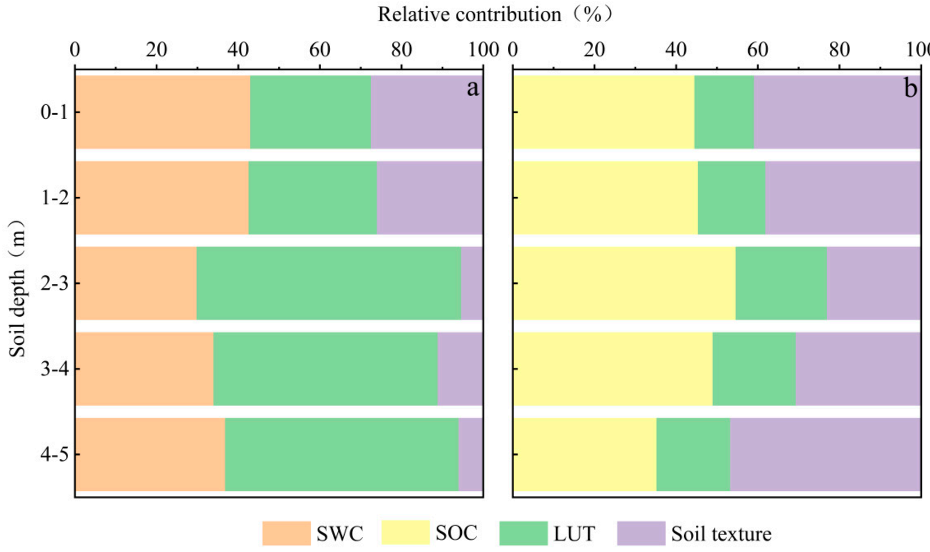

Figure 7. The relative contributions of SWC, LUT and soil texture to SOC variations (a), and the relative contributions of SOC, LUT and soil texture to SWC variations (b).

4. Discussion

4.1. The Effect of Vegetation Restoration on Deep Soil Moisture and Deep Soil Organic Content

Our study showed that artificial vegetation restoration leads to deep soil water depletion. The findings are a common sense, conforming to that of numerous studies [5,7] on the Loess Plateau. Forests had high evapotranspiration and the limited rainfall couldn't satisfy the demand of forests, causing soil water depletion and the formation of a dry soil layer (DSL). For example, Wang et al. [24] addressed the large-scale spatial variability of DSL on the Loess Plateau and found that the occurrence of DSLs showed strong spatial variation and there is a mean thickness of 160 cm below a mean soil depth of 270 cm for DSL. Jia et al. [5] collected SMC data within the 5-m soil profile from 50 sites of the Loess Plateau, and found the depth-averaged SMC was much lower under forest than under cropland and artificial forests could therefore exert the function of "water pump" in the Loess Plateau.

Compared to the grassland, *Populus simonii* fixed SOC, while *Pinus sylvestris* and *Pinus tabuliformis* consumed SOC. Different plantations had different impacts on the SOC sequestration. It is still a debate about the response of SOC to artificial forests. For instance, Yao et al. [25] found SOC significantly increased in topsoils when converting the cropland to natural grassland, woodland and artificial grassland . Yang et al. [12] also discovered that *Robinia pseudoacacia* afforestation increased significantly carbon sequestration of topsoils on the Loess Plateau of China. However, other studies found that there existed no obvious differences for SOC when converting cropland to plantations [26,27]. There are some studies showing the revegetation of croplands leads to the decrease of SOC for the surface soil layer or subsoil [28,29]. In addition, it is also reported the response of SOC to revegetation was a changed process following afforestation. Han et al. [30] discovered that the SOC stock change tended to increase in young forests, while it presented a reducing trend for middle-aged and old forests. These differences show the truth that the magnitude and direction of soil C dynamics are impacted by a few factors, such as tree species, terrain, sampling depth, initial soil physical and chemical properties, and management measures. Therefore, the response of soil organic carbon to artificial forests still needs to consider multiple factors for in-depth research in the future.

4.2. Effects of Environmental Factors on SOC and SWC

Our studies showed SOC and texture were important factors for SWC variations of 0-5 m. On the one hand, it is reported there is significantly correlation between SWC and SOC at the soil surface [12,15]. On the other hand, SOC is loose and porous, and can absorb a lot of water. Therefore, SOC were an important factor for SWC variation of 0-5 m. Soil texture is another important factors to SWC variations, which is consistent with other results [13]. The finer the soil texture, the stronger the ability to retain water, which indirectly affects the spatial distribution of SWC [31] . In addition, SWC were important factors to SOC variations of 0-2 m ,while LUT was important factors to SOC variations of 2-5 m. Similar to SWC, a significant correlation between SWC and SOC of upper soil layer led to the importance of SWC to SOC variations of 0-2 m. With the increase of depth, LUT played a more important role to SOC variations of 2-5 m. The effects of LUT on SOC mainly depend on plant productivity, decomposition of root exudates, and the number and chemical composition of leaves [32,33] . The plantations of our study have deep root systems, and then lead to the importance of LUT for deep SOC variations.

4.3. Implications for Future Vegetation Restoration and Its Limitations

Lots of plantations have been planted since the project of Grain for Green started. Although it is reported that naturally restored grassland was a suitable revegetation approach compared to forests [34,35], plantations of shrubs and trees could provide more ecosystem services, such as wood fiber products, greater biodiversity and better economic benefit in relative to natural grassland [36]. It is a common sense that plantations of shrubs and trees all lead to the deficit of deep SWC. In the current situaction, how fully utilize the ecosystem service function of artificial forests is of great importance. In our study, SWCD of Pinus sylvestris and Populus simonii were low, but Populus simonii could fix more soil cabon. In addition, the RMSEA of tradeoff of Populus simonii were the smallest. Therefore, *Populus simonii* may be a good choice in future vegetation restoration. Nevertheless, it is noted that the suitable revegetation method mainly depends on the evaluation indicators and different evaluation indicators had different results. Gao et al. [19] found R. pseudoacacia was not a good choice for revegetation, which was caused by consuming more SWC although fix relatively high SOC. While Jian et al. [37] believed that R. pseudoacacia was a good choice based on high ratios of actual evapotranspiration relative to pan evaporation. Therefore, a suitable revegetation method needs to be provided based on the main ecosysytem services of the plantations.

Our study provided a suitable revegetation technique based on the effects of typical artificial forests on SOC and SOC. However, there still are limitations. First, although Populus simonii fixed more SOC, it still consumed deep SWC. Appropriate measures are necessary to avoid the excessive consumption of SWC in the future. Second, there are complex terrains and we only studied the artificial forests located on flat ground, and artificial forests of other terrains (slope) should be studied. Third, there are existing lots of different plantations on the Loess Plateau, such as shrub, grassland, pure/mixed plantations of trees or shrubs or grasslands. Therefore, more plantations of different combinations should be studied in the future.

5. Conclusions

In our study, the changes in SWC and SOC as well as their interaction and influencing factors for three typical plantations on China's Loess Plateau were investigated. Results showed that compared to the grassland, *Pinus sylvestris* consumes the SWC but increases the SOC, while the rest plantations not only decrease the SWC but also lower the SOC. The RMSE value of tradeoff of *Pinus sylvestris* were low. The significant correlation between SWC and SOC mainly concentrated on the shallow layer. Tredundancy analysis showed LUT had a important impact on the SOC variations of deep soil layers, while SOC and soil texture for deep SWC variations. Given the SWCD, SOCC and RMSEA, *Pinus sylvestris* should be considered in future vegetation restoration.

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Author contribution All authors contributed to the study conception, design, material preparation, data collection, and analysis.

Ethical approval: We all authors read and approved the final manuscript.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

Competing interests: The authors declare no competing interests.

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