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Variations in Soil Organic Carbon after Farmland Conversion to Apple Orchard

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Abstract: The Chinese Loess Plateau has undergone extensive revegetation to restore degraded land and enhance carbon sequestration. However, soil organic carbon (SOC) sequestrated in the soil profiles of deep-rooted plants has not been fully studied. Here, we investigated the SOC within a 0–23 m profile in farmlands and apple orchards converted from farmlands with different ages (A5, <5 years; A10, ~10 years; A15, ~15 years; A20, >20 years) and the controlling factors on three loess tablelands (Changwu, Qingyang, and Luochuan). The results show that SOC stocks among farmlands and orchards showed no significant difference ($p = 0.88$); however, SOC stocks showed a trend with tree ages, i.e., a decrease for A5 and A10 but an increase for A15 and A20. For the vertical variability, the SOC stock was the highest within 0–1 m, regardless of the standing age; however, the SOC stock in this layer only accounted for 8.8% of the total SOC stock (97.93 ± 9.18 kg m^{-2}). Climate accounted for 82% of the variations and controlled the changes in SOC in the 0–1 m range, while soil texture dominated the SOC in the soil below 1 m, accounting for 57% of the SOC variations. The variations in SOC in the thick, unsaturated zones provide implications for future land use management and the sustainability of apple orchards in arid regions.

Keywords: apple orchard; carbon sequestration; deep soil layer; Loess Plateau; soil organic carbon

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1. Introduction

Soil comprises the largest carbon reservoir in the terrestrial ecosystem and plays a crucial role in global carbon cycling [1,2]. Agricultural ecosystems occupy nearly 40% of the Earth's terrestrial surface [3]. As one of the most active components of the terrestrial ecosystem, a small change in the soil organic carbon (SOC) stock of agricultural ecosystems could significantly affect soil quality, land productivity, the global carbon cycle, and climatic conditions [4,5]. Large-scale land use changes caused by afforestation have greatly affected the ability of agricultural ecosystems to maintain SOC [6–8]. Consequently, understanding the spatial distributions of SOC under agricultural land use changes and its controlling factors is crucial for accurate assessments of SOC in terrestrial ecosystems [9,10].

Although the changes in SOC have been well-documented in vegetation restoration studies, these studies mostly focus on shallow soil layers [7,10]. The interest in the role of deep-rooted plants in SOC dynamics is growing since these plants can extend their roots much deeper to perturb the properties of deep soil compared to shallow-rooted plants. In particular, deep soil has been largely emphasized for its role in carbon sequestration and carbon storage estimates [11–14]. Furthermore, due to differences in forest stands and tree species, these deep-rooted plants can affect SOC stock through litterfall and rhizodeposition, and the leaching of labile humic acids into the soil profile has occurred not only in forest soil but also in agricultural soil [15,16]. Therefore, enhancing our understanding of how deep-rooted plantations influence SOC stocks can have an impact on the development of forest-based carbon offsets and management.

Despite the fact that changes in SOC in response to afforestation have been widely observed, changes in SOC also depend on vegetation types, climatic conditions, restoration age, and soil properties [10,17,18]. In particular, apple orchards have long been used as afforestation species owing to their extensive deep root networks and high economic benefit [19]. Apple orchards extract deep soil water by developing root systems, which noticeably affects local carbon sequestration after cultivation [20]. For example, previous studies have presented different patterns (increasing, net, decreasing) in the changes in SOC contents following the plantation of apple trees [20–25]. As a result, changes in SOC after the transformation of farmland into orchards vary.

The Chinese Loess Plateau, covered with loess deposits to a depth of 92 m [26], is a typical ecological fragility in the world. To restore the degraded ecosystem, the Grain for Green Project has been carried out since 1999. Among them, the apple orchard area in this region is the largest in China, producing apples that account for one-seventh of the world's production [27,28]. To date, research on SOC in apple orchards indicates that the changes in SOC differ at various spatial scales [7,10,29,30]; studies that only focus on a single site or individual tree age cannot describe the dynamics of SOC content at the regional scale. Thus, it is crucial to realize the SOC dynamics for deep soil and different apple tree ages from multipoint observations.

This study aims to explore the variations in SOC in deep loess deposits over different apple tree ages and different regions, which could be helpful in assessing carbon sequestration potential. Accordingly, we collected a total of 1725 soil samples within depths of 0–23 m in farmlands and orchards with different stand ages from three regions. In particular, the objectives of the present study were to (1) analyze the vertical distribution of the SOC content along the profiles of 0–23 m in different regions; (2) explore whether the transformation of farmland to orchards increases carbon stock following orchard growth; and (3) analyze the environmental factors that influence SOC in different soil layers.

2. Materials and Methods

2.1. Study Area

This study was performed in the tableland–gully regions of the Chinese Loess Plateau (33°30′–38°30′ N, 103°30′–114°30′ E) [31]. The topography of the region consists of tablelands with a long history of intensive agricultural production. Winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were the main crops grown here. Because of economic benefits and policy guidance, large areas of farmlands have been gradually transformed into Fuji apple orchards over the past 30 years. In particular, Qingyang, Changwu, and Luochuan are three unique counties with extensive high-quality apple orchards (Figure 1). The mean annual temperatures (MAT) are 9.4 °C, 9.1 °C, and 9.2 °C, and the mean annual precipitation (MAP) is 538 mm, 583 mm, and 608 mm in Qingyang, Changwu, and Luochuan, respectively. The climate of the region is continental monsoon with uneven precipitation that mainly falls from June to September. Agricultural production in this region depends entirely on natural precipitation without irrigation. The widespread soil texture in this region is clay-loam, with more clay in the soil of the southern area [31].

Four apple orchards with varying stand ages and farmlands (F) were chosen for each region (Qingyang, Changwu, and Luochuan; Table 1). We selected four ages for the 'Red Fuji' (*Malus pumila* Mill.) apple trees, i.e., <5 years (A5), ~10 years (A10), ~15 years (A15), and >20 years (A20) since these trees typically bear fruit at the age of 6 (trees younger than 5 years old are referred to as young orchards A5 and trees of ~10 years old are referred as early fruiting orchards A10), reach their highest production at ~15 years (full bearing orchards A15), and gradually decrease in yield after ~20 years (old orchards A20).

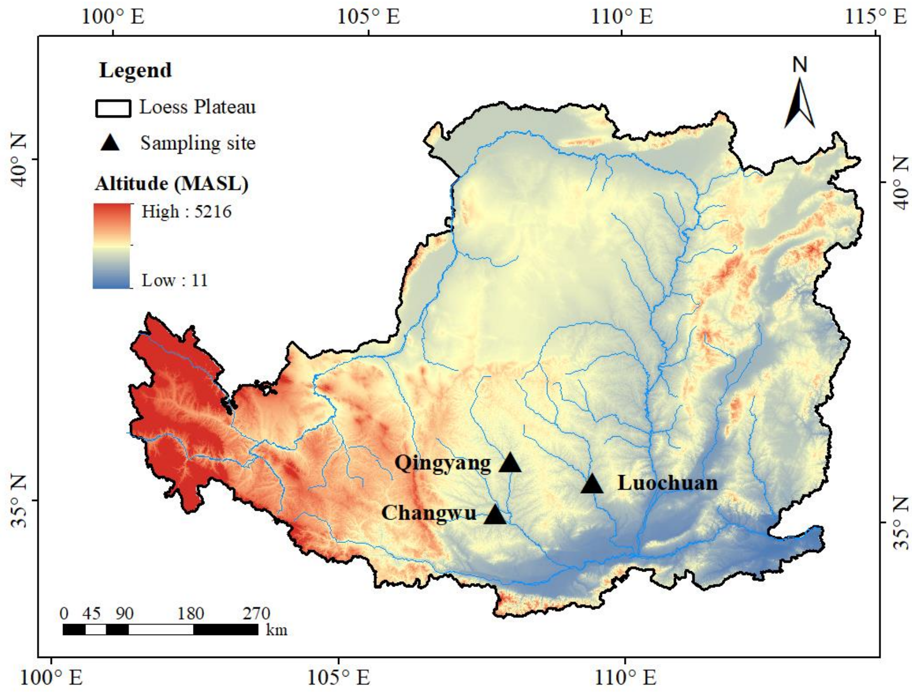

Figure 1. Location of the study region. MASL: meters above sea level.

Table 1. Details of the fifteen sampling sites selected on the loess tableland, China.

Study Region	MAT (°C)	MAP (mm)	Sampling Site (Stand Age)	Height (m)	DBH (cm)	Canopy Diameter (m)
Qingyang	9.4	538	Farmland (F)	–	–	–
			A5 (5)	2.92 ± 0.27	11.00 ± 1.13c	3.79 ± 0.52b
			A10 (12)	2.56 ± 0.32	17.73 ± 2.63b	4.08 ± 0.60b
			A15 (18)	2.69 ± 0.47	21.30 ± 3.28a	4.72 ± 0.44a
			A20 (32)	2.86 ± 0.54	20.35 ± 3.47a	3.87 ± 0.38b
Changwu	9.1	583	Farmland (F)	–	–	–
			A5 (5)	2.60 ± 0.23	6.17 ± 1.04c	2.02 ± 0.36c
			A10 (10)	2.73 ± 0.51	10.50 ± 1.32b	2.43 ± 0.24c
			A15 (15)	3.07 ± 0.23	20.56 ± 1.15a	3.19 ± 0.16b
			A20 (24)	3.16 ± 0.16	22.83 ± 0.76a	4.36 ± 0.23a
Luochuan	9.2	608	Farmland (F)	–	–	–
			A5 (5)	3.45 ± 0.46a	6.96 ± 1.40d	2.82 ± 0.67c
			A10 (10)	3.05 ± 0.20b	12.75 ± 1.30c	3.81 ± 0.58b
			A15 (15)	2.95 ± 0.23bc	15.90 ± 2.163b	3.87 ± 0.39ab
			A20 (25)	2.67 ± 0.32c	20.36 ± 1.85a	4.34 ± 0.60a

Note: The number following the sampling site represents the apple orchard stand age; MAT: mean annual temperature; MAP: mean annual precipitation; and DBH: diameter at breast height. Values are the means ± standard errors (n = 10). Values followed by different letters in a column are significantly different at $p < 0.05$. The same is true below.

2.2. Soil Sampling and Measurements

Specifically, soil samples from the orchards were collected at the point where diagonal lines were formed by the nearest four apple trees. The soil samples from the farmlands and orchards were collected for 0–23 m at an interval of 0.2 m using drilling equipment TGQ-30C (Beijing Zhongkan Drilling Co., Beijing, China). Then, each soil sample was divided into three sub-samples. Using the oven drying method, the soil water content (SWC, g g^{-1}, %) was obtained by the first sub-sample. To measure their particle size distribution, the second sub-sample was sieved through a 2 mm mesh and measured by Mastersizer 2000 (Malvern Instruments, Melvin, UK). The third sub-sample was air-dried and sieved through a 0.25 mm mesh to measure the SOC content using the $K_2Cr_2O_7$-H_2SO_4 oxidation method [32].

2.3. Calculation of SOC Stock

To calculate the SOC stocks, we estimated the soil bulk density using a pedotransfer function that was developed from 1254 soil datasets on the Loess Plateau of China [33]:

$$\begin{aligned} BD_i = 1.8284 + 0.0429 \times log_{10}^{(Clay_i)} + 0.0205 \times Clay_i^{0.5} - 0.0125 \times cos(Clay_i) \\ -0.0061 \times Silt_i - 0.0071 \times SOC_i - 0.0505 \times SOC_i^{0.5} \\ +0.0002 \times SOC_i^2 \end{aligned} \quad (1)$$

where BD_i, $Clay_i$, $Silt_i$, and SOC_i are the soil bulk density (g cm^{-3}), clay (%), silt (%), and SOC contents (g kg^{-1}) at the *i*th soil depth, respectively. This pedotransfer function was evaluated to provide a better estimation of soil bulk density than other functions and has been widely used to estimate the bulk density of deep soil layers [11,34].

For the *i*th soil layer, the SOC stock was characterized as the soil carbon mass per unit area and calculated as follows:

$$SOC_{stock} = \sum 0.01 \times SOC_i \times BD_i \times (1 - ST_i) \times \Delta d_i \quad (2)$$

where SOC_{stock} is the SOC storage (kg m^{-2}), BD_i, ST_i, and Δd_i represent the bulk density (g cm^{-3}), the fraction of coarse fragments, and thickness (cm) in the *i*th soil layer, respectively. As the Loess Plateau had a few coarse particles in its loess soil, the ST_i was neglected in the SOC stock calculation.

2.4. Statistical Analysis

The effects of land use type (orchard stand age) on the SOC content were analyzed using a one-way analysis of variance, and then Tukey's LSD method was used with significance levels of 0.05 (ANOVA). The Pearson correlation test was used to identify correlations between relevant factors (i.e., MAP, MAT, soil texture, and vegetation age) and the SOC. To reduce co-linearity among multiple variables, a principal component analysis (PCA) was used to create the indexes. All statistical analyses were carried out using SPSS version 22.0 (SPSS Inc., Chicago, IL, USA). In addition, the contribution rates of influencing factors to changes in SOC were evaluated through redundancy analysis (RDA). All figures were created with Origin 2016 (Origin Lab, Northampton, MA, USA).

3. Results

3.1. SOC Variation with Growth Stage and Regions

The SOC stock in the 0–23 m soil layer varied with sampling region, orchard growth stage, and soil depth (Figure 2). Specifically, the mean SOC stock in the whole profile was 97.93 ± 9.18 kg m^{-2} for the 15 sampling sites. The mean SOC stocks ranged from 90.33 to 108.65 kg m^{-2} in the three regions (Figure 2a), among which the SOC stock in Changwu was significantly higher than that in Qingyang and Luochuan ($p < 0.05$). Among the different growth stages, the stocks of SOC were in the order of A20 (101.11 kg m^{-2}) > F (100.89 kg m^{-2}) > A5 (97.63 kg m^{-2}) > A15 (96.4 kg m^{-2}) > A10 (93.52 kg m^{-2}). Overall, the total SOC stock could be characterized by an initial reduction in the young (A5) and early fruiting orchards (A10) and then an increase with tree age (A15 and A20). It also showed a unimodal curve ($p = 0.88$, Figure 2b). Additionally, the total SOC stock showed no significant difference between farmlands and apple orchards, indicating that the cultivation of apple trees did not promote carbon sequestration.

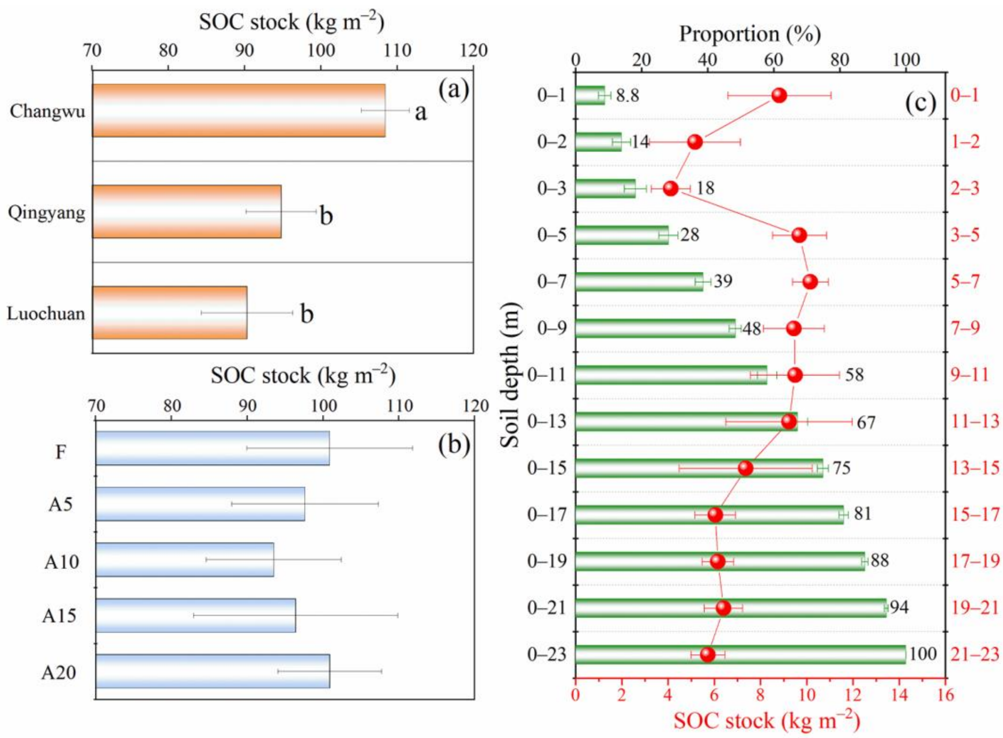

Figure 2. SOC stocks throughout the 0–23 m soil layer in (**a**) the three study regions, (**b**) farmland and different growth stage orchards, and (**c**) cumulative SOC stocks at various depths on the loess tablelands. Error bars represent the standard deviation. Different letters indicate significant differences at the level of 0.05 ($p < 0.05$). The same is true below.

The SOC stock exhibited high variability with depth across the profile (Figure 2c). The stock SOC in the unit soil layer of the farmland and orchard ranged from 2.86 ± 0.73 to 8.82 ± 2.23 kg m^{-2} m^{-1}, exhibiting a decline with soil depth. However, in terms of the 0–23 m profile, we found that among the different soil layers, the amount of accumulated SOC stocks increased with observed soil depth. The greatest SOC stock was observed in 0–1 m (8.82 ± 2.23 kg m^{-2}), accounting for 8.8% of the SOC stock across the entire profile (Figure 2c). Although the SOC stock decreased with depth, the SOC stocks in the deep soil were much larger than that in the shallow layer, with more than 90% of the total carbon stored below 1 m.

3.2. Vertical Distribution of SOC along the 0–23 m Profile

3.2.1. SOC in Farmland and Different Growth Stage Orchards

The SOC content varied vertically along the soil depths (Figure 3). The SOC content averaged over the whole profile was 2.93 ± 0.34, 2.84 ± 0.29, 2.74 ± 0.25, 2.81 ± 0.39, and 2.98 ± 0.24 g kg^{-1} for F, A5, A10, A15, and A20, respectively. Overall, the vertical distribution of the SOC content can be characterized by a decrease within 0–2 m, then stabilization within 2–10 m and 15–23 m, and an increase within 10–15 m in a unimodal state.

The vertical distribution of SOC stocks also varied with soil depth (Figure 4). The mean stocks of SOC in the farmland and orchards gradually decreased with soil depth. Taking 5 m as the interval, the stocks of SOC were 5.24–5.82, 4.45–5.13, 4.06–4.60, 2.96–3.26, 2.81–3.31 kg m^{-2} m^{-1} for 0–5 m, 5–10 m, 10–15 m, 15–20 m, and 20–23 m, respectively. Compared to F, the mean SOC stock for 0–5 m, 5–10 m, 10–15 m, and 20–23 m in the apple orchards initially decreased and then increased slightly with increasing tree ages, while that for 15–20 m showed the opposite trend. The stocks of SOC in F in Luochuan tableland were 25.37 and 16.83 kg m^{-2} for 0–5 m and 10–15 m, while that for the old orchard were 30.98 and 22.77 kg m^{-2}, suggesting a remarkable increase in SOC stock from the apple trees.

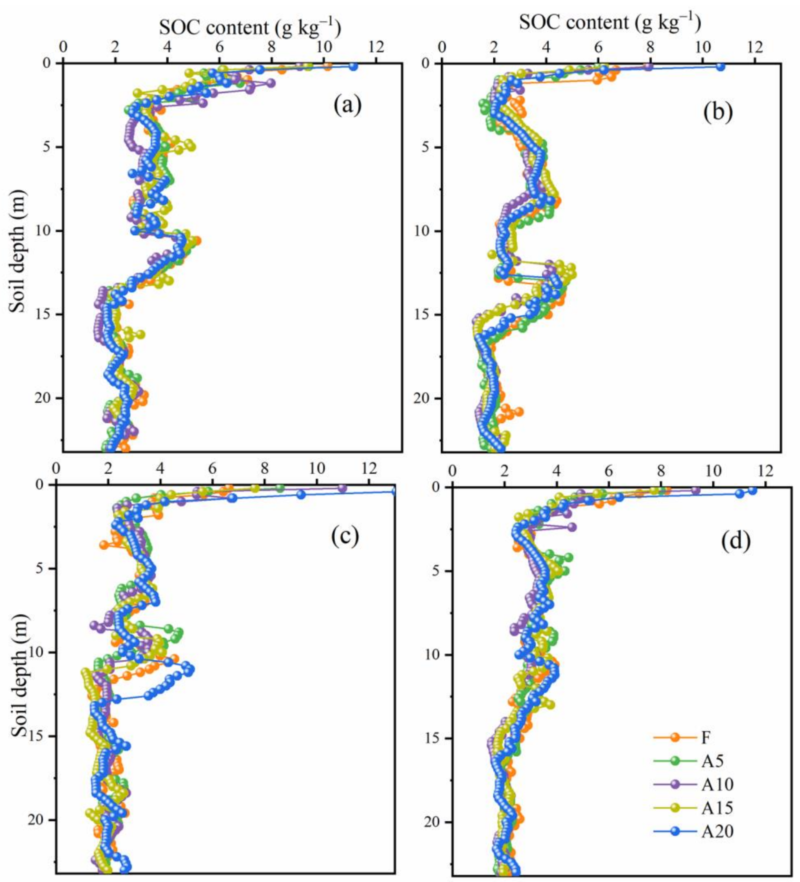

Figure 3. Vertical distributions of soil organic carbon (SOC) content under farmlands and orchards. (**a**–**d**) Changwu, Qingyang, Luochuan and the mean of these three regions.

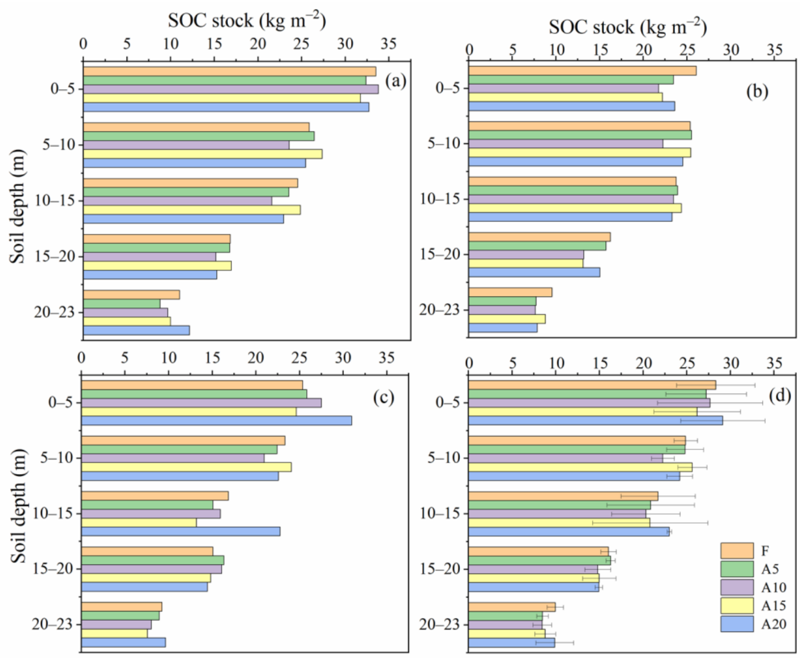

Figure 4. Vertical distributions of SOC stock at various soil depths in farmlands and orchards. (**a**–**d**) Changwu, Qingyang, Luochuan, and the mean of these three regions, respectively.

3.2.2. SOC in Different Regions

The mean SOC contents showed similar vertical distributions in the three loess tablelands, with the highest contents in 0–1 m (Figure 5). The SOC contents averaged over the whole profile were 3.18 ± 0.09, 2.79 ± 0.13, and 2.63 ± 0.19 g kg^{-1} in Changwu, Qingyang and Luochuan tablelands, respectively.

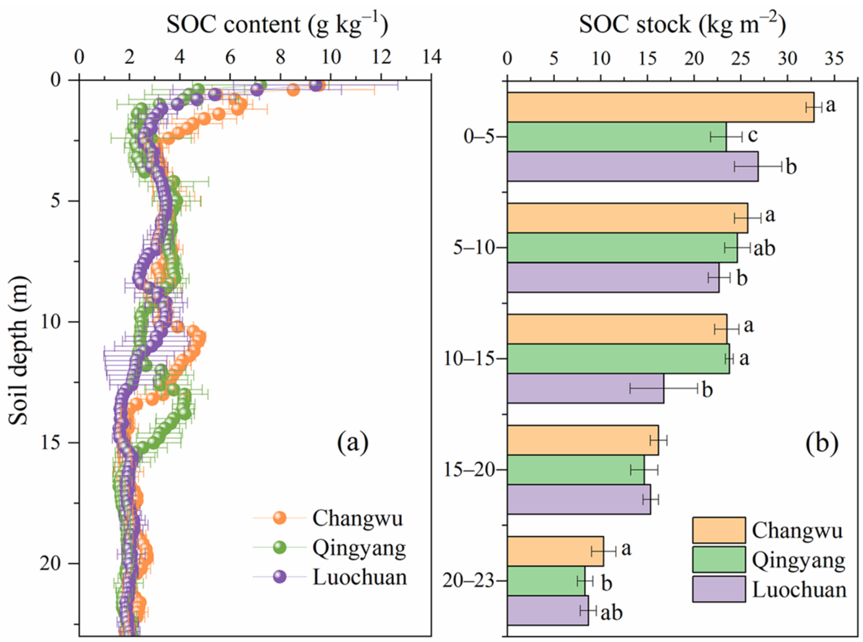

Figure 5. Vertical distributions of soil organic carbon (SOC) content (**a**) and SOC stock (**b**) at various soil depths in Changwu, Qingyang, and Luochuan tablelands. Different letters indicate significant differences at the level of 0.05 ($p < 0.05$).

The vertical variations in the SOC stock along the whole profile were plotted in Figure 5b. ANOVA results indicated a significant difference in the stocks of SOC among these three regions (Figure 5b). Specifically, the SOC stock within 0–5 m in the Changwu tableland was 32.82 kg m^{-2}, which was significantly higher than the Qingyang (23.43 kg m^{-2}) and Luochuan (26.86 kg m^{-2}) tablelands ($p < 0.05$). The stocks of SOC had slight increases in the deep soil at the three sites. The depths with a higher SOC content were mainly within 8–15 m, and the peak values of SOC content were detected at depths of 10.6 m, 13.8 m, and 9.6 m with SOC values of 4.79, 4.20, and 3.47 g kg^{-1} in Changwu, Qingyang and Luochuan, respectively.

3.3. *Controlling factors of SOC*

As shown in Figure 6, the correlation of each factor with SOC varied with soil depth. Overall, the MAT and MAP had a significant correlation with the content of SOC in 0–1 m ($p < 0.05$). However, the correlation between the SOC content and soil texture was significant below 1 m. Specifically, the clay content presented a positive correlation with SOC content in 1–23 m and was related to SWC in 1–3 m and 10–23 m, respectively. The SOC content was negatively correlated with silt and sand contents in 1–2 m and 1–23 m ($p < 0.05$).

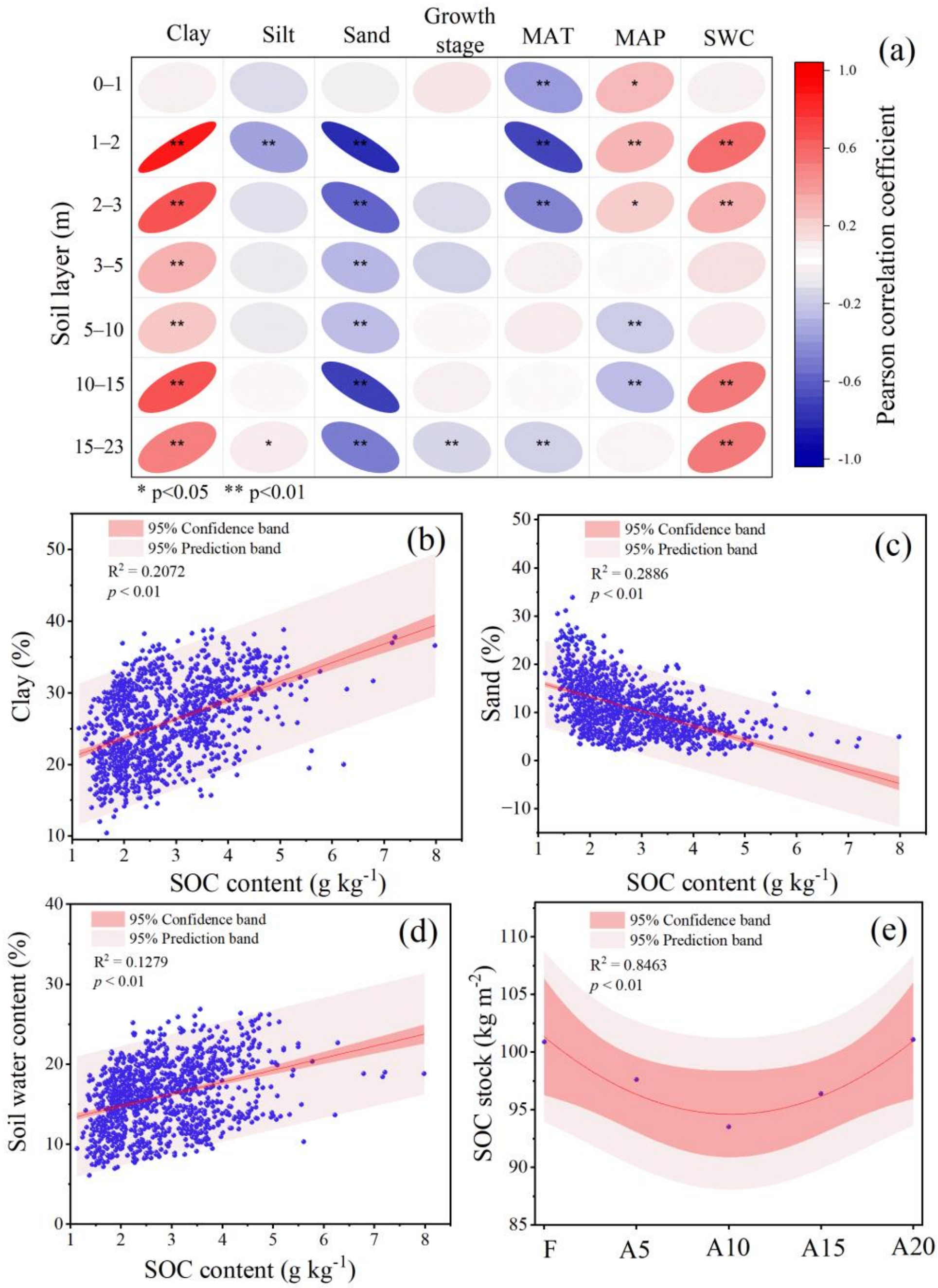

Figure 6. Pearson correlation analysis results for soil organic carbon (SOC) contents and environmental factors (**a**), and the correlation between SOC content and clay (**b**), sand (**c**), and soil water content (**d**) between SOC stock and the orchard growth stages (**e**).

For the entire 0–23 m soil layer, we found that the clay and SOC content were positively correlated ($p < 0.01$, Figure 6b), while the sand and SOC content were found to be negatively correlated ($p < 0.01$, Figure 6c). In addition, the SOC content and SWC also had a positive correlation ($R^2 = 0.13$, $p < 0.01$, Figure 6d). A strong unimodal trend was observed in the correlation between the total SOC stock and tree ages, which was characterized by a decrease initially followed by an increase with increasing age ($p < 0.05$, Figure 6e). The lowest SOC stock was detected in A10, which suggests that there is an inflection point in the SOC stock that evaluated chronosequence.

Based on the PCA, axes 1 and 2 explained 73% and 21% of the total variation in SOC contents, respectively (Figure 7a). Additionally, the relative contributions of the environmental factors that influenced the SOC were highly variable in different soil layers

(Figure 7). On average, the sand content, clay content, and MAT explained 24%, 23%, and 17%, respectively, of the variations in SOC over the entire soil profile (Figure 7b). Soil texture explained nearly 50% of the SOC variations. The relative contribution of MAT to variations in the SOC in 0–1 m was 54%, which was larger than the other soil layers. Overall, climate accounted for 82% of the variations and was the main controlling factor of SOC in 0–1 m, while soil texture was the dominant factor in the deeper layers, explaining, on average, 57% of the SOC variations (Figure 7b).

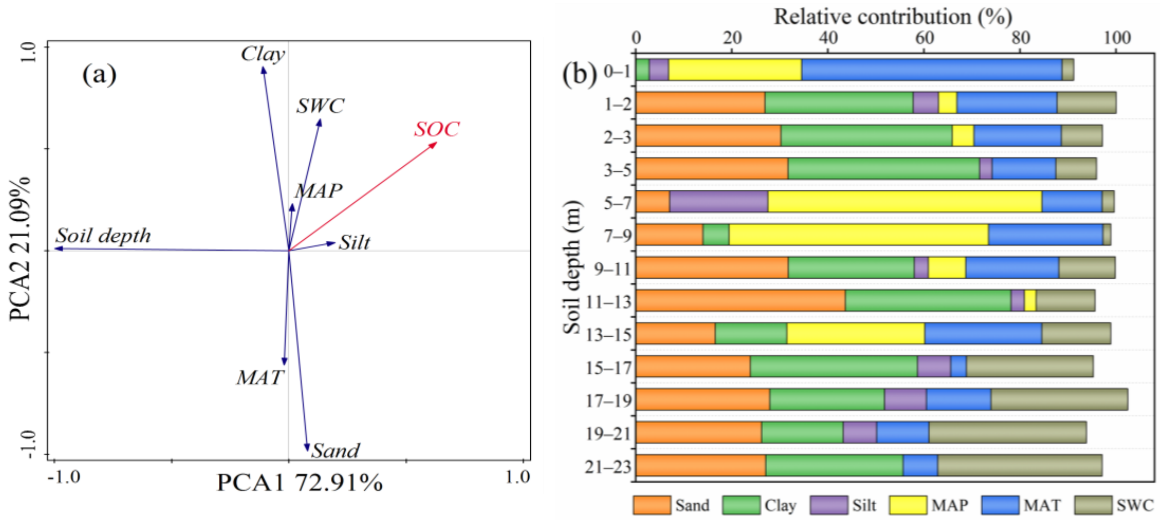

Figure 7. The relationships between various environmental factors and soil organic carbon (SOC) determined by a principal component analysis (**a**); relative contributions of each variable to the SOC content at different soil depths (**b**).

4. Discussion

4.1. Variations in SOC Affected by Apple Tree Plantation

Over the past several decades, extensive research attention has been given to the effects of afforestation on soil carbon sequestration and loss [12,21,35,36], and it is generally acknowledged that the plantation of deep-rooted plants could affect the SOC reservoirs [10,37]. Tree age is a crucial factor to be considered when assessing the SOC stock after farmland conversion [38]. This study found that the SOC decreased initially following the transformation of farmlands into apple orchards. The lower SOC contents observed during the early growth stages of the fruit tree might be attributed to the high SOC decomposition caused by low plant litter input and increased microbial activity from the trees [39]. Although plant litter plays a more significant role in SOC variations than fine roots [16], inputs of litter onto the surface of the soil during the early years of planting can be negligible due to clean cultivation orchard management practices. After long-term afforestation, the root residue and exudates produced by the fruit trees in the soil gradually increase and promote the accumulation of SOC [13,20,24].

A negative SOC sequestration effect was observed in the deep soil, and farmlands and orchards with different growth stages showed no significant difference, showing that planting apple trees did not promote carbon sequestration in deep soil [20]. The reasons for this can be attributed to three aspects. First, the severe soil water deficit accelerates the formation of suberin, which further constrains the root turnover and exudates release [40,41]. Second, although apple trees tend to gain more water by roots that are vertically downward [40], they are less prevalent in deep soils (the root dry weight density in 2–20 m only accounts for about 8% of that in 0–2 m), and thus, limits the capacity to significantly alter the SOC content in deep soil [25]. Additionally, since the accumulation of SOC is a long-term process, the old trees in this study may still be too young to significantly alter the deep SOC contents [20,39,42].

4.2. Effects of Environmental Factors on SOC

Although land use change affects SOC distribution, other environmental factors such as climate, soil texture, and fertilization exert important effects on the heterogeneity of SOC [16,18,30,43]. For example, climatic conditions may contribute to variations in SOC by affecting the rates of biodegradation, as well as the biotic processes associated with vegetation productivity [44,45]. In this study, the environmental effects on SOC were highly dependent on depth [46,47]. Climatic factors and orchard stand age mainly affected the SOC in shallow layers, while soil texture was a critical factor for the variations in SOC in deep soil [48,49]. This is because clay can effectively increase SOC by preventing SOC from decomposing through adsorption and aggregation [50]. In this study, the clay contents of the 1–2 m and 10–15 m soil layers at the Changwu sites were higher than the other two regions (Figure A1), corresponding to higher SOC contents in Changwu.

In forest ecosystems, the root exudates and litter residues were the main sources of SOC [13]. In general, trees with a greater stand or densities could absorb more water by plant transpiration [20], which further results in lower SWC. This study found that planting apple trees could aggravate SOC consumption in the early stage, which is consistent with previous studies on apricot trees [8]. The species of plant also affected the distribution of SOC, and a study from the Chinese Loess Plateau showed that natural forests stored more than twice as much carbon than planted forests in soil [10]. Additionally, the moderate correlations observed between SOC and SWC may be due to the high correlation between soil particle size distribution and SWC [51]. Overall, the SOC in the deep soil layers was driven more by soil texture than by other factors [44,49].

4.3. Implications for Future Economic Forest Management

Afforestation has long been seen as an effective measure in restoring vegetation, controlling soil erosion, and mitigating global warming [39,52]. Therefore, understanding the variations in deep SOC and its influencing factors is crucial for assessing the potential of soil carbon sequestration and providing necessary ecosystem services for ameliorating climate change. In the current study, we detected that the apple trees on the loess tableland could result in decreases in SOC stock in the initial stage, followed by a subsequent increase in the old orchards, which was affected by orchard stand age and environmental factors. The SOC content in loess soil provides necessary information and parameters for regional carbon estimations. However, future research should explore how SOC behaves in lighter, sandy soils with a low content of clay minerals. In such soils, there are probably issues of an excessive outflow of SOC into deeper layers and the oxidation of organic matter in shallow layers. Additionally, the carbon sequestration induced by roots is accompanied by significant soil water depletion [25,37], which leads to poor tree growth. This, in turn, endangers the health and services of the ecosystem. Therefore, effective measures for soil water and carbon stock should be taken into consideration to maintain the balance between environmental protection and the economic benefits of apple orchards. For example, the infiltration of soil water could be improved by taking measures to exploit rainwater (e.g., infiltration holes and horizontal ditches) [6,53]. In addition, sustainable practices (e.g., returning straw, fertilizer addition, etc.) could effectively increase the SOC content and improve soil structure, thereby reducing soil erosion and promoting sustainable land/soil management [16,21].

5. Conclusions

The establishment of deep-rooted apple trees on the loess tableland could result in decreases in SOC stock in the early stage but also a subsequent increase in old orchards. Root-induced carbon sequestration is accompanied by significant soil water extraction; thus, the conversion from farmlands to apple orchards does not significantly increase carbon sequestration as expected. Over the whole profile, the SOC stock was the highest in 0–1 m. Climate mainly affected the SOC in shallow soil, while soil texture was the dominant factor controlling SOC in deep soils. Considering that a large amount of SOC may be stored in deep soil layers, future research should not neglect the dynamics of SOC in deep soils and how SOC behaves in lighter, sandy soils with a low content of clay minerals. In conclusion, a better understanding of SOC in deep soils is fundamental for land use management and the assessment of terrestrial carbon cycling.

Author Contributions: Conceptualization, Y.W. and Z.L.; methodology, Y.W. and W.L.; formal analysis, R.L.; investigation, Y.W. and X.H.; data curation, Y.W., W.Y. and X.H.; writing—original draft preparation, Y.W.; writing—review and editing, R.L., W.Y., W.L. and Z.L.; supervision, Z.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

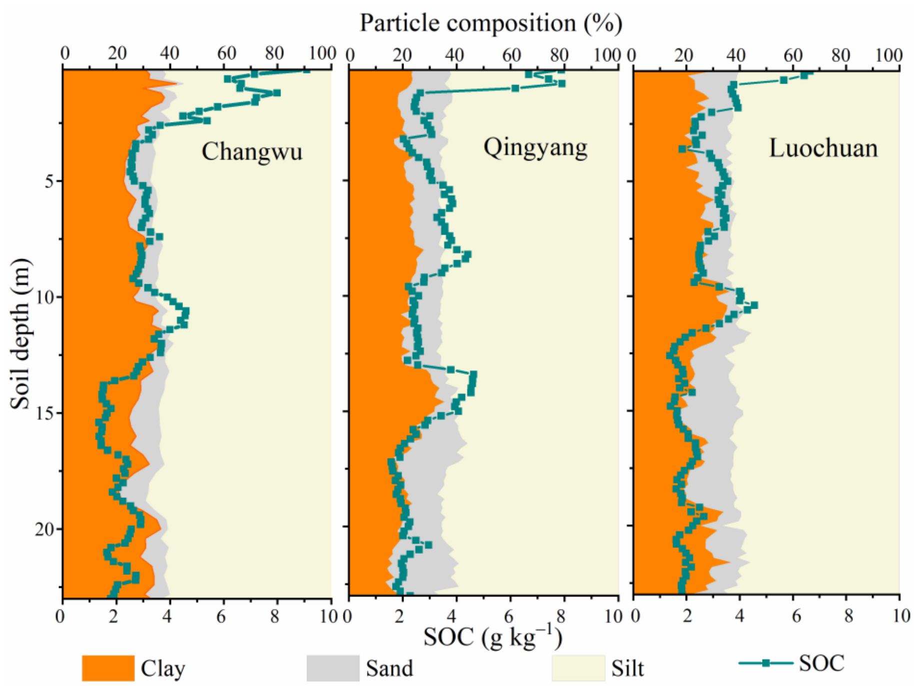

Figure A1. Vertical distribution of soil particle composition and SOC content in farmlands from the three regions.

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