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Stocks and Stoichiometry of Soil Organic Carbon, Total Nitrogen, and Total Phosphorus after Vegetation Restoration in the Loess Hilly Region, China

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Abstract: The Loess Plateau is an important region for vegetation restoration in China; however, changes in soil organic carbon (SOC), soil nutrients, and stoichiometry after restoration in this vulnerable ecoregion are not well understood. Typical restoration types, including orchardland, grassland, shrubland, and forestland, were chosen to examine changes in the stocks and stoichiometry of SOC, soil total nitrogen (TN), and soil total phosphorus (TP) at different soil depths and recovery times. Results showed that SOC stocks first increased and then stabilized in orchardland, grassland, and shrubland at 0–30 cm depths, while in forestland, SOC stocks gradually increased. Soil TN stocks first increased and then decreased in orchardland, shrubland, and forestland with restoration age at 0–30 cm depths, while soil TP stocks showed little variation between restoration types; at the same time, the overall C:N, C:P, and N:P ratios increased with restoration age. In the later stages of restoration, the stocks of SOC and soil TN at 0–30 cm soil depths were still lower than those in natural grassland and natural forest. Additionally, the SOC, soil TN, and soil TP stocks and the C:N, C:P, and N:P ratios decreased with soil depth. The forestland had the highest rate of change in SOC and soil TN stocks, at 0–10 cm soil depth. These results indicate a complex response of SOC, soil TN, and soil TP stocks and stoichiometry to vegetation restoration, which could have important implications for understanding C, N, and P changes and nutrient limitations after vegetation restoration.

Keywords: soil stoichiometry; soil nutrient; nutrient limitations; natural grassland; natural forest

1. Introduction

Soil is an important component of terrestrial ecosystems and the main source of the nutrients required for plant growth and development. Soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) are the main structural and nutritional components of soil and are also the main limiting factors in terrestrial ecosystems [1]. Soil organic C, soil TN, and soil TP stocks reflect the potential of the soil to provide nutrients to vegetation. These elements continuously circulate between the layers of the soil (the biogeochemical cycles of C, N, and P), which ensures a smooth flow of energy and maintains the stability of ecosystems [2]. The availabilities of soil TN and soil TP are major factors regulating the carbon balance of the ecosystem. Elemental stoichiometry is an important

indicator reflecting the C, N, and P cycles in soil and the accumulation and balance of nutrients in ecosystems, and it can help to determine the responses of ecological processes to global changes [3].

Vegetation restoration has received intensive interest because of its potential influence on global C and N cycling, soil quality improvement, land management, and regional economic development [4]. Land use change in the form of vegetation restoration plays an important role in improving the ecological environment and function of ecosystems and can also improve soil quality and soil nutrient cycling. Improved soil quality will, in turn, affect plant production and ecosystem function.

A large number of related studies have shown that stocks and stoichiometry of SOC, soil TN, and soil TP are closely related to land use type [5,6], and nutrient inputs and outputs are considered to be the main factors affecting soil nutrient content [7–9]. Some studies have found that vegetation restoration can promote photosynthesis, soil nutrient accumulation, and microbial activity [10–12], and increase the stoichiometry of SOC, soil TN, and soil TP [9]. However, other studies have indicated that land use change can lead to decreases in soil nutrient contents [13]. Studies estimating the impact of land use on the stocks and stoichiometry of SOC, TN, and TP have mainly focused on the topsoil (0–20 cm), as this is considered to be the most active soil layer in terms of natural and anthropogenic disturbances [14]. Recent studies have shown that the nutrient content of deep soils may also vary greatly with land use [14,15]. Therefore, understanding how C, N, and P stocks and stoichiometry change in soil with land use changes can clarify soil nutrient availability and nutrient cycling and balance mechanisms, and is of great significance for regional ecosystem health assessments.

The Loess Plateau, China, is located in a semi-arid/semi-humid climate zone which has undergone serious soil erosion. It is an ecologically fragile area and a key area for soil and water conservation efforts in China. Before the 1950s, extreme weather such as droughts, heavy rain, hailstorms, strong winds, and dust storms occurred frequently in this area, resulting in serious soil erosion. In addition, as a result of long-term and unsustainable land use, vegetation has been destroyed over large areas due to grazing and farming. The large-scale cultivation of sloping cropland further aggravated the soil erosion. The amount of nitrogen, phosphorus, and potassium lost from slope farmland has been estimated at 12.7 million tons per year [16]. Vegetation restoration was implemented in the 1970s in this region. In order to control soil erosion and improve ecosystem function, ecological restoration and environmental reconstruction work has been carried out in which slope cropland (slope > 25°) has been converted into orchardland, grassland, shrubland, and forestland. After decades of continuous efforts, vegetation coverage has increased, and the ecological environment has been greatly improved [17]. The sequestration and stoichiometry of SOC, soil TN, and soil TP varies among different vegetation types and restoration ages; therefore, its effect on soil physicochemical properties varies as well. It is important, therefore, to clarify annual and vertical variations in the SOC, soil TN, and soil TP stocks and stoichiometry in soils with different vegetation types in the Loess Hilly Region, China.

In order to better understand the SOC processes, carbon budget of the soil, and soil fertility issues after afforestation, we addressed the following questions: (1) How have stocks of SOC, soil TN, and soil TP, and their ratios, changed across the Loess Hilly Region, China, after decades of vegetation restoration? (2) Are these changes associated with soil depth? (3) How do these changes vary with restoration type? We further hypothesized that (1) as litter inputs to the soil increase with restoration age, stocks of SOC and soil TN increase, whereas soil TP stocks do not significantly change since P stocks are primarily affected by parent minerals. The change rate will be greatest for SOC, followed by soil TN, and then soil TP, causing an increase in the C:N, C:P, and N:P ratios with restoration age; (2) vegetation restoration affects stocks of SOC, soil TN, and soil TP at the soil surface more than at greater soil depths; and (3) due to differences in the litter produced by different vegetation, root secretions and soil microorganisms will also vary between restoration types, resulting in differences in stocks and ratios of SOC, soil TN, and soil TP.

2. Materials and Methods

2.1. Study Area

The study area was located in Ansai County, Shanxi Province, China in the center of the Loess Plateau (Figure 1). This region has a warm temperate and semi-arid climate with an annual average temperature of 8.8 °C. Annual precipitation is approximately 500 mm, 60% of which falls between July and September, and the frost-free period is 157 days. The soil is mainly composed of Huangmian soil developed on wind-deposited loessial parent material. This type of soil is characterized by weak cohesion, which has made it prone to severe soil erosion. The sand (2.00–0.02 mm grain size), silt (0.02–0.002 mm), and clay (<0.002 mm) contents are 65%, 24%, and 11%, respectively. The soil bulk density (BD) and soil pH of the tillage layer range from 1.15 to 1.35 g cm⁻³ and 8.4 to 8.6, respectively.

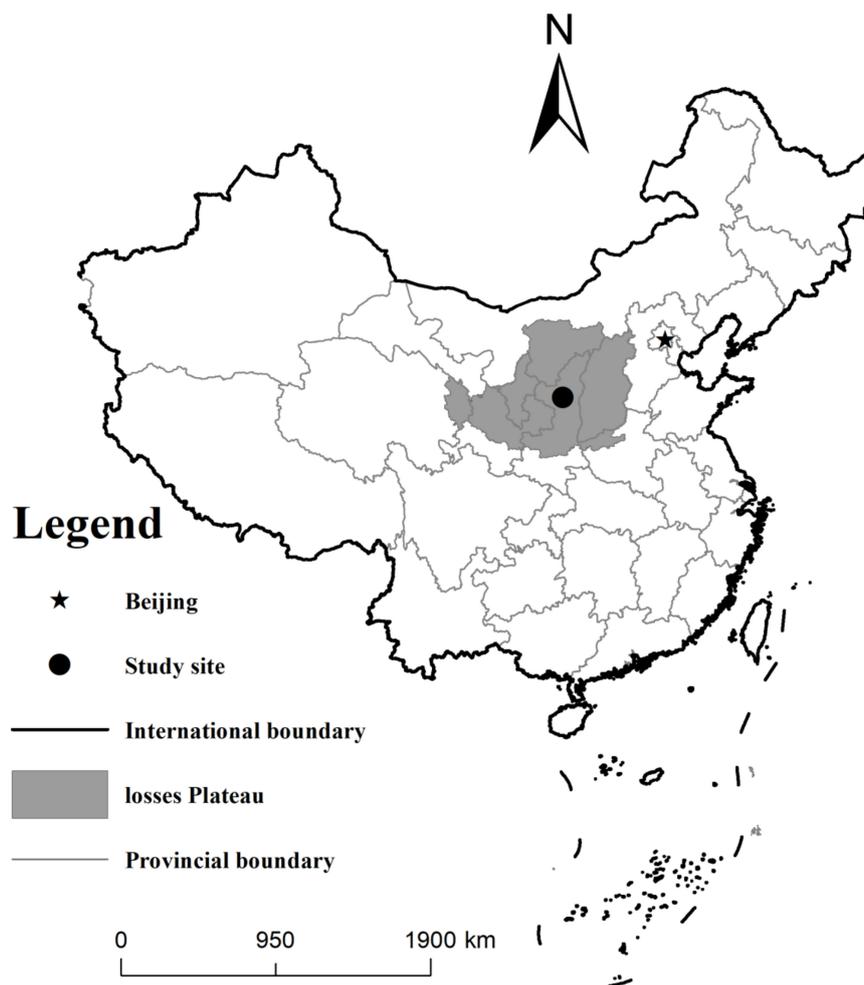


Figure 1. The locations of study sites in Ansai County, Shanxi Province, China.

2.2. Soil Sampling and Laboratory Analyses

With the aim to examine changes in the stocks and stoichiometry of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) after vegetation restoration in different restoration types, this study adopted a “space for time” approach. A total of 82 sites representing four restoration types were selected based on vegetation type, topographic features, and restoration age, comprising 9 sites of orchardland (5, 10, and 20 years), 34 sites of grassland (2, 5, 8, 11, 15, 18, 26, and 30 years), 24 shrubland (5, 10, 20, 30, 36, and 47 years), and 15 forestland (5, 10, 20, 37, and 56 years). In addition, we selected three slope cropland sites, which were studied at 0 years. Because the

four restoration areas were transformed from croplands, four natural grassland sites (age > 50 years) and nine natural forest sites (age > 100 years) were selected as controls (Table S1). Three 10 × 10 m plots were chosen in each orchardland, three 2 × 2 m plots in each grassland (grassland and natural grassland), three 10 × 10 m plots in each shrubland, and three 20 × 20 m plots in each forestland type (forestland and natural forest). Each plot was at least 50 m from the other plots. A total of 15 soil samples were collected from five soil depths (0–10, 10–20, 20–30, 30–50, and 50–100 cm) in a random sampling design using a soil drilling sampler (4 cm inner diameter). Soil samples from each plot from the same soil depth were mixed to form one sample. These soil samples were brought back to the laboratory and then divided into two parts. One part of the sample was naturally air-dried, plant roots and other impurities were removed, and then the SOC, soil TN, and soil TP were measured. The other part was stored in a refrigerator at 4 °C until further analysis of other indicators, which are not presented in this paper.

The soil bulk density (BD) of each depth was measured using the cutting ring method. The SOC was determined using the H₂SO₄–K₂Cr₂O₇ method [18]. The soil TN was measured using the Kjeldahl method [19], and the soil TP was determined colorimetrically using the ammonium molybdate method [20].

2.3. Calculation of SOC, Soil TN, and Soil TP Stocks

The stocks of SOC, soil TN, and soil TP from five soil depths of 0–10, 10–20, 20–30, 30–50, and 50–100 cm in different restoration types were selected in our study to research the carbon budget of the soil and soil fertility issues after afforestation. The SOC, soil TN, and soil TP stocks (Mg ha⁻¹) were calculated as follows:

$$\text{SOC}_i \text{ stock} = \text{SOC}_i \times \text{BD}_i \times D_i / 10, \quad (1)$$

$$\text{Soil TN}_i \text{ stock} = \text{soil TN}_i \times \text{BD}_i \times D_i / 10, \quad (2)$$

$$\text{Soil TP}_i \text{ stock} = \text{soil TP}_i \times \text{BD}_i \times D_i / 10, \quad (3)$$

where SOC_{*i*} is the soil organic carbon content of the *i*th layer of soil (g kg⁻¹), soil TN_{*i*} is the soil total N content of the *i*th layer of soil (g kg⁻¹), soil TP_{*i*} is the soil total P content of the *i*th layer of soil (g kg⁻¹), BD_{*i*} is the soil bulk density of the *i*th layer of soil (g cm⁻³), and D_{*i*} is the soil depth of the *i*th layer of soil (cm).

2.4. Statistical Analyses

Two-way ANOVAs were used to determine the effects of restoration age, soil depth, and their interaction on SOC, soil TN, and soil TP stocks and C:N, C:P, and N:P ratios. An independent samples *t*-test was used to compare the SOC, soil TN, and soil TP stocks and the C:N, C:P, and N:P ratios from sites grassland30, natural grassland, shrubland47, forestland56, and natural forest (*p* < 0.05). Before ANOVA analyses, we performed tests for normality and homogeneity of variance. In order to compare the effects of vegetation type, we selected SOC, soil TN, and soil TP contents and stoichiometry for the same or similar years from the four restoration types: orchardland (5 years, 10 years, 20 years), grassland (5 years, 11 years as 10 years, 18 as 20 years), shrubland (5 years, 10 years), and forestland (5 years, 10 years). In addition, we selected the SOC, soil TN, and soil TP contents from different soil depths as the rate of change with recovery years and compared the SOC, soil TN, and soil TP sequestration rates between different restoration types. All statistical analyses were conducted using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Figures were drawn using Origin 9.0.

3. Results

3.1. SOC, Soil TN, and Soil TP Stocks in Different Restoration Types

Restoration age had a significant effect on SOC and soil TN stocks (*p* < 0.01) (Table S2). In orchardland, the SOC stocks of the soil at 0–30 cm depth first increased and then stabilized after

5 years; the soil TN stock at the same depth first increased and then decreased with restoration age. The soil TP stocks at 0–100 cm depth showed no significant change with restoration age (Figure 2a–c). In grassland, the SOC and soil TN stocks at 0–30 cm depth first increased and then stabilized after 18 years, and the soil TP stocks at 0–100 cm depth showed no significant change with different restoration ages (Figure 2d–f). In shrubland, the SOC stocks at 0–50 cm depth and soil TN at 0–10 cm increased at first, peaked after 5 years, and then stabilized after 30 years; the soil TP stocks at 0–100 cm depth showed no significant change (Figure 2h–j). In forestland, the SOC at 0–50 cm gradually increased, and the soil TN stocks increased before peaking after 37 years, then decreased with restoration age; the soil TP stock at 0–100 cm depth showed no significant change (Figure 2k–m). In addition, SOC and soil TN stocks from the 0–30 cm soil layer of grassland30 were significantly lower than those in natural grassland (Figure 3a,b). SOC and soil TN stocks at 0–30 cm soil depth in shrubland47, as well as SOC stocks at 0–100 cm depth and soil TN stocks at 0–20 cm depth in forestland56, were significantly lower than those in natural forest (Figure 3d,e). The soil TP stocks at all soil depths showed no significant differences between grassland30 and natural grassland, shrubland47 and natural forest, or forestland56 and natural forest (Figure 3c,f).

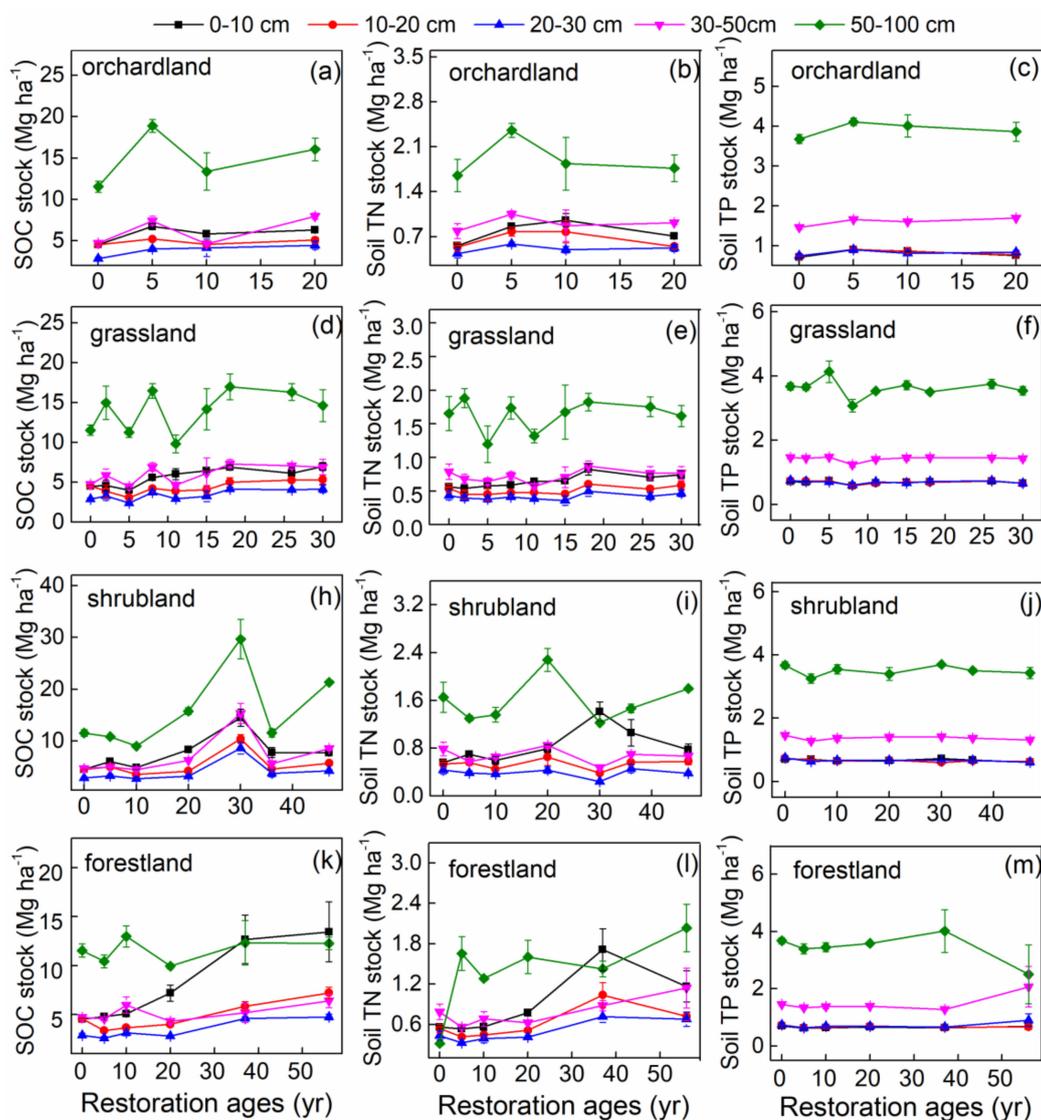


Figure 2. Changes in stocks of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) with restoration age. Note: values are mean \pm standard error.

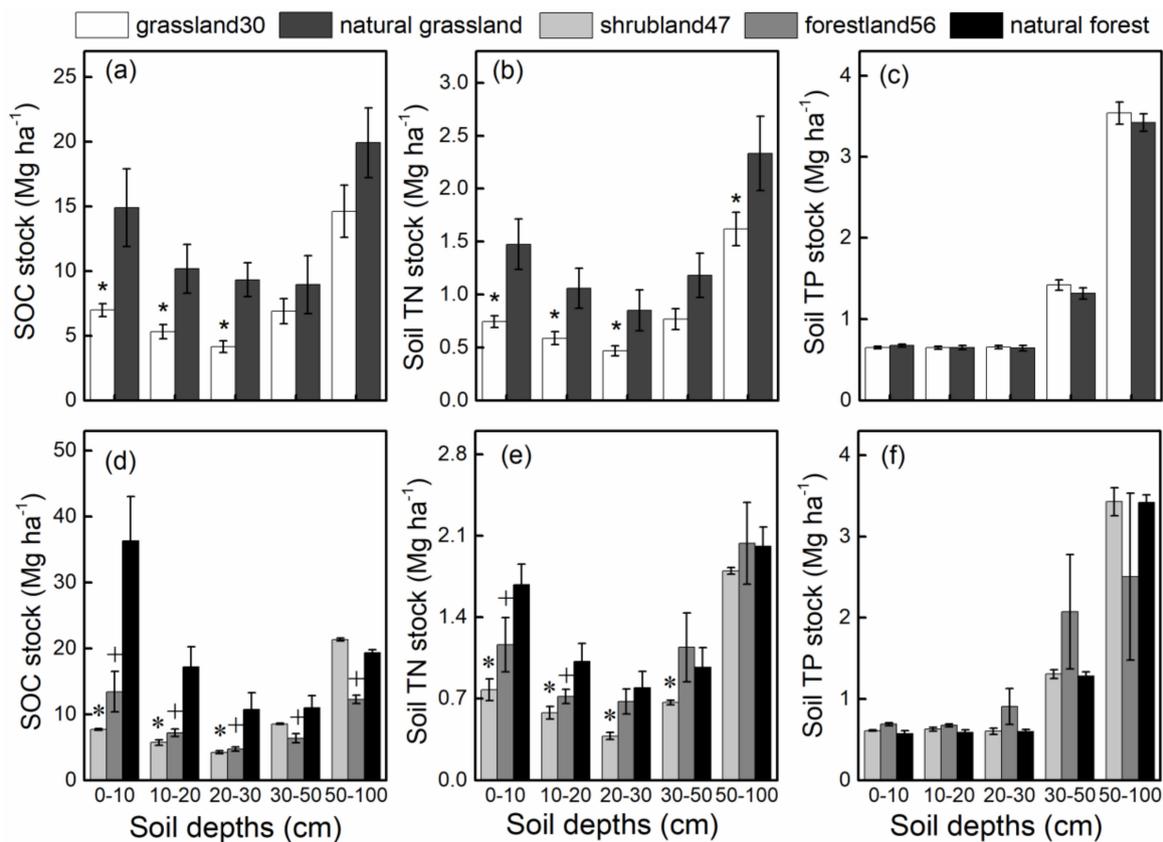


Figure 3. Stocks of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) at different soil depths in grassland at 30 years compared to those of natural grassland, and those of shrubland at 47 years and forestland at 56 years compared to those of natural forest. Note: values are mean \pm standard error. (a–c) means the SOC stock, Soil TN stock and Soil TP stock at different soil depths in grassland30 compared to those of natural grassland. (d–f) means the SOC stock, Soil TN stock and Soil TP stock at different soil depths in shrubland47 and forestland56 compared to those of natural forest * denotes significant differences between the natural grassland and grassland at 30 years after vegetation restoration ($p < 0.05$). + denotes significant differences between the natural forest and shrubland at 47 years after vegetation restoration ($p < 0.05$). * denotes significant differences between the natural forest and forestland at 56 years after vegetation restoration ($p < 0.05$).

3.2. Changes in SOC, Soil TN, and Soil TP Stoichiometry

In orchardland, the C:N ratio at 0–100 cm depth showed no obvious changes with restoration age, but there was an overall increasing trend (Figure 4a, Table S3). The C:P ratio at 0–30 cm increased, while the N:P ratio at 0–20 cm first increased and then decreased after 10 years of restoration (Figure 4b,c). In grassland, the C:N ratio at 0–100 cm showed an overall increasing trend with restoration age (Figure 4d, Table S3); the C:P and N:P ratios in soils of 0–30 cm depth gradually increased with restoration age (Figure 4e,f). In shrubland, the C:N ratio at 0–100 cm showed little variation with restoration age, but the overall trend was an increase (Figure 4h, Table S3); the C:P and N:P ratios at 0–10 cm depth first increased, then peaked at 30 years, before decreasing again with restoration age (Figure 4i,j). In forestland, the C:N ratio at 0–100 cm depth showed little change with restoration age, but the overall trend was an increase (Figure 4k, Table S3). The C:P ratio in soils of 0–100 cm depth gradually increased with restoration age (Figure 4l), and the N:P ratio at 0–50 cm first increased, then peaked at 37 years before decreasing again with restoration age (Figure 4m).

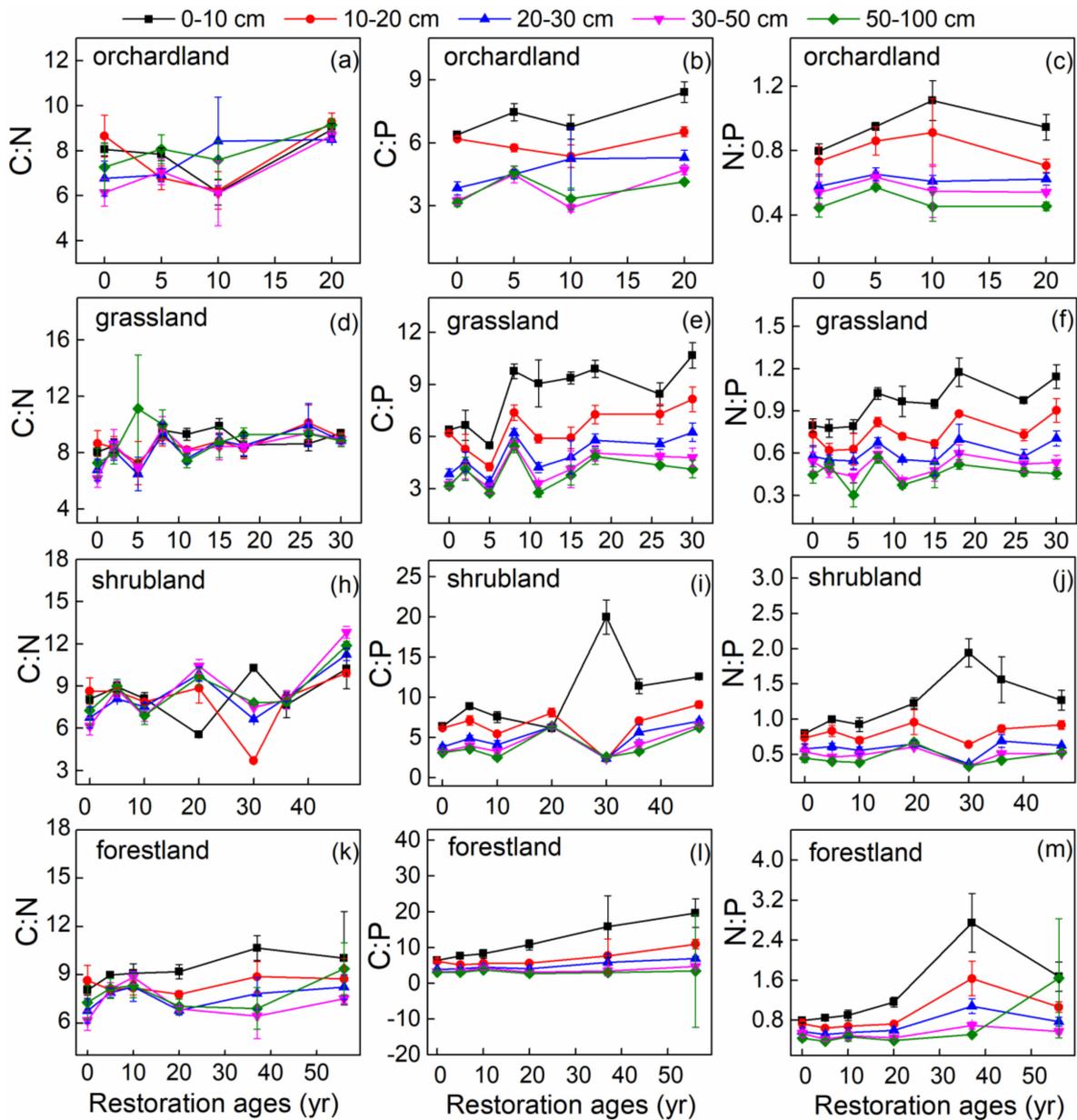


Figure 4. Stoichiometric characteristics of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) with restoration age. Note: values are mean \pm standard error.

The C:P and N:P ratios at 0–30 cm in grassland₃₀ were significantly lower than those in natural grassland (Figure 5b,c), and the C:P and N:P ratios at 0–30 cm depth in shrubland₄₇ and forestland₅₆ were significantly lower than those in natural forest (Figure 5e,f). In addition, the C:N ratio decreased with soil depth in forestland (Figure 4k). Overall, the C:P and N:P ratios gradually decreased with soil depth in the three land types (Figure 4b,c,e,f,i,j,l,m).

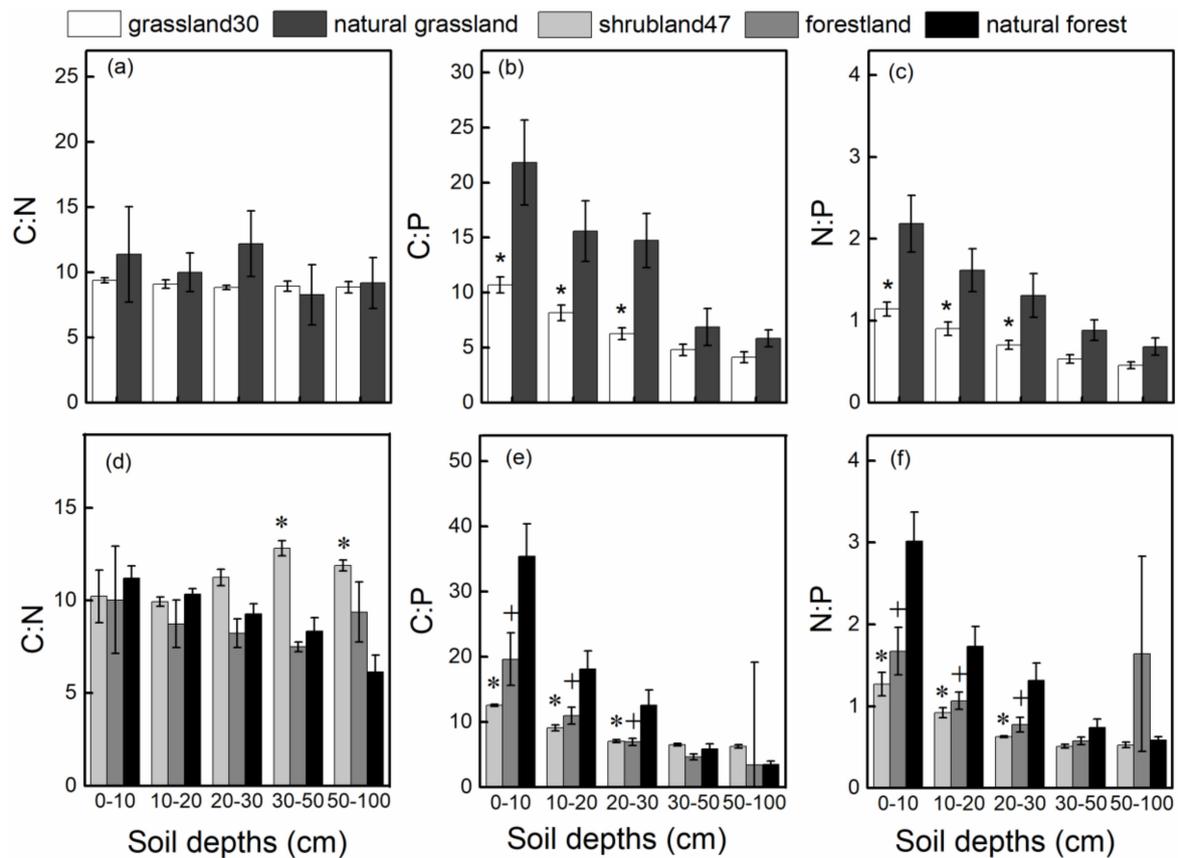


Figure 5. Stoichiometry of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) at different soil depths in grassland at 30 years compared to that of natural grassland, and those of shrubland at 47 years and forestland at 56 years compared to that of natural forest. Note: values are mean \pm standard error. (a–c) means the C:N, C:P and N:P at different soil depths in grassland30 compared to those of natural grassland. (d–f) means the C:N, C:P and N:P at different soil depths in shrubland47 and forestland56 compared to those of natural forest * denotes significant differences between the natural grassland and grassland at 30 years after vegetation restoration ($p < 0.05$). * denotes significant differences between the natural forest and shrubland at 47 years after vegetation restoration ($p < 0.05$). + denotes significant differences between the natural forest and forestland at 56 years after vegetation restoration ($p < 0.05$).

4. Discussion

4.1. Restoration Ages Altered SOC, Soil TN, and Soil TP Stocks and Stoichiometry

Our results showed that the SOC stocks at 0–30 cm soil depth in orchardland, grassland, and shrubland first increased and then stabilized with restoration age, while the SOC stocks at 0–50 cm in forestland gradually increased with restoration age. SOC is mainly derived from surface litter, root secretions, and animal residues [21,22]. After vegetation restoration, a large input of litter and organic matter can enhance the accumulation of SOC [23], and with an improvement in soil structure, the levels of surface runoff, soil erosion, and soil nutrient loss may be reduced [24]. In addition, soil microbial activity is strengthened as restoration age increases [25], and soil nutrient conversion and storage are further enhanced. However, vegetation restoration involves the coordinated development of the plant community and soil environment, and the plant community structure, soil structure, and microbial diversity reach a stable level as restoration age increases [26–28]. However, in forestland, SOC stocks had not reached a steady level at 57 years, and when these stocks may stabilize needs to be evaluated. In our study, the soil TN stocks at 0–30 cm depth decreased in the later stages of orchardland, shrubland, and forestland restoration. Plants may enter a senescence phase, and the soil

nitrogen nutrients absorbed during the plant growth process are then fed back to the soil by litter; thus, the nitrogen absorption rate is lower than the release rate, resulting in the soil TN stock decreasing [29]. We also found that soil TP stocks did not significantly change with restoration age, in contrast to the results of some previous studies [30]. Soil TP is mainly influenced by parent material, land use, and biogeochemical processes in the soil [31,32]. As the parent material and climate were similar for all vegetation types, the variability and migration rate of TP were not as obvious as those of SOC and soil TN, and restoration age had little effect on soil TP. Within the range of restoration ages that we studied, the SOC and soil TN stocks in grassland, shrubland, and forestland at 0–30 cm soil depth failed to reach the stock levels found in natural grassland or natural forest. Severe soil erosion and lack of water are typical characteristics of the Loess Plateau, which may lead to the loss of soil nutrients [24,33]. Additionally, soil tillage can also cause soil nutrient loss by affecting the soil physical structure and microbial activity [34].

The C:N ratio increased with restoration age after vegetation restoration. The main factors affecting the C:N ratio are changes in the SOC and soil TN contents [35]. Both SOC and soil TN contents increased overall with restoration age (Table S3), and the rate of increase of SOC was greater than that of soil TN; consequently, the C:N ratio increased (Table S3). A previous study showed that the C:N ratio was negatively correlated with the rate of decomposition of organic matter [36], so the decomposition rate of organic matter increases with restoration age. The C:P ratio indicates the availability of soil TP in the soil [37]. We found that the rate of increase of SOC was also greater than that of soil TP, resulting in an increase in the C:P ratio with restoration age (Table S3). In addition, the rate of increase of soil TN was greater than that of soil TP, resulting in an increase in the N:P ratio with restoration age (Table S3). The N:P ratio was reduced in the later stages of restoration, which may be related to the lower soil TN content (Figure S1). Soil N and soil TP are essential mineral nutrients for plant growth and common limiting elements in ecosystems, and the N:P ratio is a predictor of nutrient limitation [38]. In the grassland, shrubland, and forestland types, the N:P ratio at 0–30 cm soil depth in the later stages of recovery was lower than those of natural grassland and natural forest, which may result from the more alkaline soil and lower soil TN content in the Loess Plateau Region; the soil TP content did not differ significantly between the restoration and control sites. In the grassland, shrubland, and forestland restoration types, the C:P ratio in the 0–30 cm soil layer was lower than those of natural grassland and natural forest at the later stages of recovery, which may be related to the lower SOC content in restoration soils than in natural soils.

4.2. Vertical Distribution of Stocks and Stoichiometry of SOC, Soil TN, and Soil TP

Soil depth is an important factor influencing SOC, soil TN, and soil TP distribution [39]. In our study, the SOC and soil TN stocks decreased with soil depth at all restoration ages in orchardland, grassland, shrubland, and forestland (Figure 6a,b,d,e,h,I,k,l), which is consistent with the results of previous studies [40,41]. Our study also revealed that the overall rates of SOC and soil TN content change decreased with soil depth in orchardland, grassland, shrubland, and forestland (Table S3), which indicated that the SOC and soil TN sequestration rates gradually decreased with soil depth. Meanwhile, SOC, soil TN, and soil TP were most sensitive to change in the surface soil (0–30 cm). The SOC and soil TN content at 0–30 cm represented more than 65% of the total SOC and soil TN stocks from 0–100 cm depth for all restoration types; the soil TP content at 0–30 cm represented more than 60% of the total soil TP stocks from 0–100 cm (Figure S1). Such differences in the SOC, soil TN, and soil TP profiles can be explained partly by root distribution. The surface soil is affected by external environmental factors, soil microorganisms, and the return of nutrients from surface litter, resulting in a concentration of nutrients in the surface soil [42]. With increasing soil depth, the input of organic matter is limited by the permeability of the soil, microbial decomposition activity, and root absorption [21,39]. Moreover, SOC and soil TN stocks are not only affected by soil parent material, but also by the decomposition of litter and absorption and utilization by plants [40], resulting in large spatial variability. While the soil TP content of orchardland and forestland decreased, it showed little

variation with soil depth in grassland and shrubland (Figure 6c,f,j,m). Soil TP is mainly affected by the soil parent material, which, in this case, is a sedimentary mineral with low mobility in soil; therefore, there was little vertical variation in soil TP [43].

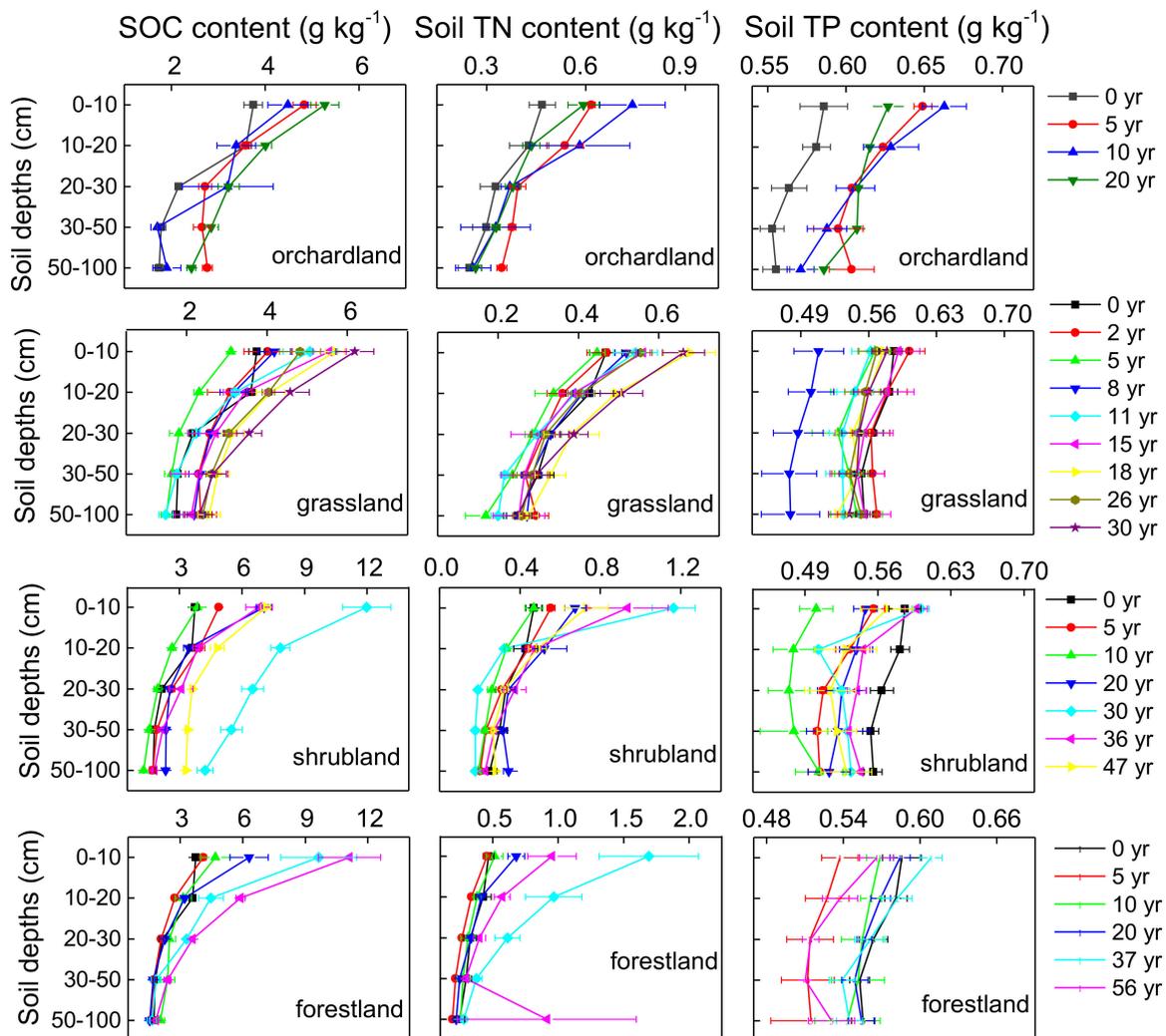


Figure 6. Vertical distributions of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) contents for different vegetation types. Note: values are mean \pm standard error.

Our study found that the overall C:N ratio gradually decreased with soil depth. It may be that the surface SOC and soil TN contents were higher, but as the soil depth increased, the SOC content change was larger than that of the soil TN content. When the decomposition process occurs, easily decomposed material vanishes, and soil TN is immobilized in decayed products, leaving behind more durable material with slower decomposition rates in the deeper layers [44]. This results in a relatively lower C:N ratio in the deeper soil layers. There was a significant difference in the C:P and N:P ratios at different soil depths. It may be that the soil TP content is relatively stable at different soil depths, and the C:P ratio and N:P ratio are mainly affected by SOC and soil TN content, so they showed greater variation.

4.3. Effect of Restoration Type on SOC, Soil TN, and Soil TP Stocks and Stoichiometry.

Our study demonstrated that the SOC and soil TN stocks in the 0–20 cm soil layer at 5 years were highest in orchardland, which may be related to the use of fertilizer. In other years, SOC, soil TN, and soil TP stocks showed no difference between orchardland, grassland, shrubland, and forestland

(Figure S2). However, the rate of SOC and soil TN change at 0–10 cm soil depth was the highest in forestland, while the rates of SOC and soil TN change at other depths varied among different restoration types (Table S3). The rapid increases in surface SOC and soil TN are closely related to the input of litter [45,46]. Guo et al. [46] showed that forest litter was 19 times greater in mass than that of shrubs in the Loess Plateau Region. At the same time, the presence of the higher amount of organic carbon over a long period of time indicated that forestland likely had developed a higher degree of humification. The long-term development of soil organic carbon stocks suggested that the afforestation improved the humification process. It has been shown that the process of humification in the soil is critical for the ecosystem, due to its strong contributions to the improvement of fertility and, hence, the storage of both carbon and nitrogen [47,48]. This also explains why the increase in SOC and soil TN in the topsoil of forests was higher than that of shrubs. As soil depth increases, root secretions and soil microorganisms are the main sources of soil nutrition [21,22]. There are significant differences in the effects of different plant roots and litters on the community composition of microorganisms [49], which may explain the large differences in the rates of SOC and soil TN change between different restoration types.

The C:N ratios of orchardland5 and grassland5 at 0–20 cm soil depth were lower than those of shrubland5 and forestland5, and the C:N ratio of orchardland10 was significantly lower than those of grassland10, shrubland10, and forestland10 (Figure S2). The C:N ratio of orchardland was lower than those of grassland, shrubland, and forestland, which may be related to anthropogenic N deposition in orchardland (Figure S2). The lower C:N ratio in grassland5 may occur because grassland retains more organic matter content and greater nutrient absorption takes place through plant roots [8]. There were no significant differences in the C:N ratio at other soil depths of orchardland, grassland, shrubland, and forestland as there were no significant differences in the stocks of SOC and soil TN (Figure S2). This finding is related to the nutrient conditions of the soil in the study area and the feedback between plant and soil, so the soil stoichiometric changes in different restoration types showed the same characteristics in the same environmental context. In addition, the overall C:P and N:P ratios of orchardland5 and shrubland5 at 0–20 cm soil depth were higher than those of grassland5 and forestland5, which is related to the relatively higher SOC and soil TN content in orchardland5 and shrubland5 (Figure S2). However, there were no significant differences in the C:P and N:P ratios at 30–100 cm soil depth between the four restoration types because there were no significant differences in the SOC, soil TN, and soil TP stocks of orchardland, grassland, shrubland, and forestland (Figure S2).

5. Conclusions

We examined the changes in SOC, soil TN, and soil TP stocks and stoichiometry at depths of 0–100 cm following vegetation restoration in the Loess Hilly Region. Our results revealed that the SOC stocks appeared to increase and reach stable levels. The soil TN stocks first increased and then decreased with restoration age, but they did not reach the levels seen in natural grassland or natural forest in the Loess Hilly Region in the absence of appropriate management. Soil TP stocks failed to improve substantially with restoration age. The C:N, C:P, and N:P ratios gradually increased with restoration age. At the same time, the SOC, soil TN, and soil TP stocks and the C:N, C:P, and N:P ratios decreased with soil depth. Reforested land had the highest sequestration rate of SOC and TN at 0–10 cm soil depth. The results of this study provide data for the assessment of the long-term SOC, soil TN, and soil TP stocks and stoichiometry after vegetation restoration under different restoration types in the Loess Hilly Region.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1999-4907/10/1/27/s1>, Figure S1: Changes in soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) content with restoration age. Figure S2: Changes in content and stoichiometry of soil organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) for different vegetation types at 5, 10, and 20 years. Table S1: The details of the sample sites selected for the study. Table S2: F and sig values for independent factors (soil depth, restoration age) and their interactions. Table S3: The slope parameters of the linear regression models for soil

organic carbon (SOC), soil total nitrogen (TN), and soil total phosphorus (TP) contents and C:N, C:P, and N:P ratios with recovery year at different soil depths under four restoration types.

Author Contributions: The research design was completed by H.X. and S.X. The manuscript was written by H.X. and Q.Q. The collection and analysis of soil samples were performed by H.X., P.L., Q.Q., Z.G. and E.W.

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