agriculture

MDPI

Article

Crop Rotation of Sainfoin on the Longzhong Loess Plateau Has a Positive Effect on Enhancing Soil Carbon Sequestration Potential

Hang Xiang [1,2], Jingjing Xu [3], Shaochong Wei [1,2], Hang Yang [1,2], Jianchao Song [1,2] and Xiaojun Yu [1,2,*]

[1] College of Grassland Science, Gansu Agricultural University, Lanzhou 730070, China; xiangh@st.gsau.edu.cn (H.X.); weisc@st.gsau.edu.cn (S.W.); yhang_gsau@163.com (H.Y.); songjc@st.gsau.edu.cn (J.S.)
[2] Key Laboratory of Forage Gerplasm Innovation and New Variety Breeding of Ministry of Agriculture and Rural Affairs (Co-Sponsored by Ministry and Province), Lanzhou 730070, China
[3] Gansu Forestry Science and Technology Extension Station, Lanzhou 730046, China; xjjgsly@163.com
* Correspondence: yuxj@gsau.edu.cn

Abstract: The impact of various crop rotation systems on the potential for soil carbon sequestration and stoichiometric characteristics is not yet fully understood, which poses challenges for effective land management and utilization. This study selected three typical crop rotation methods in the Longzhong Loess Plateau: maize–alfalfa rotation (MA), maize–sainfoin rotation (MS), and maize–wheat rotation (MW). Soil physical and chemical indices were measured, and the soil carbon density and soil stoichiometry were calculated and analyzed. The results show that the soil C/N of the surface soils was low across the rotation methods, indicating a rapid rate of organic matter decomposition and mineralization, which may hinder soil nutrient accumulation. The soil N/P was found to be lower than the national average of 8.0, indicating that nitrogen is a limited nutrient in the soil under the three crop rotation systems in this region. The soil total nitrogen content can be increased by rotation with leguminous forage. Sainfoin rotation can enhance the soil total carbon and organic carbon content, thereby improving the soil's carbon sequestration potential. The research findings provide a theoretical foundation for the selection of appropriate rotation methods and the maintenance of the stability of agricultural ecosystems in semi-arid regions.

Keywords: Longzhong Loess Plateau; crop rotation; soil carbon density; soil stoichiometry characteristics

Citation: Xiang, H.; Xu, J.; Wei, S.; Yang, H.; Song, J.; Yu, X. Crop Rotation of Sainfoin on the Longzhong Loess Plateau Has a Positive Effect on Enhancing Soil Carbon Sequestration Potential. *Agriculture* **2024**, *14*, 2160. https://doi.org/10.3390/agriculture14122160

Academic Editors: Monika Skowrońska and Beata Kołodziej

Received: 7 November 2024
Revised: 22 November 2024
Accepted: 26 November 2024
Published: 27 November 2024

1. Introduction

Soil represents one of the most diverse and intricate environments, fulfilling a crucial function in the cycling of substances and the flow of energy within terrestrial ecosystems [1]. The global soil carbon reservoir within a soil depth of 100 cm is 2–3 times as large as the terrestrial vegetation carbon pool and over twice the size of the global atmospheric carbon pool [2]. The soil organic carbon density of the 0–60 cm soil layer accounts for over 80% of that of the 100 cm soil layer [3]. As the soil depth increases, the organic carbon density gradually stabilizes at 80–100 cm [4]. Meanwhile, in agricultural production, the 0–50 cm soil layer is the main soil layer that is affected by tillage activities [5]. Soil carbon, nitrogen, and phosphorus content and their stoichiometric characteristics are important indicators reflecting the soil quality and nutrient supply capacity [6]. Soil C/N, C/P, and N/P reflect the mineralization ability and organic matter decomposition rate of the soil, as well as the limiting characteristics of carbon, nitrogen, and phosphorus, respectively [7]. In recent years, different scholars have conducted extensive research on soil ecological stoichiometry. For example, Zhang, et al. [8] through Spearman correlation analysis, found that the amounts of N and P had an influence on the elemental ecological cycle within the experimental area. When the phosphorus content increased, it was not conducive to the accumulation of organic matter [8]. Thus, the ecological chemical cycle of elements in farmland soil was regulated by N and P. Artificial forests have significantly better soil

C regulation ability than grasslands because carbon sequestration in plantation forests is enhanced by means of increasing carbon input (new vegetation) and reducing carbon loss (decomposition and erosion) [9]. Different land use patterns have an impact on the stoichiometric traits of soil C, N, and P [10]. The study of soil carbon, nitrogen, and phosphorus content and their stoichiometric characteristics in the 0–50 cm soil layer can clarify the characteristics of soil nutrient changes, reveal nutrient balance mechanisms, and facilitate the scientific management and rational utilization of land resources.

Rain-fed farming in the Loess Plateau and its adjacent regions in northern China makes up more than 70% of the entire arable land [11], making it an important grain-producing region with a significant role in grain production [12]. However, increasing temperatures have exacerbated drought stress in the dryland ecosystems [13], and irrational farming practices have exacerbated soil nutrient loss [14], which seriously threaten food security in the Loess Plateau. Enhancing carbon sinks is beneficial not only for the amelioration of soil quality but also for the abatement of atmospheric carbon pollution [15]. In this context, the issue of soil carbon sequestration under different cultivation methods has gradually become a research hotspot. Different land-use patterns are capable of altering the structure of plant communities, influencing the decomposition of litters, resulting in variations in the soil organic carbon and total carbon, and further leading to changes in the soil carbon pool [16]. However, unreasonable farming methods can excessively consume soil moisture, which is not conducive to plant growth and reduces carbon accumulation [17]. Therefore, precisely evaluating the distribution traits of the soil carbon pool under small-scale tillage approaches and expounding the influence of diverse tillage methods on the soil carbon pool hold substantial significance for the sustainable progress of soil ecosystems.

In the context of global climate change, the climate adaptability of crops has been changed by global warming, and at the same time, the increase in extreme climate has seriously reduced crop yields, resulting in losses in agricultural planting [18]. Especially in semi-arid areas, owing to water shortage and the impact of climate warming, the growth of beneficial soil microorganisms and animals has been damaged by soil drying, reducing the sequestration of organic carbon and affecting soil health [19]. Lacking the guidance of professional knowledge, farmers often continuously plant the same crop. Years of planting the same crop aggravates the loss of soil nutrients in arid areas, causing an imbalance in the dryland agricultural ecosystem and exacerbating the agricultural impacts of climate change [20]. The utilization of nutrients can be balanced by crop rotation, and the excessive consumption of certain nutrients by a single crop can be avoided. The physical properties of the soil can also be changed, and the deterioration of the soil structure caused by a single crop can be prevented. Therefore, crop rotation is an effective strategy for combating soil degradation, improving soil fertility, and increasing crop yield [21]. Maize (*Zea mays* L.) is widely planted in the Loess Plateau region with high adaptability, easy management, and high yield, making it a good choice for crop rotation systems [22]. Leguminous plants form nitrogen-fixing relationships with soil bacteria and are considered more suitable for crop rotation with other crops [23]. Alfalfa (*Medicago sativa* L.) and sainfoin (*Onobrychis viciifolia* Scop) are widely used as feed varieties in mid- to low-altitude and semi-arid areas due to their advantages of nitrogen fixation, high yield, rich protein content, and tolerance to a certain degree of drought. In-depth research has been conducted on maize–alfalfa rotation systems, showing results such as increased soil particulate organic nitrogen and microbial nitrogen [24], improved crop water use efficiency and productivity [25,26], and improved soil quality [22]. Nevertheless, at present, the research on the effects of maize, alfalfa, and sainfoin rotation on soil properties and soil carbon density is insufficient, which restricts the scientific selection of cultivated crops and farming methods in arid areas against the background of global climate change. Therefore, researching the impacts of maize rotation with different leguminous forages on the soil carbon density and soil properties in the Longzhong Loess Plateau is of great guiding significance for the selection of agricultural planting systems, sustainable agricultural development, and active responses of agriculture to global climate change in this area.

This study investigated three typical crop rotation systems in the Longzhong Loess Plateau: maize–alfalfa rotation (MA), maize–sainfoin rotation (MS), and maize–wheat rotation (MW). The analysis focused on differences in the soil physicochemical properties, soil carbon density, and stoichiometric characteristics across the three rotation systems. The findings provide a theoretical foundation for selecting appropriate crop rotation strategies and promoting the sustainable development of soil ecosystems in the Longzhong Loess Plateau.

2. Materials and Methods

2.1. Research Area

The study area (Figure 1) is located in Wenfeng Town of Longxi County in Gansu Province, China (104°40′05″–104°40′30″ E, 35°3′10″–35°3′20″ N, altitude: 2180 m a.s.l.) [1]. The region exhibits a mean annual temperature of 6–7 °C and a mean annual precipitation of 450 mm (Table 1) [1]. Rainfall is the only water source for plant growth, where the soil is classified as secondary loess soils, according to Xie et al. [27]; the soil pH value is 8.50 [28].

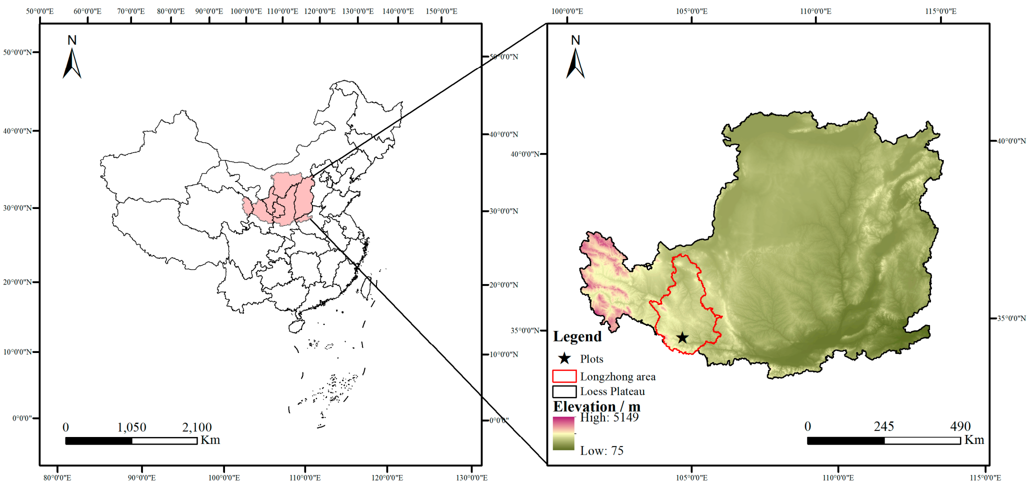

Figure 1. The study region and spatial distribution of Longzhong Loess Plateau.

Table 1. The average temperature and precipitation in the research area in 2024.

Year	Month	Average Temperature (°C)	Precipitation (mm)
2024	1	−3.5	0.5
	2	−1.2	10.4
	3	6.1	27.6
	4	13	63.5
	5	17.7	43.4
	6	20	24.2
	7	21.8	52.9
	8	22.6	69.2
	9	18.5	43.4
	10	10.6	34.9

2.2. Experimental Design

Three crop rotation systems were established in the experimental plots: maize (*Zea mays* L.)–alfalfa (*Medicago sativa* L.) rotation (MA), maize (*Zea mays* L.)–sainfoin (*Onobrychis viciifolia* Scop) rotation (MS), and maize (*Zea mays* L.)–wheat (*Triticum aestivum* L.) rotation (MW). The utilization period of alfalfa grassland has been determined to be 5–6 years, and that of sainfoin grassland is fixed at 4–5 years. Moreover, relatively high stability and yield are exhibited by both sainfoin grassland and alfalfa grassland in the fourth year [29]. Therefore, alfalfa and sainfoin grasslands with a 4-year rotation were selected as the research objects. The rotation of maize with alfalfa (1 year of maize cultivation followed by 4 years of alfalfa growth) and the rotation of maize with sainfoin (1 year of maize followed by 4 years of sainfoin) were the two main forage production regions overseen by Yurun Agriculture and Animal Husbandry Co., Ltd. (Nanjing, China) in Longxi County. For MA and MS, leguminous forage was planted with tillage after maize harvest and no tillage was performed until new crops were planted. There was no irrigation throughout the year for either MA or MS. The maize–wheat rotation field, which lacked irrigation facilities, received nitrogen and phosphorus fertilizers in amounts determined by local farmers based on their traditional planting practices.

Under each crop rotation system, three horizontal subplots (10 m × 10 m) were set up. In March 2024, soil cores of the 0–10 cm, 10–20 cm, and 20–50 cm soil layers were respectively collected by means of a soil auger with a diameter of 3.5 cm, and simultaneously, the bulk density of each layer was gathered using a cutting ring. From each sub-sample plot, samples were repeatedly collected five times by the soil auger, and the five collected soil cores were blended into one soil sample. After the visible stones and roots were removed, the samples were sieved through a 2 mm soil sieve. After natural air-drying, the physical and chemical properties of the soil were analyzed.

2.3. Soil Sample Collection and Determination

The bulk density (BD) was determined using the cutting ring method [30]. The soil organic carbon (SOC) was determined by external heating with potassium dichromate, while the Kjeldahl method was used to measure the total nitrogen (TN) content. The soil alkaline nitrogen (AN) was determined using NaOH alkaline hydrolysis combined with the culture dish diffusion absorption method. The total phosphorus (TP) content was quantified using the molybdenum antimony resistance colorimetric method [31], while the available phosphorus (AP) content was measured by potassium permanganate oxidation and glucose reduction. The total potassium (TK) was determined by the H_2SO_4 digestion flame photometry method. The soil available potassium (AK) was extracted by NH_4OAc and determined by flame photometry [32]. The soil total carbon (TC) was determined by the Multi N/C 2100S and HT 1300 total organic carbon analyzers, which are produced by Analytik Jena AG (Konrad-Zuse-Strasse 1, 07745 Jena, Germany).

2.4. Calculation of Soil Carbon Density

The calculation formula for the soil bulk density is as follows [33]:

$$\text{Soil bulk density (BD), g/cm}^3 = (\text{W}_1 - \text{W}_0) \times (1 - \text{W\%})/\text{V} \quad (1)$$

In the formula, BD represents the soil bulk density, W_0 represents the ring cutter mass, W_1 represents the ring cutter and fresh soil weight, W% represents the soil moisture content, and V represents the ring cutter volume of 100 cm^3.

The soil total carbon density (STCD) and organic carbon density (SOCD) were calculated according to the following formulas [34]:

$$\text{STCD}_i = \text{BD}i \times \text{STC}_i \times \text{h}_i \times (1 - \text{C}_i)/100, \quad (2)$$

$$\text{SOCD}_i = \text{BD}i \times \text{SOC}_i \times \text{h}_i \times (1 - \text{C}_i)/100, \quad (3)$$

where BD represents the soil bulk density ($g \cdot m^{-3}$), STC represents the soil total carbon ($g \cdot kg^{-1}$), h and C represent the content of gravel larger than 2 mm (%) and soil thickness, respectively (there was basically no gravel in the bulk density sample, so gravel was not considered as a correction factor for estimating the soil total carbon density), SOC represents the soil organic carbon ($g \cdot kg^{-1}$), and *i* represents the soil characteristic values in different soil surface layers [35].

2.5. Statistical Analysis

The data were collated using Microsoft Excel 2019. One-way analysis of variance (ANOVA) followed by Duncan's multiple range test was employed to assess significant differences ($p < 0.05$) in the soil properties among the three crop rotation methods (SPSS 26.0, SPSS Inc., Chicago, IL, USA). The results of the measurements are expressed as the means and standard errors. The soil carbon density, stoichiometric characteristics, and correlation heatmap were plotted by Origin 2020.

3. Results

3.1. The Differences in Soil Characteristics Under Different Rotation Systems

As shown in Table 2, in the 0–10 cm soil layer, significant differences ($p < 0.05$) in the BD and AN content were present among the MA, MS, and MW. The trends of the TC and SOC contents were MS > MA > MW. However, no remarkable distinctions in the TN, TP, TK, or AK were found among the three systems in this specific soil layer.

Table 2. Soil characteristics of different crop rotation methods (means ± standard deviations).

Soil Depth (cm)	Treatment	BD (g/cm^3)	TN (g/kg)	TP (g/kg)	TK (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)	TC (g/kg)	SOC (g/kg)
0–10	MA	1.50 ± 0.06 a	1.60 ± 0.02 a	0.50 ± 0.09 a	3.36 ± 0.20 a	26.07 ± 0.84 ab	2.9 ± 0.46 b	176.42 ± 3.33 a	21.63 ± 0.59 b	12.23 ± 0.66 b
	MS	1.35 ± 0.02 b	1.82 ± 0.20 a	0.62 ± 0.01 a	2.97 ± 0.19 a	27.13 ± 0.99 a	1.25 ± 0.07 b	166.46 ± 8.80 a	26.44 ± 0.59 a	14.75 ± 0.70 a
	MW	1.26 ± 0.03 b	1.66 ± 0.10 a	0.60 ± 0.11 a	3.3 ± 0.07 a	21.88 ± 1.93 b	8.28 ± 0.76 a	169.85 ± 5.79 a	17.77 ± 0.49 c	11.11 ± 0.37 b
10–20	MA	1.43 ± 0.03 a	2.86 ± 0.14 a	0.53 ± 0.16 a	3.17 ± 0.12 a	16.55 ± 1.29 b	1.14 ± 0.15 b	126.63 ± 12.03 a	19.50 ± 0.26 b	8.05 ± 1.08 b
	MS	1.34 ± 0.02 b	1.41 ± 0.05 c	0.44 ± 0.13 a	3.04 ± 0.23 a	22.53 ± 0.91 a	0.87 ± 0.09 b	133.23 ± 6.66 a	25.33 ± 1.07 a	12.67 ± 0.43 a
	MW	1.47 ± 0.02 a	2.00 ± 0.32 b	0.55 ± 0.06 a	2.98 ± 0.31 a	16.91 ± 1.26 b	3.64 ± 0.94 a	133.26 ± 6.66 a	16.13 ± 0.48 c	10.06 ± 0.44 b
20–50	MA	1.34 ± 0.01 b	2.96 ± 0.13 a	0.45 ± 0.06 b	3.31 ± 0.29 a	5.55 ± 0.65 c	0.67 ± 0.12 b	113.24 ± 3.35 a	17.92 ± 0.45 b	5.71 ± 1.03 b
	MS	1.27 ± 0.03 b	1.09 ± 0.08 b	0.96 ± 0.19 a	2.97 ± 0.31 a	16.03 ± 1.10 a	0.92 ± 0.07 b	123.16 ± 6.66 a	23.57 ± 1.49 a	7.29 ± 1.13 ab
	MW	1.47 ± 0.02 a	0.83 ± 0.11 b	0.23 ± 0.02 c	3.04 ± 0.29 a	11.62 ± 1.66 b	2.22 ± 0.05 a	116.59 ± 3.31 a	15.12 ± 0.30 b	9.09 ± 0.20 a

Note: The data are the average values of three repetitions. Distinct lowercase letters within a column signify significant discrepancies in the identical soil layer based on the analysis using Duncan's test ($p < 0.05$). MA, maize–alfalfa rotation; MS, maize–sainfoin rotation; MW, maize–wheat rotation. BD, bulk density; SOC, soil organic carbon; TN, total nitrogen; AN, soil alkaline nitrogen; TP, total phosphorus; AP, available phosphorus. TK, total potassium; AK, soil available potassium; TC, soil total carbon.

In the 10–20 cm soil layer, the BD and TN in the MS system were significantly lower than those in the MA and MW systems ($p < 0.05$). Like the 0–10 cm layer, the trends of the AN and TC contents were MS > MA > MW. No significant differences were detected in the TP, TK, and AK contents among the systems in this layer.

In the 20–50 cm soil layer, significant differences in the TP and AN were observed among the MS, MA, and MW, with the trends of the TP and TC contents being MS > MA > MW, while the trend of the SOC content was MW > MS > MA. Across all three soil layers, the available phosphorus (AP) content in the MW was significantly higher than that in the MS and MA ($p < 0.05$).

3.2. The Impact of Different Crop Rotation Methods on the Soil Total Carbon (STCD) and Organic Carbon Density (SOCD)

The calculated results of the STCD and SOCD are shown in Table 3. The STCD of the MS soil was consistently higher than that of the MA and MW in all soil layers. As the depth of the soil layer increased, the STCD of the MW became closer to the MA (Figure 2a). In the 0–10 cm soil layer, the SOCD of the MS was significantly higher than that of the MW soil ($p < 0.05$), but with the increase in the soil depth, the SOCD of the MS and MA soil showed a decreasing trend, while the SOCD of the MW soil gradually increased (Figure 2b).

Table 3. Soil total carbon density and organic carbon density of different crop rotation methods (means ± standard deviations).

Soil Depth (cm)	Treatment	Soil Total Carbon Density (kg/cm^2)	Soil Organic Carbon Density (kg/cm^2)
0–10	MA	3.25 ± 0.22 a	1.83 ± 0.10 a
	MS	3.57 ± 0.05 a	1.99 ± 0.10 a
	MW	2.23 ± 0.05 b	1.40 ± 0.01 b
10–20	MA	2.79 ± 0.06 b	1.15 ± 0.13 b
	MS	3.39 ± 0.11 a	1.70 ± 0.04 a
	MW	2.36 ± 0.08 c	1.47 ± 0.04 a
20–50	MA	7.20 ± 0.17 b	2.30 ± 0.43 b
	MS	8.98 ± 0.33 a	2.77 ± 0.37 b
	MW	6.66 ± 0.21 b	4.00 ± 0.12 a

Note: Different lowercase letters within a column indicate significant differences in the same soil layer as analyzed by Duncan's test ($p < 0.05$). MA, maize–alfalfa rotation; MS, maize–sainfoin rotation; MW, maize–wheat rotation.

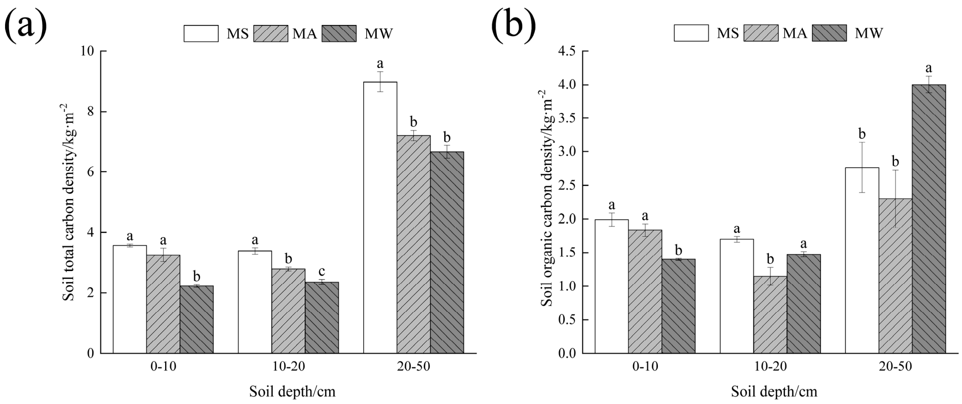

Figure 2. Soil total carbon density (**a**) and organic carbon density (**b**) of different crop rotation methods. Statistical test used; letters indicate significant differences in diversity ($p < 0.05$). MA, maize–alfalfa rotation; MS, maize–sainfoin rotation; MW, maize–wheat rotation.

3.3. The Differences in Soil Stoichiometric Characteristics Under Different Rotation Systems

Significant differences ($p < 0.05$) in the soil layer C/N among the different planting types were found in the 0–10 cm and 20–50 cm soil layers. However, the magnitudes of the differences varied. In the 0–10 cm soil layer, the order was MS > MA > MW, while in the 10–20 cm and 20–50 cm soil layers, it was MS > MW > MA (Figure 3a).

A significant difference ($p < 0.05$) was found in the C/P among the different planting types in the 10–20 cm soil layer, but no significant differences in the C/P were observed among the three different planting types in the 0–10 cm soil layer or in the 20–50 cm soil layer between the MS and MA. As the soil layer deepened, a trend of first increasing and then decreasing the C/P in the MS soil was exhibited (Figure 3b).

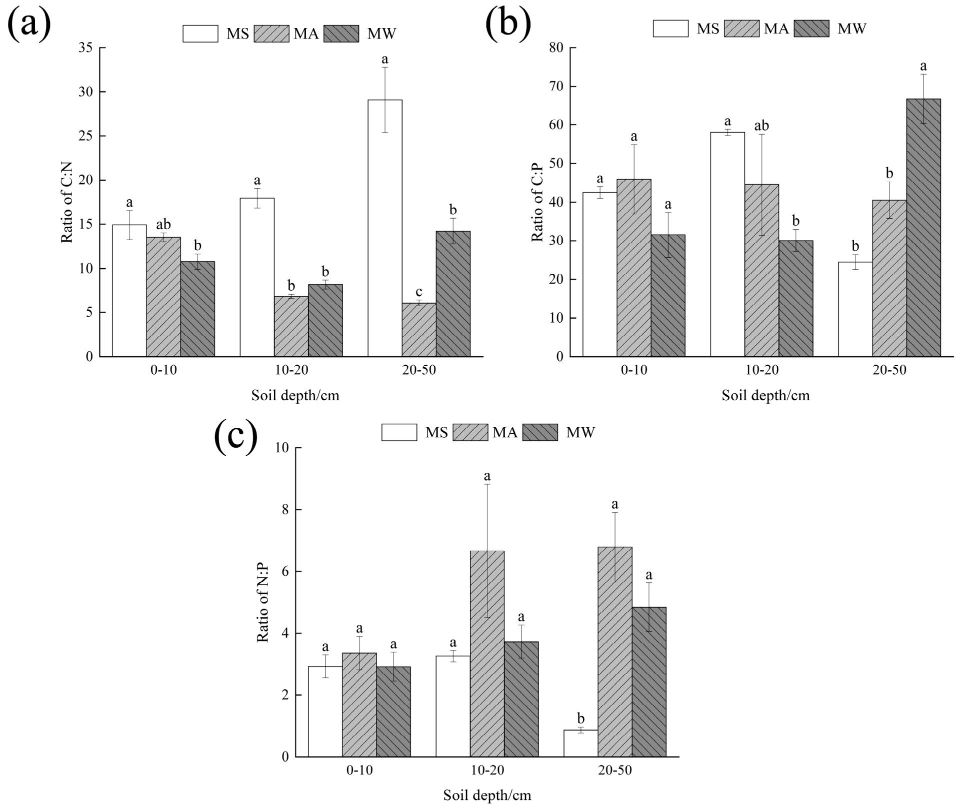

Figure 3. Chemical stoichiometric characteristics of C, N, and P in different crop rotation methods. Statistical test used; letters indicate significant differences in diversity ($p < 0.05$). (**a**) soil C/N; (**b**) soil C/P; (**c**) soil N/P. MA, maize–alfalfa rotation; MS, maize–sainfoin rotation; MW, maize–wheat rotation.

At soil depths of 0–10 cm and 10–20 cm, no significant difference in the soil N/P was noted among the three different planting types. At soil depths of 20–50 cm, the soil N/P in the MA and MW was significantly higher than that in the MS ($p < 0.05$), presenting the order of MA > MW > MS. However, among all soil layers, the highest soil N/P was in the MA (Figure 3c).

3.4. Analysis of the Correlation Between Soil Physicochemical Properties and Stoichiometric Characteristics Under Different Rotation Systems

As depicted in Figure 4a, within the 0–10 cm soil layer, a significant positive correlation was found between the BD and C/P. A significant positive correlation was found for the AN with the TC, and a significant negative correlation for the AN with the AP. A significant negative correlation was shown for the AP with TC, SOC, and C/N. A significant negative correlation with the AP ($p < 0.05$) and a significant positive correlation with the C/N ($p < 0.05$) were found for the TC and SOC.

As illustrated in Figure 4b, in the 10–20 cm soil layer, significant negative correlations are presented for the BD with the AN, TC, SOC, and C/N. A significant negative correlation existed between the TN and SOC. Significant positive correlations ($p < 0.05$) were found between the AN and the TC, SOC, C/N, and C/P.

As presented in Figure 4c, in the 20–50 cm soil layer, a significant positive correlation is shown for the BD with the C/P, and a significant negative correlation is shown for the TP with the TC. A significant negative correlation occurred between the TN and AN. A significant positive correlation with the C/N and a significant negative correlation with the N/P were found for the AN. A significant positive correlation with the TP and C/N and a significant negative correlation with the C/P and N/P ($p < 0.05$) were found for the TC.

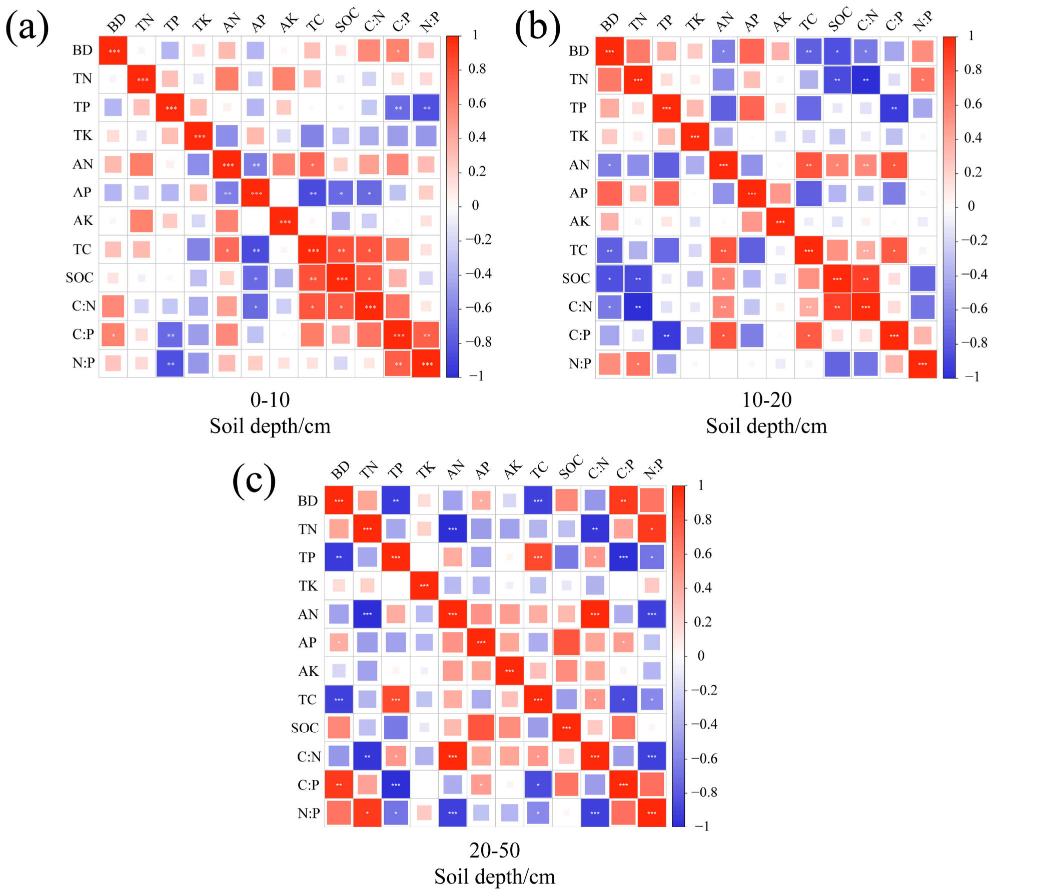

Figure 4. Correlations between soil nutrients and their stoichiometric ratios under different soil depths. (**a**–**c**) represent the 0–10 cm soil layer, 10–20 cm soil layer, and 20–50 cm soil layer respectively. Red symbolizes a positive correlation, whereas blue stands for a negative one. Moreover, the darker the color is, the stronger the correlation is. BD, bulk density; SOC, soil organic carbon; TN, total nitrogen; AN, soil alkaline nitrogen; TP, total phosphorus; AP, available phosphorus. TK, total potassium; AK, soil available potassium; TC, soil total carbon. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4. Discussion

4.1. The Impact of Different Crop Rotation Methods on Soil Characteristics

Different crop rotation methods alter the physical structure, hydrothermal conditions, and nutrient levels of soil and affect the biochemical cycling processes of terrestrial ecosystems [36]. This study found that in the 0–10 cm soil layer, the soil bulk density (BD) in the maize–wheat (MW) system was lower than that in the maize–alfalfa (MA) and maize–sainfoin (MS) systems, likely due to the disruption of the surface soil aggregate structures by traditional agricultural practices [37]. However, as the soil depth increased, the BD in the MW system rose, while the BD in the MA and MS systems decreased. This can be attributed to the well-developed root systems of leguminous forages, which physically impact the soil [38]. The BD in the MS system was lower than that in the MA, which may have been due to the greater root distribution and higher proportion of sainfoin roots compared to alfalfa in the 0–50 cm soil layer [39].

The available phosphorus (AP) content in the MW system decreased with increasing soil depth, likely as a result of phosphorus accumulation at the surface due to fertilization. Because grasses require large amounts of phosphorus for growth, a substantial portion of AP migrates toward the root system, resulting in lower AP contents in leguminous grass soils. The findings indicate that the total nitrogen (TN) content increased in the deeper soil layers of the MA system, likely due to the nitrogen-fixing effect of alfalfa root nodules, which enhances nitrogen levels in deeper soils [38]. Although both alfalfa and sainfoin are leguminous crops, the TN content in the deeper soil layers of the MA system was significantly higher than in the MS, possibly because sainfoin has a lower nitrogen fixation capacity and its condensed tannins inhibit soil nitrification [40,41].

This study also found that the soil organic carbon (SOC) content in the MA and MS systems was relatively high in the 0–20 cm soil layer, with a noticeable surface enrichment. This surface accumulation occurs because vegetation transports nutrients to the soil via roots, and high surface coverage increases litter input into the soil, providing ample organic matter to the upper soil layers [42]. Regardless of the crop rotation system, the occurrence of agricultural activities, such as tillage, accelerates soil mineralization [43], resulting in a decline in the total carbon (TC) and SOC content as the soil depth increases.

As depicted in Figure 4a, within the 0–10 cm soil stratum, a statistically significant positive correlation was found between the BD and C/P. The AN exhibited a pronounced positive correlation with the TC and a conspicuous negative correlation with the AP. The AP displayed a substantial negative correlation with the TC, SOC, and C/N. The TC and SOC present a marked negative correlation with the AP and a distinct positive correlation with the C/N.

4.2. The Impact of Different Crop Rotation Methods on Soil Carbon Density

Different crop rotation systems and soil depths lead to variations in the soil total carbon density (STCD) and the soil organic carbon density (SOCD). These differences are attributed to variations in plant carbon uptake, the depth of root systems, and the types of litter and root exudates absorbed by the soil [44]. In this study, significant differences in the STCD and SOCD were observed between the maize–alfalfa (MA) and maize–sainfoin (MS) systems compared to the maize–wheat (MW) system in the 0–10 cm soil layer. This is likely due to soil erosion caused by crop harvesting and tillage, which limits the return of plant carbon to the soil, resulting in carbon loss from cultivated land [45]. At the same time, due to the higher root density of leguminous plants compared to the MW, carbon in the soil is accumulated through the input of litter and the turnover of roots [46].

As the soil layer deepened, the SOCD in the MW system became significantly higher than that in the MA and MS, suggesting that traditional crop rotation systems have a more pronounced impact on the surface SOCD in the Longzhong Loess Plateau. However, the STCD in the MA and MS systems remained consistently higher than that in the MW, and with increasing soil depth, both the STCD and SOCD in the MS system surpassed those in the MA. This indicates that leguminous forage crop rotations in the Longzhong Loess Plateau enhance the soil's carbon sequestration potential, with sainfoin showing superior carbon sequestration potential compared to alfalfa.

4.3. The Influence of Different Crop Rotation Methods on the Stoichiometric Characteristics of Soil C, N, and P

The C/N of soil is associated with the mineralization rate of organic matter by microorganisms. Microorganisms mainly decompose organic matter through the secretion of various extracellular enzymes. Under the condition of a C/N ratio of 25, microorganisms are capable of reasonably allocating resources for the synthesis of enzymes with proper types and quantities, thereby resulting in the optimal decomposition rate of organic matter by soil microorganisms [47]. In this study, unlike the 20–50 cm soil layer of the MS, the C/N ratio in each soil layer of the MA and MW was lower than 25, indicating that the decomposition and mineralization rate of organic matter in the surface soil of the Longzhong Loess Plateau is relatively fast, which is not conducive to the accumulation of soil nutrients. The soil C/N in the 20–50 cm soil layer of the MW was significantly higher than that of the MA, indicating that the carbon sequestration capacity of deep soil in the MW was greater than that of the MA. This is consistent with the research results of Bai et al. [48], who found that with increases in the soil depth, the soil C/N in the MA showed a decreasing trend, which was due to the surface enrichment of nitrogen and phosphorus in the soil, while phosphorus changed less with the soil layer. The MS soil C/N showed an increasing trend with the depth of the soil layer. Secondary metabolites in sainfoin, such as tannins, can be combined with organic matter in the soil, and the release rate of soil organic carbon can be reduced. Moreover, the metabolic processes of microorganisms can be inhibited, causing the carbon–nitrogen cycle process to be slowed down. Since it becomes difficult for energy to be obtained by decomposing organic matter, microorganisms will tend to make more use of the carbon sources in the secondary metabolites to maintain their own survival; thus, the carbon amount of the microorganisms themselves can be increased. Meanwhile, the existence of secondary metabolites in sainfoin can induce microorganisms to secrete more carbon-cycle-related enzymes [41]. The research results indicate that the soil of the MS in this study area had a high carbon sequestration capacity. The soil C/P can reflect the release of phosphorus by soil microorganisms and the potential for absorption and transformation of phosphorus from the outside world [49]. When the C/P is below 200, the soil microbial carbon will briefly increase while the net mineralization of organic phosphorus will occur [50]. The soil C/P values of the three different crop rotation methods were all below 200, indicating that the net mineralization rate of the soil phosphorus in the Longzhong Loess Plateau is relatively high. The balance of phosphorus in the soil can be maintained and the fertility level of the soil can be improved with the help of a higher net phosphorus mineralization rate. Plant growth can also benefit and the activities of soil microorganisms can be promoted. The microbial decomposition of organic matter is less limited by the available phosphorus, and the soil phosphorus showed high availability. The soil C/P in the 0–20 cm soil layer of the MW was relatively low, while the soil C/P in the 20–50 cm soil layer increased. This is due to years of fertilization reducing the available phosphorus limitation of the surface soil. The soil N/P can reflect the properties of soil nutrients and also indicate whether the soil is saturated with nitrogen [51]. The soil N/P in this study area was lower than the national average of 8.0, and nitrogen was a limited nutrient element for the soil in the three different crop rotation systems in the Longzhong Loess Plateau. The N/P of the soil in each soil layer of the MA was higher than that of the MS and MW, which was due to the biological nitrogen fixation effect of alfalfa, which can increase the soil nitrogen content. However, the soil phosphorus content was similar and evenly distributed [52], and the effect of fertilization on the TP content in the MW was relatively small.

4.4. The Correlation Between Soil Characteristics and C, N, and P Stoichiometry Under Different Crop Rotation Methods

The chemical stoichiometry of soil C, N, and P is influenced by multiple environmental factors, and different crop rotation patterns affect the structure and function of terrestrial ecosystems by altering land cover patterns, thereby affecting the soil nutrient contents. In this study, the BD showed a significant positive correlation with the soil C/P in the 0–10 cm and 20–50 cm soil layers, but a significant negative correlation with the TC, SOC, and soil C/N in the 10–20 cm soil layer. This indicates that increasing the soil bulk density can increase the availability of phosphorus in this soil layer, and a decrease in the soil bulk density is beneficial for increasing the accumulation of the TC and SOC in this soil layer, improving the soil C/N, and enhancing the soil carbon sequestration potential. Consistent with the research results of Lu et al. [53], the potassium element had strong heterogeneity, and the correlation analysis results show that the potassium element had no significant effect on the soil C, N, or P contents or the ecological stoichiometry ratio of each soil layer. The soil C/N was positively correlated with the TC, SOC, and AN contents and negatively correlated with the TN content, indicating close coupling relationships among the C, N, and P cycling in the study area. The soil C/P and N/P in the study area were significantly correlated with the soil TP, TC, TN, and AN contents. The soil TN was negatively correlated with the soil TC and SOC, while the soil AN was positively correlated with the soil TC and SOC. This indicates that the distribution and utilization of nitrogen in the study area soil were influenced by carbon accumulation and decomposition rates. This is because the SOC, TC, and TN come from the same primitive organic matter and have similar retention mechanisms in the soil [54].

This study only examined the impacts of three rotation methods in one region on the soil physiochemical properties, soil carbon density and stoichiometric characteristics of the 0–50 cm soil layer, rather than investigating multiple regions in the Loess Plateau area and deeper soil layers. Small-scale and single investigations may have some unexplained variations. In order to better understand the influences of seasonal changes, external practical management, and soil heterogeneity on soil properties, it is necessary to conduct more in-depth research in similar fields so as to obtain more reliable conclusions that are more in line with the context of climate change based on a larger sample size.

5. Conclusions

The N/P in the study area was lower than the national average of 8.0, indicating that nitrogen was a limited nutrient in the soils under the three crop rotation systems in this region. Crop rotation with leguminous forage can increase the soil total nitrogen (TN) content. Compared to alfalfa rotation, the incorporation of sainfoin into the rotation system can enhance the soil total carbon and organic carbon contents, thereby improving the soil's carbon sequestration potential. Therefore, incorporating sainfoin into the crop rotation system, along with the reasonable application of exogenous nitrogen, can effectively prevent nutrient loss in the Longzhong Loess Plateau. The research on the rotation of alfalfa and sainfoin in the Loess Plateau region is enriched by this study. References for stabilizing soil carbon pools, reducing the application amounts of nitrogen fertilizers and maintaining the stability of semi-arid agricultural ecosystems in semi-arid areas are provided by the research results. In the future, continuous in-depth research should be carried out based on the existing studies. The research scope should be expanded, and the existing rotation methods should be optimized so that better adaptation to climate change can be achieved.

Author Contributions: Conceptualization, and X.Y.; formal analysis, H.X. and J.S.; funding acquisition, and X.Y.; investigation, H.X., H.Y., S.W. and J.S.; methodology, H.X., J.X., S.W. and H.Y.; project administration, X.Y.; software, H.X.; visualization, H.X. and H.Y.; writing—original draft, H.X.; writing—review and editing, H.X. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Research and Demonstration of Technology for Improving Grassland Productivity on the Loess Plateau in Central Gansu Province: GLZ-2023-55.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank all the reviewers who participated in the review, as well as the Key Laboratory of the Ministry of Education of the Grassland Ecosystem of Gansu Agricultural University for providing the experimental equipment.

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

References

1. Xiang, H.; Xu, J.; Yang, H.; Song, J.; Yu, X. Reduced Soil Quality but Increased Microbial Diversity in Cultivated Land Compared to Other Land-Use Types in the Longzhong Loess Plateau. *Agriculture* **2024**, *14*, 2106. [CrossRef]
2. Batjes, N.H. Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci.* **2005**, *47*, 151–163. [CrossRef]
3. Li, M.; Zhang, X.; Pang, G.; Han, F. The estimation of soil organic carbon distribution and storage in a small catchment area of the Loess Plateau. *Catena* **2013**, *101*, 11–16. [CrossRef]
4. Rahman, M.; Wang, Y.; Zhang, K.; Ahmad, B.; Ali, A.; Ahamd, A.; Muhammad, D.; Afzaal, M.; Zhang, Z.; Bohnett, E. Variations in Soil C, N, P Stocks and Stoichiometry with Soil Depth and Forest Types in Qilian Mountains of Northwest China. *Front. Environ. Sci.* **2022**, *10*, 882842. [CrossRef]
5. Zhou, T.; Wu, P.; Sun, S.; Li, X.; Wang, Y.; Luan, X. Impact of Future Climate Change on Regional Crop Water Requirement—A Case Study of Hetao Irrigation District, China. *Water* **2017**, *9*, 429. [CrossRef]
6. Li, H.; Zhao, Y.; Weng, X.; Zhou, Y.; Huo, Y.; Zhang, S.; Liu, L.; Pei, J. Effects of exogenous calcium additions on the ecological stoichiometric characteristics of various organs and soil nutrients and their internal stability in *Pinus tabuliformis*. *Front. Plant. Sci.* **2024**, *15*, 1428011. [CrossRef]
7. Tong, Y.; Ding, J.; Xiao, M.; Shahbaz, M.; Zhu, Z.; Chen, M.; Kuzyakov, Y.; Deng, Y.; Chen, J.; Ge, T. Microplastics affect activity and spatial distribution of C, N, and P hydrolases in rice rhizosphere. *Soil Ecol. Lett.* **2022**, *5*, 220138. [CrossRef]

8. Zhang, Y.; Liu, M.; Han, L.; Yang, J.; Zhao, X.; Qu, J.; Li, L.; Bai, Y.; Yan, D.; Hou, G. Spatial Distribution Characteristics of Soil C:N:P:K Eco-Stoichiometry of Farmland and Grassland in the Agro-Pastoral Ecotone in Inner Mongolia, China. *Agronomy* **2024**, *14*, 346. [CrossRef]
9. Yang, X.; Li, T.; Shao, M.a. Factors controlling deep-profile soil organic carbon and water storage following *Robinia pseudoacacia* afforestation of the Loess Plateau in China. *For. Ecosyst.* **2022**, *9*, 100079. [CrossRef]
10. Wang, L.; Sheng, M. Responses of Soil C, N, and P Stoichiometrical Characteristics, Enzyme Activities and Microbes to Land Use Changes in Southwest China Karst. *Forests* **2023**, *14*, 971. [CrossRef]
11. Wang, J.-B.; Xie, J.-H.; Li, L.-L.; Adingo, S. Review on the fully mulched ridge–furrow system for sustainable maize production on the semi-arid Loess Plateau. *J. Integr. Agric.* **2023**, *22*, 1277–1290. [CrossRef]
12. Li, T.; Zhao, D.; Li, Y.; Wang, Z.; Wen, X.; Liao, Y. Assessment of the effects of integrated rotation-tillage management on wheat productivity in the Loess Plateau region. *Eur. J. Agron.* **2023**, *149*, 126906. [CrossRef]
13. Fang, C.; Song, X.; Ye, J.-S.; Yuan, Z.-Q.; Agathokleous, E.; Feng, Z.; Li, F.-M. Enhanced soil water recovery and crop yield following conversion of 9-year-old leguminous pastures into croplands. *Agric. Water Manag.* **2023**, *279*, 108189. [CrossRef]
14. Yu, Q.; Wang, H.; Wen, P.; Wang, S.; Li, J.; Wang, R.; Wang, X. A suitable rotational conservation tillage system ameliorates soil physical properties and wheat yield: An 11-year in-situ study in a semi-arid agroecosystem. *Soil Tillage Res.* **2020**, *199*, 104600. [CrossRef]
15. Fu, X.; Wang, J.; Sainju, U.M.; Liu, W. Soil Carbon Fractions in Response to Long-Term Crop Rotations in the Loess Plateau of China. *Soil Sci. Soc. Am. J.* **2017**, *81*, 503–513. [CrossRef]
16. Tong, J.; Hu, J.; Lu, Z.; Sun, H.; Yang, X. The impact of land use and cover change on soil organic carbon and total nitrogen storage in the Heihe River Basin: A meta-analysis. *J. Geogr. Sci.* **2019**, *29*, 1578–1594. [CrossRef]
17. Zhang, Z.; Jia, X.; Zhu, P.; Huang, M.; Ren, L.; Shao, M.a. Estimating the optimal vegetation coverage for the dominant tree and shrub species over China's northwest drylands. *Sci. China Earth Sci.* **2024**, *67*, 1500–1517. [CrossRef]
18. Yu, T.; Mahe, L.; Li, Y.; Wei, X.; Deng, X.; Zhang, D. Benefits of Crop Rotation on Climate Resilience and Its Prospects in China. *Agronomy* **2022**, *12*, 436. [CrossRef]
19. Wei, C.; Adamowski, J.F.; Liu, Y.; Zhang, Y.; Liu, C.; Zhou, J.; Wang, X.; Zhang, X.; Cao, J. A Comparative Study of Rotation Patterns on Soil Organic Carbon in China's Arid and Semi-Arid Regions. *Agronomy* **2020**, *10*, 160. [CrossRef]
20. Chamberlain, L.A.; Bolton, M.L.; Cox, M.S.; Suen, G.; Conley, S.P.; Ané, J.-M. Crop rotation, but not cover crops, influenced soil bacterial community composition in a corn-soybean system in southern Wisconsin. *Appl. Soil Ecol.* **2020**, *154*, 103603. [CrossRef]
21. Li, H.; Zhang, Y.; Sun, Y.; Liu, P.; Zhang, Q.; Wang, X.; Wang, R.; Li, J. Long-term effects of optimized fertilization, tillage and crop rotation on soil fertility, crop yield and economic profit on the Loess Plateau. *Eur. J. Agron.* **2023**, *143*, 126731. [CrossRef]
22. Wu, P.; Zhao, G.; Liu, F.; Ahmad, S.; Fan, T.; Li, S.; Zhang, J.; Dang, Y.; Wang, L.; Wang, S.; et al. Agronomic system for stabilizing wheat yields and enhancing the sustainable utilization of soil: A 12-year in-situ rotation study in a semi-arid agro-ecosystem. *J. Clean. Prod.* **2021**, *329*, 129768. [CrossRef]
23. Shi, M.; Guo, A.; Kang, Y.; Yang, X.; Zhang, W.; Liu, Y.; Zhang, R.; Wang, Y.; Qin, S. Effects of plastic film mulching and legume rotation on soil nutrients and microbial communities in the Loess Plateau of China. *Chem. Biol. Technol. Agric.* **2023**, *10*, 38. [CrossRef]
24. Liu, R.; Liu, Y.; Gao, Y.; Zhao, F.; Wang, J. The Nitrogen Cycling Key Functional Genes and Related Microbial Bacterial Community $\alpha-$Diversity Is Determined by Crop Rotation Plans in the Loess Plateau. *Agronomy* **2023**, *13*, 1769. [CrossRef]
25. Sun, T.; Li, Z. Alfalfa-corn rotation and row placement affects yield, water use, and economic returns in Northeast China. *Field Crops Res.* **2019**, *241*, 107558. [CrossRef]
26. Peng, Y.; Li, Z.; Sun, T.; Zhang, F.; Wu, Q.; Du, M.; Sheng, T. Modeling long-term water use and economic returns to optimize alfalfa-corn rotation in the corn belt of northeast China. *Field Crops Res.* **2022**, *276*, 108379. [CrossRef]
27. Xie, M.; Yuan, J.; Liu, S.; Xu, G.; Lu, Y.; Yan, L.; Li, G. Soil Carbon and Nitrogen Pools and Their Storage Characteristics under Different Vegetation Restoration Types on the Loess Plateau of Longzhong, China. *Forests* **2024**, *15*, 173. [CrossRef]
28. He, M.; Ren, J.; Bai, G.; Zhao, P.; Li, C.; Tang, L. Spatial Distribution Patterns of Soil Fertility in Producing Area of Traditional Chinese Medicine of Longxi County, Gansu Province. *Chin. J. Soil Sci.* **2023**, *54*, 21–29. [CrossRef]
29. Zhu, X.; Yu, F.; Yu, L.; Li, Z. Study on nutritional value of red bean grass and alfalfa. *Pratacult. Sci.* **1988**, *5*, 31–35.
30. Wang, Z.; Wang, Z.; Ma, L.; Lv, X.; Meng, Y.; Zhou, Z.J. Straw returning coupled with nitrogen fertilization increases canopy photosynthetic capacity, yield and nitrogen use efficiency in cotton. *Eur. J. Agron.* **2021**, *126*, 126267. [CrossRef]
31. Wang, D.; Chen, J.; Xiong, X.; Wang, S.; Liu, J. Allelopathic Effects of *Cinnamomum migao* on Seed Germination and Seedling Growth of its Associated Species *Liquidambar formosana*. *Forests* **2019**, *10*, 535. [CrossRef]
32. Chai, J.; Yu, X.; Xu, C.; Xiao, H.; Zhang, J.; Yang, H.; Pan, T. Effects of yak and Tibetan sheep trampling on soil properties in the northeastern Qinghai-Tibetan Plateau. *Appl. Soil Ecol.* **2019**, *144*, 147–154. [CrossRef]
33. Bandyopadhyay, K.; Aggarwal, P.; Chakraborty, D.; Pradhan, S.; Garg, R.N.; Singh, R. Division of Agricultural Physics. In *Practical Manual on Measurement of Soil Physical Properties*; Indian Agricultural Research Institute: New Delhi, India, 2012; p. 62.
34. Li, Y.; He, G.; Liu, X.; Xu, H.; Ji, T.; Lin, D.; Jiang, J. Distribution Characteristics of Carbon Density in Plant–Soil System of Temperate Steppe and Temperate Desert in the Longzhong Loess Plateau. *Agriculture* **2024**, *14*, 177. [CrossRef]
35. Wu, W.; Zhao, G.; Zhao, B.; Zheng, Z.; He, Y.; Huang, K.; Zhu, J.; Zhang, Y.J. Decadal soil total carbon loss in northern hinterland of Tibetan Plateau. *Sci. Total Environ.* **2024**, *922*, 171190. [CrossRef]
36. Topa, D.; Cara, I.G.; Jităreanu, G. Long term impact of different tillage systems on carbon pools and stocks, soil bulk density, aggregation and nutrients: A field meta-analysis. *Catena* **2021**, *199*, 105102. [CrossRef]

37. Kuzyakov, Y.; Zamanian, K. Reviews and syntheses: Agropedogenesis—Humankind as the sixth soil-forming factor and attractors of agricultural soil degradation. *Biogeosciences* **2019**, *16*, 4783–4803. [CrossRef]
38. Zhang, M.; Zhang, Z.; Yang, Y.; Zhang, L.; Li, R.; Han, X.; Lin, W. Effects of Different Land Use Patterns on Soil Physicochemical Properties in the Loess Plateau Area. *J. Soil Water Conserv.* **2024**, *38*, 192–202. [CrossRef]
39. Zhang, J.; Zhang, J.; Wang, Y.; Li, J. Productive Performance and Development Characteristics of Root Systems of 4 Forage Legmume Species in Loess Plateau, China. *Acta Agrestia Sin.* **2013**, *21*, 965. [CrossRef]
40. Mora-Ortiz, M.; Smith, L.M.J. *Onobrychis viciifolia*; a comprehensive literature review of its history, etymology, taxonomy, genetics, agronomy and botany. *Plant Genet. Resour. Charact. Util.* **2018**, *16*, 403–418. [CrossRef]
41. Clemensen, A.K.; Villalba, J.J.; Rottinghaus, G.E.; Lee, S.T.; Provenza, F.D.; Reeve, J.R. Do plant secondary metabolite-containing forages influence soil processes in pasture systems? *Agron. J.* **2020**, *112*, 3744–3757. [CrossRef]
42. Shen, A.; Shi, Y.; Mi, W.; Yue, S.; She, J.; Zhang, F.; Guo, R.; He, H.; Wu, T.; Li, H.; et al. Effects of desert plant communities on soil enzyme activities and soil organic carbon in the proluvial fan in the eastern foothills of the Helan Mountain in Ningxia, China. *J. Arid. Land* **2024**, *16*, 725–737. [CrossRef]
43. Yu, X.; Zhou, W.; Wang, Y.; Cheng, P.; Hou, Y.; Xiong, X.; Du, H.; Yang, L.; Wang, Y. Effects of land use and cultivation time on soil organic and inorganic carbon storage in deep soils. *J. Geogr. Sci.* **2020**, *30*, 921–934. [CrossRef]
44. Deng, R.; Wang, B.; Liu, P.; Liu, D.; XU, J. Effects od Different Lang Use Patterns on Soil Organic Carbon Loss on the Loess Slope. *Res. Soil Water Conserv.* **2011**, *18*, 104–107.
45. Lu, Q.-Q.; Song, Y.-F.; Pan, K.-Q.; Li, Y.; Tang, M.-X.; Zhong, G.-H.; Liu, J. Improved crop protection and biodiversity of the agroecosystem by reduced tillage in rice paddy fields in southern China. *J. Integr. Agric.* **2022**, *21*, 2345–2356. [CrossRef]
46. Geng, S.; Li, L.; Miao, Y.; Zhang, Y.; Yu, X.; Zhang, D.; Yang, Q.; Zhang, X.; Wang, Y. Nitrogen rhizodeposition from corn and soybean, and its contribution to the subsequent wheat crops. *J. Integr. Agric.* **2024**, *23*, 2446–2457. [CrossRef]
47. Qin, J.; Kong, H.; Liu, H. Stoichiometric characteristics of soil C, N, P and K in different *Pinus massoniana* forests. *J. Northwest A F Univ. (Nat. Sci. Ed.)* **2016**, *44*, 68–82. [CrossRef]
48. Bai, Y.; Zhang, X.; Bao, W.; Wang, Y.; Zhao, Y. The soil carbon, nitrogen, and phosphorus contents and their stoichiometry under different land uses in loess hilly region. *Agric. Res. Arid. Areas* **2019**, *37*, 117–123. [CrossRef]
49. Jiang, X.; Wang, X.; Qiao, Y.; Cao, Y.; Jiao, Y.; Yang, A.; Liu, M.; Ma, L.; Song, M.; Fu, S. Atmospheric nitrogen deposition affects forest plant and soil system carbon:nitrogen:phosphorus stoichiometric flexibility: A meta-analysis. *For. Ecosyst.* **2024**, *11*, 100192. [CrossRef]
50. Huo, W.-G.; Chai, X.-F.; Wang, X.-H.; Batchelor, W.D.; Kafle, A.; Feng, G. Indigenous arbuscular mycorrhizal fungi play a role in phosphorus depletion in organic manure amended high fertility soil. *J. Integr. Agric.* **2022**, *21*, 3051–3066. [CrossRef]
51. Yang, W.; Yu, J.; Li, Y.; Jia, B.; Jiang, L.; Yuan, A.; Ma, Y.; Huang, M.; Cao, H.; Liu, J.; et al. Optimized NPK fertilizer recommendations based on topsoil available nutrient criteria for wheat in drylands of China. *J. Integr. Agric.* **2024**, *23*, 2421–2433. [CrossRef]
52. Zhao, R.; Zhang, B.; Wang, X.; Han, F. Ecological stoichiometry characteristics of soil and plant of alfalfa with different growing years on the Loess Plateau. *Pratacult. Sci.* **2019**, *36*, 1189–1199.
53. Lu, S.; Zhou, N.; Cai, Y.; Gou, M.; Xia, M.; Liu, K.; Shan, H. Ecological Stoichiometric Characteristics of Carbon, Nitrogen, and Phosphorus in Sediments of the Hyporheic Zone within the Lake Wetland. *Earth Sci.* **2024**. Available online: https://link.cnki.net/urlid/42.1874.P.20240702.1138.006 (accessed on 25 November 2024).
54. Wei, Y.; Dang, X.; Wang, J.; Gao, J.; Gao, Y. Response of C:N:P in the plant-soil system and stoichiometric homeostasis of *Nitraria tangutorum* leaves in the oasis-desert ecotone, Northwest China. *J. Arid Land* **2021**, *13*, 934–946. [CrossRef]