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Evaluation of soil carbon characteristics under different planting patterns on sloping farmland in the hilly and gully region of the loess plateau

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A six-year field experiment was conducted in the Loess Plateau to explore the impacts of five planting patterns, namely fallow(C0), continuous maize cropping(C1), continuous alfalfa cropping(C2), maize-sorghum-sorghum-millet (cereal) rotation(C3), and kidney bean-sorghum-sorghum-millet (legume-cereal) rotation(C4), on different forms of soil carbon. The results showed that, compared with the C0 pattern, long-term continuous cropping or rotation of different crops significantly increased the mass fractions of various forms of carbon in the 0–40 cm soil layer. Specifically, the total carbon increased by 57.11 – 122.52%, the organic carbon increased by 81.93 – 244.12%, the inorganic carbon mass fraction increased by 29.52 – 39.25%, and the light fraction organic carbon showed the most prominent increase, being 3–11 times that of the C0 pattern. In the soil layers from 0 to 15 cm, there were differences among different planting patterns. Under the C2 pattern, the mass fractions of soil total carbon, organic carbon, and light-fraction organic carbon were the highest, followed by those under the C3 and C4 patterns, while those under the C1 pattern were relatively low. The performance of inorganic carbon was different. The C2 pattern only increased the inorganic carbon content in the 0–5 cm soil layer. As the soil depth increased, the contents of various types of carbon decreased, and the decrease rate of C2 were the largest. In summary, long-term continuous alfalfa cropping is an effective approach to increasing soil carbon in dry lands, especially organic carbon and light fraction organic carbon. However, this effect is mainly concentrated in the surface soil above 15 cm. When comparing continuous cropping and rotation, rotation has a stronger effect on increasing soil carbon content than continuous cropping, and there is no significant difference in the impact on soil carbon content among different rotation patterns.

Keywords Loess Plateau, Crop Rotation, Continuous Cropping, Sloping Farmland, Carbon

Human activities are having an increasingly severe impact on the global environment. CO_2 is considered the gas that contributes the most to global warming, accounting for 60% of the greenhouse effect[1]. Soil carbon is a crucial component of the global carbon storage[2]– [3]approximately twice that of the atmosphere. Any change in soil carbon directly affects the stability and balance of atmospheric carbon. Soil carbon, especially organic carbon, is directly involved in various physical, chemical, and biological processes in the soil. It combines with these processes, endowing the soil with the characteristics of life-productivity or soil fertility[4]. It plays a vital role in maintaining and improving soil pore conditions, ion exchange capacity, water-holding capacity, alleviating soil erosion, improving tillage properties, and enhancing the availability and cycling of nutrients such as carbon, nitrogen, and phosphorus for crops[5]– [6]. Additionally, soil organic carbon affects the degradation processes or biological activities of chemical substances such as pesticides and heavy metal ions entering the soil, and is an important factor determining soil quality.

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Light fraction organic carbon in the soil consists of semi - decomposed plant and animal residues, which are rich in monosaccharides, polysaccharides, and hemicellulose[7]. Compared with soil organic matter, light fraction organic matter is loosely bound to soil particles and has a fast degradation rate, serving as a substrate that is easily decomposed by soil microorganisms[8]– [9]. Its quantity reflects the balance level of the input, retention, and decomposition of plant and animal residue substances in the soil, and can sensitively reflect the impacts of external environmental changes or human factors on soil organic matter or the organic carbon pool[10–13]. Clarifying the fixation and mineralization characteristics of this part of light fraction organic carbon, its relationship with the soil organic carbon pool, and correctly evaluating its role in the material cycle of the soil-plant system are of great significance for improving crop cultivation and water-fertilizer management, enhancing the fixation of atmospheric carbon by the soil, and reducing the emissions of greenhouse gases such as CO_2.

Inorganic carbon accounts for more than 23% of the total soil carbon[14]. Carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), carbon dioxide (CO_2) in soil air, and deposited carbonates in the soil[15] are the main forms of inorganic carbon. The mass fraction of soil carbonates directly affects soil development, aggregate structure formation, the existence form and availability of plant nutrients, and the activity of heavy metal ions[16]. It has an active interaction with soil moisture and organisms[17]and is important for soil texture, structure, fertility, and quality.

The Loess Plateau is the birthplace of Chinese civilization, with a farming history spanning thousands of years. However, due to long-term excessive reclamation, overgrazing, soil erosion, and land desertification, as well as the resulting reduction in ecosystem biomass, the degradation of the soil organic carbon pool has accelerated, and the mass fraction of organic carbon has become extremely low. The mass fraction of soil organic matter in farmland is only 3.5–6.9 g/kg[18]. Sloping farmland, as an important agricultural production carrier and land use type in this area, plays a crucial role in the regional agricultural economy. However, the situation of soil erosion on sloping farmland is more severe, mainly featuring intense and extremely intense erosion. Among them, the slightly eroded area accounts for 10.50% of the total sloping farmland area in the region, the moderately eroded area accounts for 18.20%, the intensely eroded area accounts for 45.00%, the extremely intensely eroded area accounts for 22.30%, and the severely eroded area accounts for 4.00%[19]. Enhancing the soil carbon sequestration capacity of sloping farmland and increasing the mass fraction of soil organic carbon are of great significance for improving soil fertility and ecological functions of sloping farmland, and achieving the sustainable and coordinated development of agriculture and the environment. There are many factors affecting the quantity and transformation of soil carbon in farmland. The types and patterns of planted crops have attracted much attention[20]– [21]. However, in the Loess Plateau region, research reports in this regard have been scarce. Therefore, this study used a six - year field experiment in the sloping farmland of Jiulongquanggou, Nanniwan, Baota District, Yan'an City, in the hilly-gully region of the Loess Plateau. Several cropping patterns were selected, including fallow(C0), continuous maize cropping(C1), continuous alfalfa cropping(C2), maize-sorghum-sorghum-millet (cereal) rotation(C3), and kidney bean-sorghum-sorghum-millet (legume-cereal) rotation(C4). The C0 pattern was used as a control to directly reflect the natural changes of soil carbon when no crops were planted. C1 was a common single - cropping method, and studying its impact on soil carbon had practical guiding significance. C2 had special ecological functions such as nitrogen fixation, which could be used to explore its unique role in improving soil carbon conditions. The rotation patterns of C3 and C4 took into account factors such as the growth characteristics of different crops and nutrient differences. Through diversified planting, it was hoped to find ways more conducive to soil carbon sequestration and transformation. This was the first systematic study in the Loess Plateau region and was expected to provide new ideas and a scientific basis for the sustainable development of agriculture in this area. Based on this, soil samples from the 0–40 cm soil layer were collected in layers in this study to explore the effects of crop types and cropping patterns on different forms of soil carbon.

Materials and methods

Overview of the study area

The field experiment was carried out in Jiulongquanggou, Nanniwan, Baota District, Yan'an City, Shaanxi Province (Fig. 1) (36°30′N, 109°32′E). The altitude of this area is 1300–1400 m, the average annual temperature is 9.9 °C, and the average annual precipitation is 500–600 mm, which is mainly concentrated from July to September. The long-term field experiment started in 2019, and soil sampling was conducted during the crop maturity period in 2024. The tested soil was loessial soil, its basic properties were as shown in Table 1. without irrigation conditions. The experimental crop varieties included kidney beans (Zhongyun No.1), maize (Shaandan 650), sorghum (Jinza 22), and millet (Longmi 8).

Design of the experiment

The field experiment began in 2019. Eighteen plots with an area of 2×3 m² were set up in a randomized block design on the same slope. There were a total of 6 treatments, with 3 replicates. There were five treatments in total: (1) C0 fallow treatment: The plot was left fallow with bare land, and weeds on the ground were regularly removed. (2) C1 continuous maize cropping treatment: Maize was sown in mid - May every year and harvested in late October. (3) C2 continuous alfalfa cropping treatment: The tested sample was alfalfa. Since it was sown in 2019, it had been growing continuously until then. It was cut once in early June and once in late October every year. (4) C3 rotation of maize - sorghum - sorghum - proso millet (cereal - based) treatment: Maize was sown in mid - May and harvested in late October each year. In the second year, sorghum was sown in mid - May and harvested in late October. Sorghum was sown again in the third year. In the fourth year, proso millet was sown in late May and harvested in late October, and this cycle repeated (When the samples were collected for the experiment, the crop was maize.). (5) C4 rotation of kidney bean - sorghum - sorghum - proso millet (legume - cereal) treatment: Kidney bean was sown in mid - May and harvested in early October every year. Sorghum

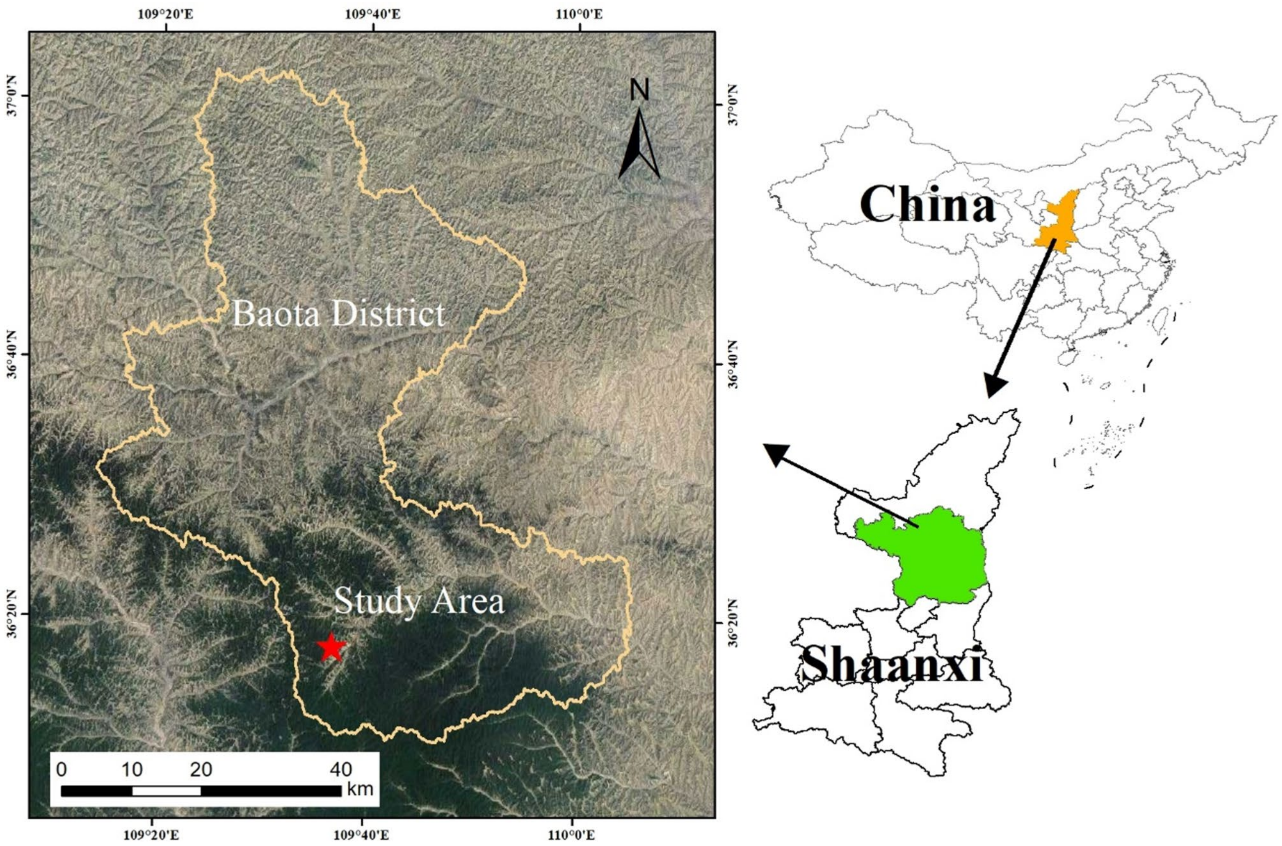

Fig. 1. Geographical location of test area. The figure was drawn by ArcGIS10.8 (Esri China Information Technology Co. Ltd. http://my.ally.net.cn/index.php?c=com_index&m=yp&userid=10876).

Soil Layer(cm)	Total carbon contents(g/kg)	Organic carbon contents(g/kg)	Inorganic carbon contents(g/kg)	Light fraction organic carbon contents(g/kg)	Clay(%)	Silt(%)	Sand(%)	Texture
0 ~ 5	11.5 ± 1.2	5.6 ± 0.6	5.8 ± 0.6	0.6 ± 0.1	5.0 ± 0.5	69.5 ± 3.5	25.5 ± 2.6	silt loam
5 ~ 10	10.6 ± 1.1	4.7 ± 0.5	6.0 ± 0.6	0.3 ± 0.1	6.3 ± 0.6	74.0 ± 3.7	19.7 ± 2.0	silt loam
10 ~ 15	10.3 ± 1.0	4.0 ± 0.4	6.1 ± 0.6	0.2 ± 0.1	6.9 ± 0.7	74.3 ± 3.7	18.8 ± 1.9	silt loam
15 ~ 20	10.0 ± 1.0	3.9 ± 0.4	6.0 ± 0.6	0.2 ± 0.1	7.5 ± 0.8	74.2 ± 3.7	18.4 ± 1.8	silt loam
20 ~ 30	8.5 ± 0.9	3.4 ± 0.3	5.1 ± 0.5	0.1 ± 0.1	7.7 ± 0.8	74.3 ± 3.7	18.1 ± 1.8	silt loam
30 ~ 40	5.1 ± 0.5	2.6 ± 0.3	2.5 ± 0.3	0.1 ± 0.1	5.8 ± 0.6	58.0 ± 2.9	36.2 ± 3.6	silt loam

Table 1. Basic information of the tested soil.

was sown in the second and third years, and proso millet was sown in the fourth year, following a cycle (When the samples were collected for the experiment, the crop was kidney bean.). None of the five treatments were fertilized.

Sampling and determination

In late October 2024, soil samples were collected from the experimental plots at six soil layers: 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–30 cm, and 30–40 cm. Based on the spatial variation law of soil properties and the optimization of practical operations, and following the principle of ensuring scientific reliability and high - efficiency feasibility of the data, 10 cores were taken from the 0–10 cm soil layer in each plot, with a drill bit diameter of 2 cm; 5 cores were taken from the 10–20 cm soil layer; and 3 cores were taken from the 20–40 cm soil layer, with a drill bit diameter of 4 cm for both the 10–20 cm and 20–40 cm layers. The soil from the same soil layer was mixed evenly to form one analytical sample. When collecting soil samples in the field, efforts were made to avoid mixing in obvious large roots. The collected soil samples were air - dried naturally, passed through a 2 - mm sieve, and thick roots larger than the sieve pore diameter were removed. The sieved soil was then stored for future use.

The extraction and determination of soil light fraction organic matter[22] were conducted as follows: 25 g of soil sample that had passed through a 2 mm sieve was weighed and placed into a 100 mL centrifuge tube. Then, 50 mL of NaI solution with a mass concentration of 1.70 g/mL was added. The mixture was shaken at a speed of 200 r/min for 1 h, and then centrifuged at a speed of 1000 g for 20 min. The light fraction organic matter floating on the surface of the NaI solution was poured into a container filter equipped with a 0.45 μm fiber filter membrane for suction filtration. Subsequently, the light fraction organic matter adhering to the surface of the filter membrane was transferred to a beaker using distilled water. Next, another 50 mL of NaI solution with a mass concentration of 1.70 g/mL was added to the centrifuge tube for a second extraction, following the same method as before. The light fraction organic matter obtained from the two extractions was combined, and it was successively suction filtered and rinsed with 0.01 mol/L CaCl and distilled water, and then transferred to a beaker. The sample in the beaker was dried at 60 °C and weighed. The dried light - fraction part was ground finely in an agate mortar and passed through a 60-mesh sieve for future use.

The determination of soil total carbon (TC), inorganic carbon (IC), organic carbon (TOC), and light fraction organic carbon (LFOC) was conducted as follows[23]: Air-dried soil samples were passed through a 100-mesh sieve. A 0.140–0.150 g subsample of the sieved soil was accurately weighed and placed into a sample boat. Using a TOC-VSeries SSM-5000 A carbon analyzer, TC was directly determined via high-temperature combustion (typically ≥ 900 °C). For IC, 1 mol/L HCl was injected to acidify the soil, decomposing carbonate minerals and releasing CO_2; the carbon content of the evolved CO_2 was measured as IC. Soil organic carbon was calculated using the formula: TOC = TC - IC. A 0.020–0.030 g subsample of the pre-separated light fraction organic matter (prepared via NaI flotation, as described previously) was weighed and analyzed with the same carbon analyzer to determine its carbon content.

Data processing and analysis

Data were sorted and tables were created using Excel 2017, and data analysis was performed using SPSS 2.0. The Shapiro - Wilk test and Levene test were used to conduct normality and homogeneity of variance tests (with all P values greater than 0.05). Subsequently, the Duncan method was employed to test for differences among parameters.

Results and analysis

Impacts of different crops and planting patterns on soil total carbon (STC)

Measurements of the 0–40 cm soil under long - term continuous cropping or rotation of different crops (as shown in Table 2) indicated that the soil total carbon (STC) content was the highest in the 0–5 cm surface soil layer, ranging from 11.3 to 35.5 g/kg. It decreased significantly with the increase of soil depth and reached the lowest value in the 30–40 cm soil layer. Among them, the decrease rate of C2 was the largest, reaching 72.39%; that of C0 ranked second, at 54.87%, followed by C3 and C4, with decrease rates of 43.37% and 42.92% respectively; the decrease rate of C1 was relatively small, at 36.25%. Evidently, crops and cropping patterns could significantly influence the profile distribution of STC.

Compared with C0, both long - term continuous cropping and rotation significantly increased the STC content. In the 0–40 cm soil layer, rotation and continuous cropping increased the average STC content by 57.11 – 122.52%. In terms of different cropping patterns, in each soil layer of 0–15 cm, C2 had the highest STC content, ranging from 22.0 to 35.5 g/kg. C3 and C4 followed, with STC contents ranging from 18.9 to 19.6 g/kg, while C1 had a relatively lower STC content, ranging from 10.2 to 26.0 g/kg. In the 15–30 cm soil layer, the STC content of C2 was lower than that of C1, C3, and C4. In the 30–40 cm soil layer, there was no significant difference in the STC content between C2 and the other two rotation or continuous cropping treatments. Compared with C1, the STC content of C2 was significantly higher in each layer of 0–15 cm. Below 15 cm, there was no significant difference in the STC content between C3 and C4. There was no significant difference in the STC content of each soil layer between the two rotation patterns.

Impacts of different crops and planting patterns on soil organic carbon(SOC)

The mass fraction of soil organic carbon also decreased with the increase of soil depth (Table 3), reaching the lowest value in the 30–40 cm soil layer. However, the soil layer with the highest mass fraction of organic carbon varied depending on the crop and planting pattern. Among them, the decline of C2 was the most significant,

	Crop and Planting Pattern				
Soil Layer(cm)	C0(g/kg)	C1(g/kg)	C2(g/kg)	C3(g/kg)	C4(g/kg)
0 ~ 5	11.3 ± 1.2dA	16.0 ± 1.5cA	35.5 ± 2.8aA	19.6 ± 1.8bA	19.1 ± 1.7bA
5 ~ 10	10.4 ± 1.1dAB	15.9 ± 1.4cA	29.7 ± 2.5aB	19.1 ± 1.7bA	18.9 ± 1.6bA
10 ~ 15	10.2 ± 1.0dB	16.0 ± 1.5cA	22.0 ± 2.0aC	19.6 ± 1.8bA	19.0 ± 1.7bA
15 ~ 20	10.0 ± 1.0dB	15.8 ± 1.4bA	15.4 ± 1.6bD	18.8 ± 1.7aA	17.8 ± 1.6aA
20 ~ 30	8.5 ± 0.9dC	13.3 ± 1.2bB	11.1 ± 1.3cE	15.1 ± 1.5aB	14.5 ± 1.4abB
30 ~ 40	5.1 ± 0.7bD	10.2 ± 1.0aC	9.8 ± 1.1aE	11.1 ± 1.2aC	10.9 ± 1.1aC

Table 2. STC with different crops and cropping systems. Notes: Lowercase letters indicate comparisons among different crops and planting patterns in the same soil layer, and uppercase letters indicate comparisons among different soil layers of the same pattern ($P < 0.05$).

	Crop and Planting Pattern				
Soil Layer(cm)	C0(g/kg)	C1(g/kg)	C2(g/kg)	C3(g/kg)	C4(g/kg)
0 ~ 5	5.4 ± 0.6dA	8.4 ± 0.9cA	26.4 ± 2.5aA	11.7 ± 1.2bA	11.6 ± 1.1bA
5 ~ 10	4.5 ± 0.5dB	8.2 ± 0.8cA	21.8 ± 2.2aB	11.7 ± 1.1bAB	11.5 ± 1.1bA
10 ~ 15	4.0 ± 0.4dC	8.3 ± 0.8cA	14.8 ± 1.5aC	12.2 ± 1.2bAB	11.0 ± 1.0bA
15 ~ 20	3.9 ± 0.4dC	8.2 ± 0.8cA	9.3 ± 1.0bD	11.3 ± 1.1aB	10.2 ± 1.0bA
20 ~ 30	3.4 ± 0.4eD	6.0 ± 0.6cdB	5.2 ± 0.6dE	8.0 ± 0.8aC	7.4 ± 0.7abB
30 ~ 40	2.6 ± 0.3bE	4.2 ± 0.5aC	4.4 ± 0.5aE	4.8 ± 0.5aD	5.0 ± 0.5aC

Table 3. SOC with different crops and cropping systems. Notes: Lowercase letters indicate comparisons among different crops and planting patterns in the same soil layer, and uppercase letters indicate comparisons among different soil layers of the same pattern ($P < 0.05$).

	Crop and Planting Pattern				
Soil Layer(cm)	C0(g/kg)	C1(g/kg)	C2(g/kg)	C3(g/kg)	C4(g/kg)
0 ~ 5	5.9 ± 0.6cA	7.6 ± 0.8bA	9.1 ± 0.9aA	7.8 ± 0.8bA	7.5 ± 0.8bAB
5 ~ 10	5.9 ± 0.6bA	7.7 ± 0.8aA	7.9 ± 0.8aB	7.3 ± 0.7aA	7.4 ± 0.7aAB
10 ~ 15	6.2 ± 0.6cA	7.6 ± 0.8abA	7.2 ± 0.7bC	7.4 ± 0.7abA	8.0 ± 0.8abA
15 ~ 20	6.0 ± 0.6bA	7.6 ± 0.8aA	6.1 ± 0.6bD	7.5 ± 0.8aA	7.6 ± 0.8aAB
20 ~ 30	5.1 ± 0.5bA	7.3 ± 0.7aA	5.9 ± 0.6bD	7.0 ± 0.7aAB	7.1 ± 0.7aB
30 ~ 40	2.5 ± 0.3bB	6.0 ± 0.6aB	5.4 ± 0.5aD	6.3 ± 0.6aB	5.8 ± 0.6aC

Table 4. SIC with different crops and cropping systems. Notes: Lowercase letters indicate comparisons among different crops and planting patterns in the same soil layer, and uppercase letters indicate comparisons among different soil layers of the same pattern ($P < 0.05$).

with a decrease rate of 83.33%. For C3 and C4, there were no significant differences in the soil organic carbon (SOC) content among the 0–15 cm soil layers, and their average SOC contents were 11.9 g/kg and 11.4 g/kg respectively. The average SOC content in the 0–15 cm soil layers decreased by 59.55% and 56.01% in the 30–40 cm soil layer. For C1, there were no significant differences in the SOC content among the 0–20 cm soil layers, with an average of 8.3 g/kg, and it decreased by 49.24% in the 30–40 cm soil layer. For C0, the SOC content was also the highest in the 0–5 cm soil layer, and it decreased by 51.85% in the 30–40 cm soil layer. It can be seen that the decreasing amplitude of organic carbon in the soil profile of C2 was also the fastest, followed by different crop continuous cropping and rotation, and the variation range of the mass fraction of organic carbon in the soil profile of C0 was relatively small.

In the 0–40 cm soil layer, long - term crop cultivation increased the average SOC content by 3.3–9.7 g/kg compared to C0, with an increase range of 82 −244%. Regarding different rotation and continuous cropping patterns, in each soil layer of 0–15 cm, C2 had the highest SOC content, ranging from 14.8 to 26.4 g/kg. C3 and C4 followed, with SOC contents ranging from 11.0 to 12.2 g/kg, while C1 had a relatively lower SOC content, ranging from 8.2 to 8.4 g/kg. In the 15–30 cm soil layer, there was no significant difference in the SOC content between the two rotation patterns, but both were higher than that of C2. In the 30–40 cm soil layer, except for C0, there was no significant difference in the SOC content among the other treatments. When comparing C1 and C2, the SOC content in the 0–20 cm soil layer of C2 was significantly higher than that of C1. Below 20 cm, there was no significant difference between the two continuous cropping patterns. Except for the 15–20 cm soil layer, there was no significant difference in the SOC content among each soil layer of the two rotation patterns.

Effects of different crops and planting patterns on soil inorganic carbon(SIC)

Consistent with the situation of, the content of SIC generally showed a decreasing trend with the increase of soil depth (Table 4). In the 0–5 cm surface soil layer, C2 had the highest SIC content, reaching 9.1 g/kg, and it decreased by 40.66% in the 30–40 cm soil layer. There was no significant difference in the SIC content of C1, C3, and C4 in the 0–30 cm soil layer, with average values of 7.6 g/kg, 7.4 g/kg, and 7.5 g/kg respectively. In the 30–40 cm soil layer, their SIC contents decreased by 20.63%, 14.86%, and 22.87% respectively compared to the average values in the 0–30 cm soil layer. In the 0–30 cm soil layers of C0, there was also no significant difference in the SIC content, with an average of 5.8 g/kg. However, in the 30–40 cm soil layer, the SIC content of C0 decreased by 57.04% compared to the 0–30 cm average. Evidently, although the decrease rate of SIC in C2 soil was still the highest, the decrease rate of SIC in the soil profile of C0 was higher than that of other continuous cropping and rotation patterns with different crops.

Compared with C0, long-term continuous cropping or rotation of different crops not only significantly increased the SOC content but also remarkably raised the SIC content. In the 0–40 cm soil layer, the average SIC content increased by 1.6–2.1 g/kg, which was 30 −39% higher than that of C0. Regarding different rotation and continuous cropping patterns, in the 0–5 cm soil layer, C2 had a high SIC content (9.1 g/kg), which was

	Crop and Planting Pattern				
Soil Layer(cm)	C0(g/kg)	C1(g/kg)	C2(g/kg)	C3(g/kg)	C4(g/kg)
0 ~ 5	0.6 ± 0.1cA	1.6 ± 0.2bcA	8.0 ± 0.8aA	2.4 ± 0.3bAB	2.4 ± 0.3bAB
5 ~ 10	0.3 ± 0.1cB	1.5 ± 0.2bcA	5.2 ± 0.5aB	2.4 ± 0.3bAB	2.2 ± 0.3bAB
10 ~ 15	0.2 ± 0.1cC	1.4 ± 0.2dAB	2.9 ± 0.3aC	2.6 ± 0.3abA	2.3 ± 0.3bcA
15 ~ 20	0.2 ± 0.1dC	1.1 ± 0.2cB	1.3 ± 0.2bcD	1.9 ± 0.2aB	1.7 ± 0.2aB
20 ~ 30	0.1 ± 0.1cD	0.5 ± 0.1bC	0.6 ± 0.1abD	0.8 ± 0.1aC	0.7 ± 0.1abC
30 ~ 40	0.1 ± 0.1bD	0.3 ± 0.1aC	0.4 ± 0.1aD	0.4 ± 0.1aC	0.4 ± 0.1aC

Table 5. Soil LFOC with different crops and cropping systems. Notes: Lowercase letters indicate comparisons among different crops and planting patterns in the same soil layer, and uppercase letters indicate comparisons among different soil layers of the same pattern ($P < 0.05$).

significantly higher than that of other crops and cropping patterns (7.5–7.8 g/kg). In soil layers below 5 cm, the SIC content of C2 showed a distinct decreasing trend. Particularly in the 15–30 cm soil layer, its SIC content was significantly lower than that of other continuous cropping and rotation patterns. There was no significant difference in the SIC content in the 30–40 cm soil layer. When comparing the two rotation patterns with the two continuous cropping patterns, there was no significant difference in the SIC content of each soil layer among them.

Effects of different crops and planting patterns on soil light - fraction organic carbon(LFOC)

Similar to the situation of the SOC, the content of LFOC also showed a decreasing trend with the increase of soil depth (Table 5). In the 0–5 cm surface soil layer, C2 had the highest LFOC content, reaching 8.0 g/kg, and it decreased by 95.00% in the 30–40 cm soil layer. There was no significant difference in the LFOC content of C3 and C4 in each soil layer of 0–15 cm, with average contents of 2.5 g/kg and 2.3 g/kg respectively. In the 30–40 cm soil layer, their LFOC contents decreased by 83.78% and 82.61% respectively compared to those in the 0–15 cm soil layer. There was no significant difference in the LFOC content of C1 in each soil layer of 0–15 cm, with an average of 1.5 g/kg, and it decreased by 80.00% in the 30–40 cm soil layer. For C0, the LFOC content was also the highest in the 0–5 cm soil layer, and it decreased by 83.33% (a decrease of 0.5 g/kg) in the 30–40 cm soil layer. Evidently, the decrease rate of LFOC in C2 soil was the fastest. The decrease rates of other patterns were not significantly different from each other, while the decrease in the LFOC content of C0 was the smallest.

The LFOC content was also significantly increased due to long - term crop cultivation. The average LFOC content of rotation and continuous cropping soils increased by 0.8–2.8 g/kg, which was 3–11 times higher than that of C0. In terms of different rotation and continuous cropping patterns, in the 0–15 cm soil layer, the LFOC content of C2 was significantly higher than that of other cropping patterns, ranging from 2.9 to 8.0 g/kg. C3 and C4 followed, with LFOC contents ranging from 2.2 to 2.6 g/kg, while C1 had a relatively lower LFOC content, ranging from 1.4 to 1.6 g/kg. In soil layers below 15–30 cm, the LFOC content of C2 was between those of C3, C4, and C1. There was no significant difference in the LFOC content in the 30–40 cm soil layer. There was also no significant difference in the LFOC content of each soil layer between the two rotation patterns.

Discussion

The results of this study showed that, compared with the fallow mode (C0), long - term continuous cropping or rotation of different crops significantly increased the contents of various forms of carbon in the 0–40 cm soil layer. Specifically, the STC increased by 57.11 – 122.52%, the SOC increased by 81.93 – 244.12%, the SIC content increased by 29.52 – 39.25%, and the LFOC content increased by 3–11 times. There were multiple potential mechanisms behind this phenomenon. From the perspective of carbon input, crop cultivation increased soil carbon input. During the growth of crops, the litter above the ground and the root exudates and residual roots below the ground all provided carbon sources for the soil. For example, alfalfa, as a perennial leguminous plant, had a large biomass. The residues generated after annual mowing of its above - ground part and its developed underground roots could input a large amount of organic carbon into the soil. This was one of the important reasons why the SOC and LFOC contents in the 0–15 cm soil layer of continuous alfalfa cropping (C2) were relatively high. Existing studies[24,25]have shown that leguminous plants improved soil nitrogen nutrition through nitrogen fixation, promoted their own growth and biomass accumulation, and thus increased soil carbon input, which was consistent with the results of continuous alfalfa cropping in this study.

The effect of rotation on increasing soil carbon content was stronger than that of continuous cropping, and there was no significant difference between different rotation patterns. This might be because rotation increased the biodiversity in the time series of the farmland ecosystem. Different crops had different nutrient requirements. Rotation made the nutrient supply in the soil more balanced and simultaneously changed the organic components input into the soil and the structure of the microbial community. Microorganisms played a key role in the decomposition and transformation of soil carbon. A diverse microbial community could more efficiently utilize organic carbon sources and promote soil carbon sequestration. For example, the rotation patterns of maize - sorghum - sorghum - millet (C3) and kidney bean - sorghum - sorghum - millet (C4) optimized the soil ecological environment and increased the soil carbon content through the alternate planting of different crops.

With the increase of soil depth, the contents of STC, SOC, and LFOC all showed a decreasing trend, which was consistent with the results of many studies[7,8,11,26]. This was related to crop growth characteristics and tillage management methods. In particular, the continuous alfalfa cropping plot (C2) adopted no tillage management. A large amount of residual branches and leaves accumulated in the surface soil, increasing the carbon content in the surface layer. However, the deep layer soil lacked organic carbon input and was affected by the decomposition of soil microorganisms, so the carbon content decreased rapidly with the increase of depth. In contrast, due to long term tillage in continuous maize cropping (C1), the crop residues were relatively evenly distributed in the plough layer, so the carbon content in each soil layer changed relatively gently.

The SIC content decreased with the increase of soil depth, which was contrary to the results of general studies[9,10,27,28]. This might be significantly affected by the differences in crop root activities. Especially in continuous alfalfa cropping, the roots were concentrated in the surface layer. The root exudates and microbial activities increased the SIC content in the surface layer soil, but there were fewer roots in the deep layer, so the SIC content decreased. In other cropping patterns, the root distribution was relatively uniform, and the SIC content also showed a decreasing trend with depth. Secondly, the vertical change of soil microbial activities played a certain role[29]. The surface layer soil had good aeration, suitable temperature and humidity, and active microorganisms, which would consume SIC. The situation was the opposite in the deep layer, resulting in a decrease in the SIC content with the increase of soil depth. Moreover, the leaching and precipitation of the soil also had an impact. The precipitation in the study area was concentrated. Leaching caused the SIC in the surface layer soil to move downward, but it was difficult to accumulate in the deep layer. The amount of SIC precipitated on the surface during evaporation could hardly compensate for the loss[30]. The influence of different cropping patterns was limited. In addition, the soil parent material was loessial soil, which had fine particles and a small porosity, affecting the movement of water and nutrients[31]. The initial distribution differences of SIC in the parent material might also lead to this phenomenon.

The results of this study were of great significance for improving agricultural production and sustainability in arid environments. Long term continuous alfalfa cropping could significantly increase the carbon content in the surface layer soil and improve soil fertility. In areas with severe surface layer soil degradation in arid regions, alfalfa planting could be appropriately promoted to improve soil quality. Rotation patterns were more effective in increasing soil carbon sequestration. In agricultural production, rotation combinations could be reasonably selected according to local climate, soil conditions, and crop requirements. For example, in the Loess Plateau region, promoting the rotation patterns of maize - sorghum - sorghum - millet or kidney bean - sorghum - sorghum - millet could not only increase the soil carbon content but also reduce soil erosion and achieve sustainable agricultural development. At the same time, this study provided a scientific basis for the management of soil carbon in farmland in arid regions, which was helpful for formulating more reasonable agricultural production strategies and promoting the coordinated development of the ecological environment and agricultural production.

Conclusions

Research has shown that, compared with fallow, long-term continuous cropping or rotation of different crops significantly increases the contents of various forms of carbon in the 0–40 cm soil layer. Among different cropping patterns, in each soil layer of 0–15 cm, the contents of STC, SOC, and LFOC are the highest in continuous alfalfa cropping. Next come the rotations of cereal based crops or legume cereal crops, while continuous maize cropping has relatively lower values. However, the situation is different for SIC. Continuous alfalfa cropping only increases the SIC content in the 0–5 cm soil layer. As the soil depth increases, the contents of STC, SOC, and LFOC all show a decreasing trend, and the decrease is the most significant in continuous alfalfa cropping. Evidently, long-term continuous alfalfa cropping is an effective measure to increase soil carbon in dry land, especially SOC and LFOC. However, this effect is mainly manifested in the surface soil above 15 cm. Rotation is more effective than continuous cropping in increasing soil carbon, but there is no significant difference between different rotation patterns.

Data availability

The datasets generated and analysed during the current study are not publicly available due this experiment was a collaborative effort, the trial data does not belong to me alone but are available from the corresponding author on reasonable request.

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Author contributions

The manuscript was reviewed and approved for publication by all authors. P.Z. conceived and designed the experiments. P.Z., Y.Z. and Z.S. performed the experiments, analyzed the data, Z.Y. drew the figures, wrote the paper. P. Z. and P.Z. revised the paper.

Competing interests

The authors declare no competing interests.

Competing financial interests

The authors declare no competing financial interests. The use of plants in the present study complies with international, national and/or institutional guidelines.

Additional information

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