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Effects of Human Activities on Soil Carbon, Nitrogen, Phosphorus, and Ecological Stoichiometry in Desert Oasis Regions

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Abstract: This study focused on three typical land-use types in the desert oasis region of the lower Shiyang River: farmland, abandoned farmland, and shrubland. Soil samples were collected and analyzed to investigate the seasonal and depth variations of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and their ecological stoichiometric ratios. The impact of human activities on the soil carbon, nitrogen, phosphorus, and their ecological stoichiometric ratios in these three land types was also explored. The results indicated that: (1) SOC, TN, and TP contents in farmland soil were higher than those in abandoned farmland and shrubland, reflecting that human cultivation and fertilization activities significantly enhanced the carbon and nitrogen sequestration capacity of the soil. Although fertilization can improve cropland soil productivity in the short term, long-term nitrogen and phosphorus inputs disrupt the natural nitrogen cycle and transformation system of the soil and lead to the formation of insoluble phosphorus compounds, reducing the available phosphorus for crops. This ultimately results in a low soil C: N ratio (12.71) and high C:P (12.34) and N:P (1.03) ratios. In the long run, low C:N and high C:P ratios greatly increase the risk of soil fertility decline, degradation, and rapid organic matter turnover. (2) After farmland was abandoned, SOC, TN, and TP contents decreased to varying degrees. Compared to farmland, the vertical trends of soil C:N and N:P ratios in abandoned farmland were roughly similar, while the vertical trend of the C:P ratio differed significantly. The C: N, C:P, and N:P ratios in abandoned farmland gradually approached those of shrubland (18.64, 9.91, and 0.54, respectively), indicating that after farmland abandonment, the soil is transitioning towards natural soil conditions. However, the recovery of nutrient content levels and the balance of ecological stoichiometric ratios in abandoned farmland is a slow process, requiring the planting of drought-resistant plants to improve soil quality and prevent desertification. (3) This study underscores the importance of sustainable land management. Local farmers should be encouraged to adopt intermittent cultivation and combine balanced fertilization with moderate organic matter incorporation (e.g., straw return) to reduce the negative impacts of agriculture on soil health and ecosystem functions. Future efforts should focus on restoring the soil quality of abandoned farmland and adopting sustainable practices in cropland to ensure long-term ecological stability and sustainability in desert oasis regions.

1. Introduction

Soil is the most fundamental carrier and important component unit of terrestrial ecosystems, as well as a crucial participant and regulator of nutrient cycling within ecosystems (Bui and Henderson, 2013; Zhong et al., 2023). Soil provides various nutrients necessary for vegetation growth, among which the most important elements are carbon (C), nitrogen (N), and phosphorus (P) (Mooshammer et al., 2017; Yi, 2023). Carbon is the skeletal element of life, Nitrogen is a mineral nutrient essential for plant growth, and Phosphorus is a key limiting element required for plant growth. Their levels are closely related to the types and quantities of soil microorganisms, the decomposition rate of litter, and the long-term accumulation of soil nutrients and fertility (Xu et al., 2020; Hui et al., 2021). Meanwhile, they are key elements affecting the biogeochemical cycles of terrestrial ecosystems (Westheimer et al., 1987). The nitrogen and phosphorus cycles are closely coupled with the carbon cycle in ecosystems, yet they are also independent of each other (Gao et al., 2014; Zhou et al., 2022). As important bioelements in soil and key elements in the nutrient cycling and transformation of soil, C, N, and P regulate and drive the evolution process of the entire ecosystem (Xie et al., 2023). Therefore, studying the content characteristics and balance relationships of soil C, N, and P is of great significance for exploring the coupling relationship between soil quality and soil nutrients, as well as the composition and function of plant communities (Zeng et al., 2015; Ma et al., 2021). The stoichiometric ratios of soil nutrients reveal the interactions and balance of multiple chemical elements, and can be used to assess soil quality, soil nutrient supply capacity, and fertility status in ecological processes (Yan et al., 2021). Among them, the soil C:N plays an important role in regulating soil microbial activity and affecting the processes of mineralization and nitrification, and it can reflect the decomposition or mineralization rate of organic matter. The soil C:P is an important indicator for assessing the release or absorption of phosphorus during organic carbon mineralization, inversely related to the potential for phosphorus release by microorganisms. The N:P can serve as a diagnostic indicator of nitrogen saturation in soil (Tao et al., 2015; Song et al., 2019; Tao et al., 2020; Wang et al., 2022; Liu et al., 2023). Thus, investigating the content and stoichiometric ratios of soil nutrients can not only be used to assess the balance and coupling relationships of major components in ecosystems (Yang et al., 2019; Xie et al., 2023), but also provide theoretical support for the balanced use of land (Wang et al., 2018)[1-7].

In the context of global climate change, human activities have led to changes in land use and soil properties, resulting in alterations in soil nutrient content and increasingly complex regional differences in soil nutrient levels. For example, in the agro-pastoral areas of Northwest China, converting pastures into farmland caused significant losses of surface soil and subsoil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP), with a greater reduction rate in subsoil than in surface soil. However, when farmland was converted to forest land, SOC, TN, and TP levels significantly increased (Liu et al., 2017; Liu et al., 2018). In the Loess Plateau, the implementation of the 'Grain for Green' project, which converted farmland into forest or grassland, significantly increased soil C and N content and storage, enhancing the region's soil carbon sink function and improving nitrogen nutrient levels, although it decreased soil P content and storage (Xu et al., 2015). In the typical karst areas of Southwest China, the conversion of sloping farmland to forest markedly promoted the accumulation of soil carbon and nitrogen, with significant differences in SOC and TN levels among different reforested areas (Tang et al., 2014). This indicated that reforestation and grassland restoration effectively promoted the recovery of soil nutrient levels and improved soil quality (Li et al., 2016). However, when grassland was converted to arable land, it accelerated soil erosion, and tillage caused the breakdown of soil aggregates, leading to significant losses of soil nutrients and microbial populations, ultimately resulting in SOC loss (Tang et al., 2019). After farmland abandonment, the surface layer showed a clear aggregation of soil organic matter, total nitrogen, and alkali-hydrolyzable nitrogen, which decreased with soil depth (Yan et al., 2022; Raiesi et al., 2012; Xue et al., 2016; Wang et al., 2018). During the process of reclaimed farmland, with the increase in reclamation years, SOC and TN levels, as well as the C and N ratios in reclaimed farmland, gradually increased (Zhang et al., 2023). These land-use changes caused by human activities, such as reforestation and grassland restoration, conversion of grassland to farmland, farmland abandonment, and farmland reclamation, not only affected the physical distribution of nutrients between the surface and subsoil but also directly impacted the dynamic functional properties of soil, such as pH, soil aggregation, microbial biomass, and activity (Baddeley et al., 2017; Cherubin et al., 2016). Even if frequent human activities did not change the land-use types, they could still alter soil nutrient levels. For instance, applying phosphorus fertilizers to farmland to sustain soil fertility and crop yield directly increased soil phosphorus concentration and indirectly affected soil phosphorus cycling by altering soil properties or microbial communities (Chen et al., 2021). The long-term use of nitrogen fertilizers in farmland not only increased the biological phosphorus cycle in both the surface and subsoil layers but also promoted the absorption of phosphorus by soil microorganisms for crops (Wang et al., 2021).Therefore, exploring the effects of human activities on land-use changes, soil nutrient levels, and ecological stoichiometry in different regions can help us protect regionally fragile ecological environments and optimize and adjust ecological restoration policies and systems[8-15].

The Shiyang River Basin is one of the three major inland rivers in the Hexi Corridor, located at the edge of the monsoon region and is a sensitive area to ecological environmental changes. The lower reaches of the basin form a desert-oasis region, with a desert area of 15,200 km ^{2}and an oasis area accounting for only 9% of the total area (Zhou et al., 2019; Jin et al., 2013). Although the ecological environment in this region is extremely fragile, with low resistance to disturbance and weak self-maintenance and self-regulation functions (Zhang et al., 1990; Berdugo et al., 2020; Fu et al., 2021), it still plays a significant role in regional hydrological and carbon cycles. In the early 21st century, large-scale reclamation of sandy grasslands and indiscriminate deforestation of shrub forests not only severely disrupted the balance between agriculture, forestry, and animal husbandry (Zhou , 2012), but also triggered soil salinization, desertification, and further exacerbated the process of desertification (Yang et al., 2020; Niu et al., 2016). Under the combined effects of global climate change and human activities, the physical and chemical properties of the soil, as well as the carbon, nitrogen, and phosphorus cycles, have continuously changed, impacting the stability of the desert-oasis ecosystem. However, to date, there has been limited research on the carbon, nitrogen, and phosphorus cycles in the arid desert-oasis region of the lower Shiyang River Basin, and the mechanisms by which climate change and human activities jointly affect these cycles remain unclear, posing challenges for soil conservation and land resource management. Therefore, this study focused on different land-use types—farmland, abandoned farmland, and shrubland—in the desert-oasis region of the lower Shiyang River Basin. By comparatively analyzing the changes in soil carbon, nitrogen, and phosphorus content and their stoichiometric ratios under human activity disturbances, the study aimed to reveal the mechanisms by which human activities affected the carbon, nitrogen, and phosphorus cycles in soils, providing a scientific basis for ecological restoration and land management in arid desert-oasis regions[16-24].

2. Overview of the study area

The study area is located in Caiqi Town, in the southwestern part of Minqin County, downstream of the Shiyang River in Gansu Province (see Figure 1). Its geographical coordinates are 102°67′-102°82′E and 38°15′-38°37′N. The region falls under a temperate continental arid climate, characterized by high evaporation, low precipitation, and significant temperature differences between day and night. The annual average precipitation is 113.6 mm, while the annual evaporation rate is 24 times that of precipitation, indicating a significant disparity between the two (Chen et al., 2018). The land use types in Caiqi Town mainly include farmland, construction land, unused land, shrubland, and grassland, with instances of land reclamation and abandonment. The farmland area covers approximately 46,000 mu. The crops in the sampled farmland area are primarily maize (*Zea mays L.*) and wheat (*Triticum aestivum L.*), while the abandoned farmland has been left fallow since 2016, with the main herbaceous plants being *Leymus secalinus* and *Salsola ikonnikovii*. The primary shrub species in the sampling area include Kalidium foliatum and Tamarix chinensis Lour. The soil types in the sampled farmland and abandoned farmland are gray-calcic soil, while the shrubland soil type is gray-brown desert soil.

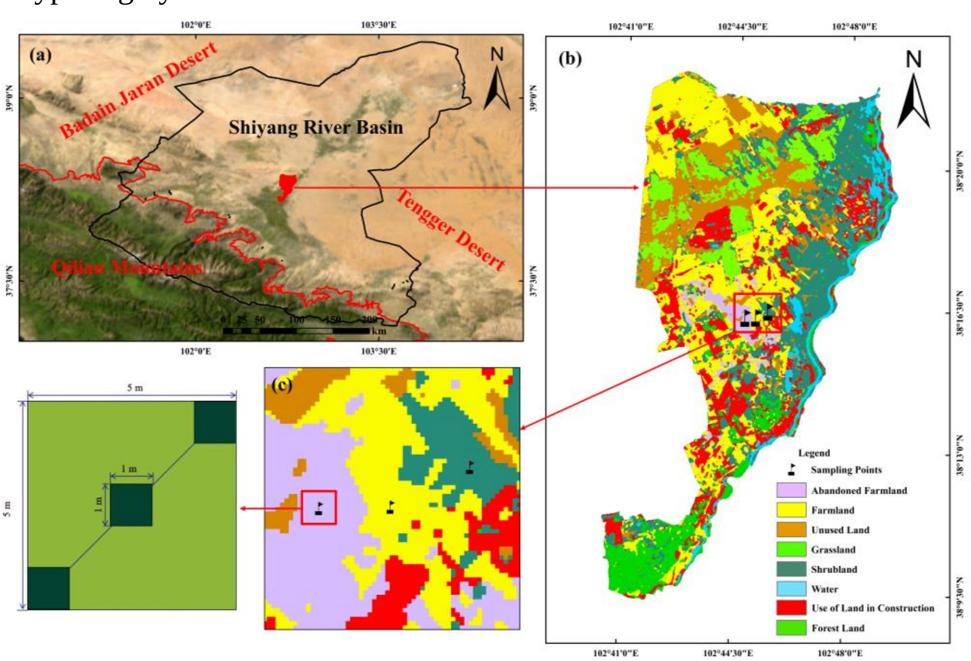

Figure 1: Overview of the study area: (a) Satellite imagery of the Shiyang River Basin; (b) Land use classification of Caiqi Town; (c) Land use types at each sampling point.

3. Data and methods

3.1 Soil sample collection and measurement

3.1.1 Soil sample collection

In 2019, three typical local land use types—farmland, abandoned farmland (fallowed since 2016), and natural shrubland—were selected near Caiqi Bridge in Caiqi Town. Soil samples were collected during the vegetation growth period from May to October. The specific sampling process was as follows: In the farmland, abandoned farmland, and shrubland, one independent plot (5m × 5m) was randomly selected for each type. Within each plot, three quadrats (each 1m × 1m) were set along the diagonal, and soil samples were taken using the five-point sampling method within each quadrat. Before taking soil samples, surface vegetation litter was removed, and then an undisturbed soil auger (1m in length, 5cm in diameter) was used to collect soil samples from six soil layers: 0-10cm, 10-20cm, 20-30cm, 30-40cm, 40-50cm, and 50-60cm. The soil samples collected from the three points in each quadrat were mixed uniformly by layer, placed in sealed sample bags, and labeled with the sampling location, time, and depth before being transported to the laboratory. A total of 1,620 soil samples were collected (6 months × 6 depths × 3 land types × 3 quadrats × 5 points)

3.1.2 Soil sample analysis

In the laboratory, soil samples were air-dried for two weeks in a cool, well-ventilated environment. After two weeks, plant residues and gravel were removed from the soil samples. The air-dried soil samples were then broken down, ground, and passed through a 100-mesh sieve to remove coarse fragments and debris, which were used for the determination of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP). Soil organic carbon (SOC) was measured using the potassium dichromate external heating method. Total nitrogen (TN) was determined by digesting the soil with concentrated sulfuric acid, followed by the Kjeldahl method. Total phosphorus (TP) was determined using the perchloric acid-sulfuric acid digestion method and the molybdenum-antimony colorimetric method, with the final TN and TP concentrations measured using the *Smartchem200* automatic discrete chemical analyzer[25-31].

3.2 Other data sources and processing

3.2.1 Land use data

The land use data used in this study is from Landsat-8 OLI for the year 2019. The data underwent preprocessing, including clipping, band fusion, and geometric correction, using ENVI 5.6 software. The preprocessed data were then classified into land use categories using ArcGIS 10.8 software, supplemented by Aowei Interactive Map, through manual visual interpretation. Based on the study's focus and the actual conditions of the study area, the land use types in this study were classified into farmland, abandoned farmland, unused land, construction land, grassland, forest land, and shrubland.

3.2.2 Meteorological Data

Daily meteorological data, including temperature and precipitation, from May to October 2019 were obtained from the China Meteorological Administration's data sharing platform (https://www.cma.gov.cn/), with accuracies of 0.1 ℃ and 0.1 mm, respectively (see Figure 2).

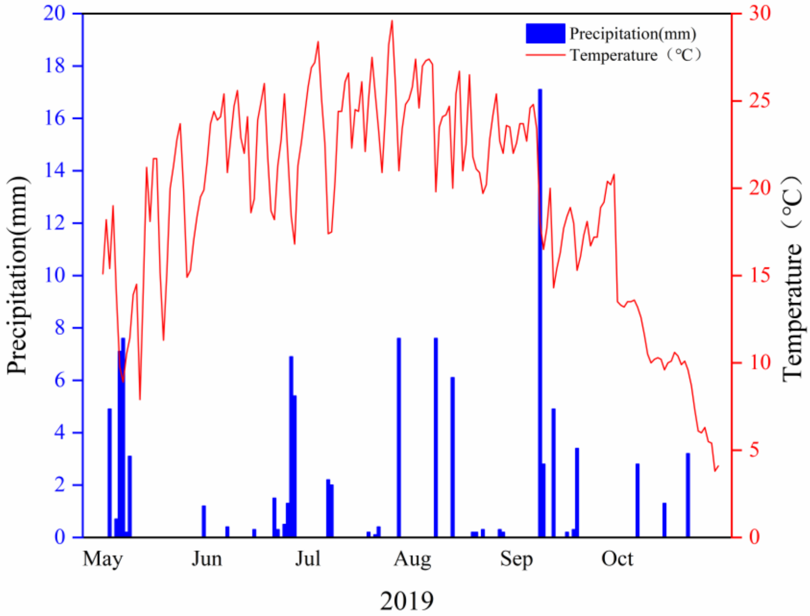

Figure 2: Daily average temperature and daily precipitation variation from May to October in the study area

4. Results and analysis

4.1 Variation in soil carbon, nitrogen, and phosphorus content under different land use types

4.1.1 Temporal variation characteristics

From Figure 3, it can be seen that the soil SOC, TN, and TP contents in farmland were higher than those in abandoned farmland and shrubland, with shrubland being slightly lower than abandoned farmland. On average, the SOC content in farmland was 1.85 times and 2.52 times higher than in abandoned farmland and shrubland, respectively; TN content was 2.2 times and 3.93 times higher; TP content was 1.54 times and 2 times higher. This indicated that human cultivation had altered soil nutrient content and nutrient cycling, enhancing soil carbon sequestration and nitrogen fixation, and promoting phosphorus cycling. After three years of abandonment, soil SOC, TN, and TP contents decreased rapidly, approaching the levels found in natural shrubland.It is anticipated that after approximately five years of abandonment, soil nutrient contents will recover to the levels and conditions of natural shrubland. This process represents a transition from carbon sink to carbon source, with soil carbon being released into the atmosphere. Therefore, the management of abandoned farmland should be given attention.

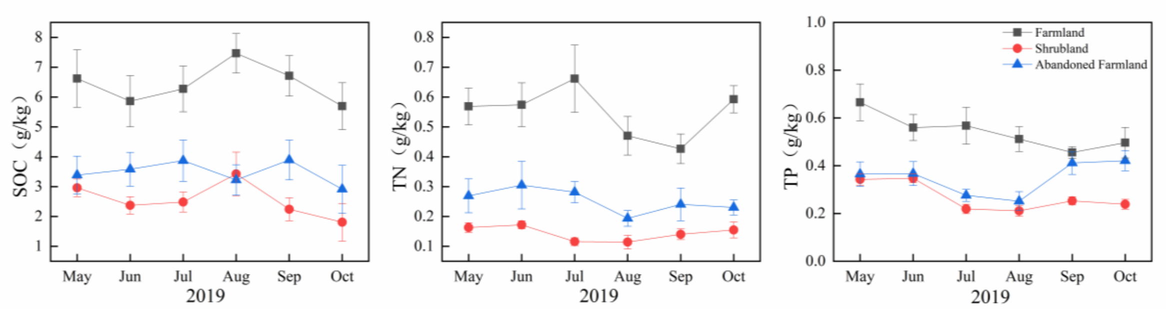

Figure 3: Temporal variation of soil SOC, TN, and TP content in farmland, shrubland, and abandoned farmland

From the perspective of temporal fluctuations, the soil SOC content in farmland and shrubland exhibited a 'decrease-increase-decrease' trend from May to October, with the highest values occurring in August and a rapid decrease in autumn, resulting in lower contents. In contrast, the temporal variation in soil SOC content in abandoned farmland was slightly different, with the lowest value occurring in August.

The soil TN content in farmland showed an 'increase-decrease-increase' fluctuation from May to October, with the highest value in July and the lowest in September, with a rapid decrease within July. Compared to farmland, the temporal variation of soil TN content in shrubland and abandoned farmland was somewhat different. Both exhibited a 'decrease-increase' trend from May to October, with the lowest values in August. The fluctuation in soil TN content was greater in abandoned farmland than in natural shrubland.

The soil TP content in shrubland and abandoned farmland also showed a 'decrease-increase' fluctuation from May to October, with the lowest values in August. Specifically, the soil TP content in shrubland decreased rapidly in June, while in abandoned farmland, the increase in TP content was more rapid in August. Additionally, the soil TP content in farmland also followed a 'decrease-increase' trend from May to October, but the lowest value was observed in September.

In summary, at the edge of the desert-oasis area, the conversion of shrubland to farmland enhanced the soil's carbon and nitrogen sequestration capacity, while the process of abandoning farmland led to a continuous release of soil carbon into the atmosphere. During the growing season, the soil SOC content in farmland and shrubland peaked in August (except for abandoned farmland) and declined to varying degrees in the fall. Soil TN and TP contents decreased to varying extents in summer but showed some recovery in autumn, with the changes in soil SOC and TN contents occurring asynchronously[32-40].

4.1.2 Vertical variation characteristics of soil profiles

From Figure 4, it could be seen that the contents of SOC, TN, and TP in different soil layers of farmland were significantly higher than those in shrubland and abandoned farmland, especially for SOC and TN. This indicated that human cultivation had altered the original soil nutrient content and nutrient cycling, and had enhanced the soil's carbon sequestration and nitrogen fixation capabilities.

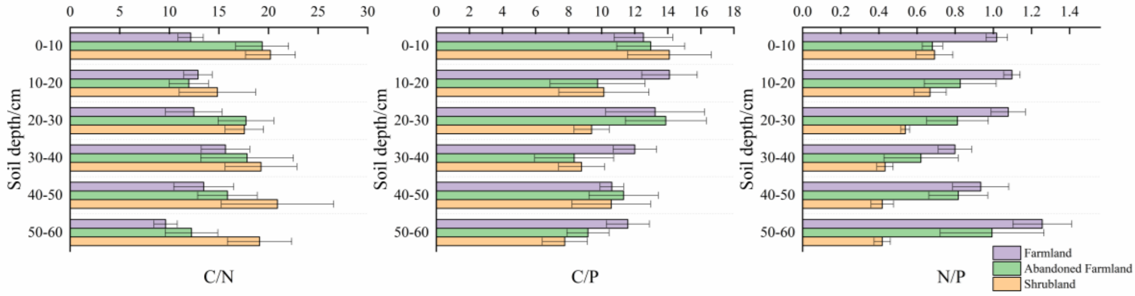

Figure 4: Vertical variation process of SOC, TN, and TP contents in farmland, shrubland, and abandoned farmland

The SOC content in the soil of farmland and shrubland showed a decreasing trend from the surface layer to the middle and lower layers, with reductions of 43.3% and 56.3%, respectively. In contrast, the SOC content in the abandoned farmland exhibited an "S" shaped decreasing trend along the vertical soil profile (0-60 cm depth), with a total reduction of 55.8% from the surface layer to the middle and lower layers. Notably, slightly higher SOC contents were observed at the 20-30 cm and 40-50 cm depths compared to the layers above them.

Although the soil TN content in the top 0-10 cm layer was higher than that in the 50-60 cm layer for all three land use types, there were notable differences in the variation patterns. For farmland and abandoned farmland, the soil TN content decreased from the 0-40 cm layers, but increased in the 40-60 cm layers, with the minimum value observed in the 30-40 cm layer. The TN content decreased by 30.7% and 13.8% from the surface to the 60 cm depth, respectively. In contrast, the soil TN content in shrubland showed a decreasing trend from the surface to the middle and lower layers, with a total reduction of 55%.

The soil TP content in all three land use types showed a decreasing trend along the vertical profile (0-60 cm soil layers), but the specific patterns of decrease varied slightly. In shrubland, the soil TP content decreased progressively by 23.3%. Although in abandoned farmland the TP content was slightly higher in the 30-40 cm and 50-60 cm layers compared to the layers above, the overall reduction was 37.5%. For farmland, the soil TP content decreased following an "S" shaped trend, with an overall reduction of 44.4%, showing slightly higher values in the 20-30 cm and 40-50 cm layers compared to the layers above.

In summary, the soil nutrient content for all three land use types showed an overall decreasing trend along the vertical soil profile. Among them, the soil SOC and TN content in shrubland decreased the most from the surface to the lower layers, by 56.3% and 55%, respectively. Farmland showed the greatest decrease in soil TP content from the surface to the lower layers, with a reduction of 44.4%.

4.2 Ecochemical stoichiometric characteristics of soils under different land use types

4.2.1 Temporal variation characteristics of soil ecochemical stoichiometric ratios

From Figure 5, it could be seen that although the soil C:N and C:P for all three land use types exhibited the characteristic of being "higher in summer and lower in spring and autumn," there were still significant differences in their temporal variation processes. Additionally, there were notable differences in the temporal variation of the soil N: P among the three land use types.

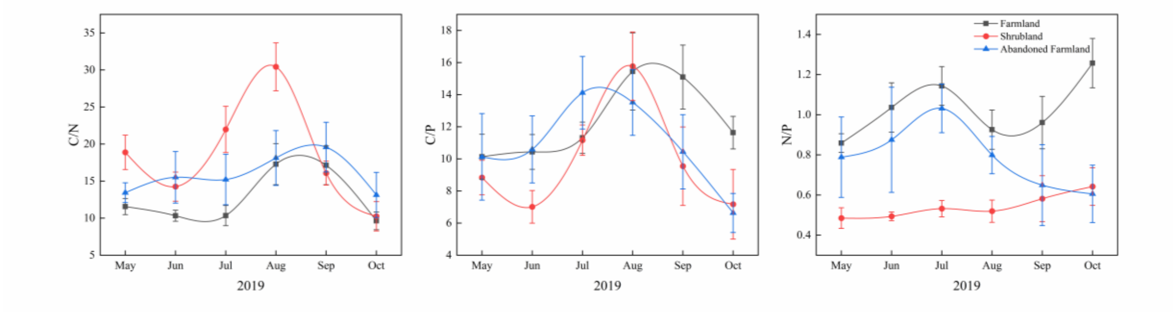

Figure 5: Temporal variation of ecological stoichiometric ratios in soil for farmland, shrubland, and abandoned farmland

The C:N in farmland and abandoned farmland soils ranged between 10 and 20, with relatively small fluctuations. The maximum values occurred in August and September, indicating that soil mineralization and assimilation processes were at a dynamically balanced and relatively low critical state during that period. In contrast, the C:N in shrubland soils ranged between 14 and 30, with greater fluctuations, and the maximum value also occurred in August, suggesting that soil mineralization and assimilation processes were at a dynamically balanced and higher critical state during that time.

Although the C:P in shrubland soils ranged between 6 and 16 and showed a fluctuation pattern of "decreasing then increasing then decreasing," and the C:P in farmland soils ranged between 10 and 16 and exhibited an "increasing then decreasing" pattern, both reached their maximum values in August. This was due to the fact that during the summer growing season, both shrubs and crops absorbed phosphorus, leading to phosphorus loss from the soil and resulting in a higher C:P. After the growing season ended, soil phosphorus content started to increase while carbon content remained relatively low, causing the C:P to decrease. The C:P in abandoned farmland soils ranged between 6 and 15 and showed an overall "increasing then decreasing" fluctuation pattern, with the maximum value occurring in July.

The N:P in farmland soils ranged between 0.8 and 1.3 and exhibited a fluctuation pattern of "increasing then decreasing then increasing," with the highest value occurring in July. A high N:P at this time may indicate nitrogen surplus, which could lead to excessive crop growth or increased competition in the agricultural niche. The lowest value was observed in May, where a low N:P might limit the crops' ability to absorb and utilize phosphorus. In abandoned farmland soils, the N:P ranged between 0.6 and 1.1 and showed an overall "increasing then decreasing" fluctuation pattern, with the maximum value occurring in July. In shrubland soils, the N:P ranged between 0.48 and 0.65, showing very little variation, with the maximum value observed in October.

In summary, the C:N and C:P in both farmland and shrubland soils peaked in August and decreased to varying extents in the fall. For abandoned farmland soils, the C:N and C:P reached their maximum values in September and July, respectively, and then started to decline. Due to the influence of human activities, the N:P in farmland and abandoned farmland soils showed significant fluctuations, whereas the N:P in shrubland soils remained relatively stable[41-46].

4.2.2 Variation characteristics of ecological stoichiometric ratios in soil profiles at different depths

From Figure 6, it could be seen that the N:P in the soil profile was significantly higher in farmland compared to abandoned farmland and shrubland. However, there were notable differences in the vertical variation patterns of the C:N and C:P along the soil profiles among the three land types.

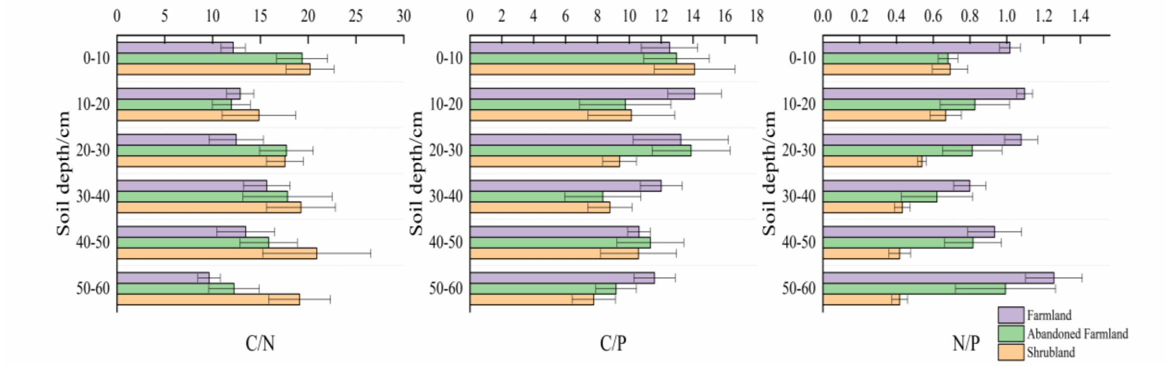

Figure 6: The variation of soil ecological stoichiometric ratios in farmland, shrubland, and abandoned farmland along vertical soil profiles

The C:N in farmland soil decreased in an "M" shape along the vertical soil profile, with the highest and lowest ratios occurring in the 30-40 cm and 50-60 cm soil layers, respectively. In both abandoned farmland and shrubland soils, the C:N decreased in an "S" shape along the vertical soil profile, with the lowest ratio found in the 10-20 cm soil layer.

The C:P in farmland soil showed a "first increase, then decrease, and then increase" trend along the vertical soil profile, with the lowest ratio occurring in the 40-50 cm soil layer and the highest ratio in the 10-20 cm soil layer. In shrubland soil, the C:P decreased in an "S" shape along the vertical profile, with higher values in the 40-50 cm layer compared to the layer above it. For abandoned farmland soil, the C:P exhibited significant fluctuation and followed an "S" shape decrease, with the lowest ratio in the 30-40 cm layer and the highest in the 20-30 cm layer.

In farmland and abandoned farmland soils, the N:P along the vertical soil profile showed a similar trend, increasing from the 0-20 cm layers and then exhibiting a "first decrease, then increase" pattern from the 20-60 cm layers, with the lowest ratio occurring in the 30-40 cm layer. In shrubland soil, the N:P decreased along the vertical profile, with a more significant reduction observed in the 10-40 cm layers.

In summary, along the vertical soil profile, shrubland soils showed distinct decreasing trends in C:N, C:P, and N:P. Farmland and abandoned farmland soils exhibited similar trends in C:N and N:P, with higher values observed in certain layers compared to those above. However, the changes in C:P between farmland and fallow soils differed significantly.

5. Discussion

5.1 Impact of human activity on soil carbon, nitrogen, and phosphorus

Through interviews with local farmers, it was learned that base fertilizers (a mixture of diammonium phosphate and compound fertilizers) were applied before sowing crops. During the growing season, compound fertilizers were continuously applied, along with additional urea and organic fertilizers (sheep manure and cow manure). The main components of these applied fertilizers were nitrogen and phosphorus, with a ratio of approximately 2:1. The additional nitrogen and phosphorus inputs into cultivated land not only increased the soil nitrogen and phosphorus supply levels, resulting in much higher soil nitrogen and phosphorus content compared to abandoned farmland and shrubs but also led to a lower soil C:N and a higher N:P in farmland compared to abandoned land. The nitrogen fertilizers used disrupted the original nitrogen cycle and transformation characteristics of the soil and affected the forms of phosphorus in the soil (Liu et al., 2020; Chen et al., 2021). Meanwhile, phosphorus fertilizers promoted the release of phosphorus by microorganisms in the surface soil, triggering soil assimilation and intensifying the competition between microorganisms and plants, further absorbing the phosphorus originally retained in the soil, leading to an increase in the C:P of the soil. Compared to abandoned farmland and shrubs, the higher carbon content in cultivated soil was mainly due to carbon sequestration by crops, decomposition of plant litter by microorganisms, and the organic fertilizers applied by humans. Organic fertilizers not only increased microbial activity but also promoted microbial growth and reproduction, thus increasing soil SOC content. However, the amount of added organic fertilizers was much smaller than the amount of nitrogen fertilizers, which resulted in a decrease in the soil C ratio (Song et al., 2019; Hu et al., 2010). From the perspective of soil vertical profiles, due to the accumulation of fertilizers and decomposition of plant litter, which primarily occurred in the surface soil, the surface soil had higher carbon, nitrogen, and phosphorus content compared to the lower soil layers. This result was consistent with other studies (Zhao et al., 2012). Overall, human activities such as plowing and crop planting involved periodic soil disturbance (Six et al., 1998), and these activities mainly influenced soil SOC, TN, and TP content changes by altering the input of plant litter and fertilizers and the turnover rate of soil organic matter.

After abandoning cultivation, the input of soil organic matter decreased, leading to a reduction in the soil carbon pool. A large amount of carbon stored in the soil would be released into the atmosphere with the cessation of cultivation activities, which was detrimental to enhancing the soil's carbon sequestration capacity (Wen et al., 2016). The lack of additional nitrogen and phosphorus inputs from fertilizers, along with the absorption and utilization of soil microorganisms, resulted in a decrease in soil nitrogen and phosphorus content. Following the abandonment of cultivation and subsequent natural restoration, there was usually an accumulation of plant biomass in the soil, resulting in a relatively closed nutrient cycle (Cotching et al., 2013; Wang et al., 2021). From the perspective of soil vertical profiles, the changes in carbon, nitrogen, and phosphorus content in abandoned farmland showed a trend similar to that in cultivated land. This was because the abandonment of cultivation began in 2016, and the period of abandonment was relatively short, so the soil was still influenced by residual effects from fertilization during cultivation. The results of this study indicated that soil SOC, TN, and TP contents significantly decreased after the abandonment of cultivation. However, some studies suggested that soil carbon and nitrogen levels may rebound within a short period after cultivation abandonment (Fan et al., 2013).Therefore, the distribution characteristics of soil carbon, nitrogen, and phosphorus after the abandonment of cultivation still have certain uncertainties, and these characteristics may be influenced by factors such as pre-cultivation surface cover, local soil moisture and thermal conditions, and artificial fertilization practices. The specific mechanisms of these effects warrant further research[47-50].

5.2 The indicative role of ecological stoichiometry characteristics of soil carbon, nitrogen, and phosphorus

The stoichiometric ratios of soil carbon, nitrogen, and phosphorus (C:N, C:P, N:P) are important predictive indicators for reflecting organic matter composition, soil quality, and soil degradation. They are also key indicators of the mineralization and retention processes of carbon, nitrogen, and phosphorus. Due to the influence of human fertilization activities, the C:N, C:P, and N:P characteristics of soils in the three land types differ significantly.

Table 1: Ecological stoichiometry ratios of soil carbon, nitrogen, and phosphorus for three types of land use in Caiqi Town

Soil types in the research area	C:N	C:P	N:P
Farmland	12.71	12.34	1.03
Abandoned farmland	15.83	10.90	0.79
Shrubland	18.64	9.91	0.54

The soil carbon to nitrogen ratio (C:N) is a sensitive indicator of soil environment and soil quality changes, which can be used to measure soil carbon and nitrogen mineralization capacity and organic matter decomposition rate (Wang Shaoqiang et al., 2008). When the C:N ratio is less than 20, it indicates that soil organic matter is easily decomposed and utilized by microorganisms, with a strong mineralization capacity. The closer the ratio is to 10, the stronger the mineralization capacity and the faster the organic matter decomposition rate (Kirkby et al., 2013). The soil carbon to phosphorus ratio (C:P) is a characteristic parameter of phosphorus effectiveness or availability, with lower values indicating higher phosphorus availability in the soil. The soil nitrogen to phosphorus ratio (N:P) can be used as a diagnostic indicator of nitrogen saturation, and can also be used to assess the magnitude of nitrogen and phosphorus element limitations on plant growth and development (Zhang Han et al., 2019).

From Table 1, it can be seen that the soil C:N ratio of farmland in Caiqi Town was 12.71, which was relatively lower compared to the average values of abandoned farmland and shrubland soils, indicating an overall low level. This could reflect that farmland, due to long-term cultivation and tillage activities, had increased soil aeration, promoted microbial decomposition activities, accelerated organic matter decomposition (Pan et al., 2013); however, farmers usually applied nitrogen fertilizer to increase crop yields, excessive nitrogen input significantly increased soil nitrogen content, ultimately leading to a low C:N ratio in the soil, and disrupting the original nitrogen cycling system in the soil. Furthermore, the C:P and N:P ratios of farmland in Caiqi Town were 12.35 and 1.03, respectively, which were generally higher compared to the average values of fallow land and shrubland soils. This was because the nitrogen and phosphorus content in farmland soil mainly depended on external nitrogen and phosphate fertilizer supplementation, with the ratio of nitrogen to phosphate fertilizer application being approximately 2:1. The applied phosphate fertilizer was prone to becoming fixed into insoluble phosphate, and phosphate elements easily formed insoluble compounds with iron, aluminum, and other elements, thereby reducing the phosphorus available for crop absorption in the soil (Li et al., 2010). At the same time, the effective phosphorus content in the soil would be lower, resulting in higher C:P and N:P ratios in farmland soil.

It was observed that both farmland and abandoned farmland, through cultivation, fertilization, and other activities, not only altered the original distribution characteristics of soil carbon, nitrogen, and phosphorus content, but also changed the values and variations of the ecological stoichiometry ratios of soil carbon, nitrogen, and phosphorus, and even disrupted and damaged the original soil carbon, nitrogen, and phosphorus cycling system. In the long term, the imbalance of soil ecological stoichiometry ratios (C/N, C/P, N/P) typically led to a series of problems such as declining soil fertility, rapid organic matter restructuring, soil degradation, and so on (Liu et al., 2024). Long-term application of fertilizer to the land not only hindered the improvement of soil structure and water retention capacity but also compromised soil health, increasing the risk of soil pollution (Chen et al., 2024). Therefore, it was necessary to urge farmers to adopt intermittent cultivation, that is, suspending cultivation during specific planting seasons or years to allow the land to fallow. This cultivation method not only allowed the soil and soil nutrient cycle to fully recover, restoring soil fertility and enhancing productivity, but also helped maintain soil health, reduce environmental pollution, and ensure long-term sustainability of the land.For abandoned farmland, we cannot simply ignore it. Instead, we should plant plants with strong resistance to prevent land desertification, improve soil quality, or promote the ecological restoration of abandoned farmland. Additionally, through interviews with local farmers, it was found that straw returning was rarely practiced on local farmland. However, proper straw returning could not only increase soil organic matter, improve soil structure (making it loose and increasing porosity), promote microbial activity and crop root development, but also significantly increase land fertility and yield (Pan et al., 2013; Li et al., 2002). Therefore, it was advocated for local farmers to consider using an appropriate level of straw returning on farmland to replace a portion of fertilizer application. This approach could reduce fertilizer use, relatively alleviate soil pollution, and maintain the long-term sustainability of land cultivation.

6. Conclusion

Based on field sampling data collected over time, this study analyzed and compared the spatial and temporal variations of soil carbon, nitrogen, phosphorus contents, and their ecological stoichiometric ratios in farmland, abandoned farmland, and shrubland in the desert oasis region of the lower Shiyang River. The impact of human activities on the cycling of soil carbon, nitrogen, and phosphorus was also examined. The results show that human activities (such as fertilization and cultivation) significantly alter the characteristics of soil carbon, nitrogen, and phosphorus contents and their stoichiometric ratios, leading to notable differences among the three land-use types.

The contents of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) in farmland were higher than those in abandoned farmland and shrubland, indicating that cultivation and fertilization activities in cropland significantly enhanced the soil's carbon and nitrogen sequestration capacity. However, the soil C:N (12.71), C:P (12.34), and N:P (1.03) ratios in farmland were lower for C:N but higher for C:P and N:P compared to abandoned farmland and shrubland. It was concluded that while fertilization can increase farmland productivity in the short term, long-term nitrogen and phosphorus inputs can disrupt the soil's nitrogen cycle and nitrogen transformation system, leading to the formation of insoluble phosphorus compounds, reducing the availability of phosphorus for crop uptake. This results in lower soil C:N and higher C:P and N:P ratios. In the long term, the low C:N and high C:P caused by fertilization may result in soil fertility decline, degradation, and rapid organic matter turnover, particularly affecting nutrient cycling and ecological balance. After farmland was abandoned, the contents of SOC, TN, and TP decreased to varying degrees but remained higher than those in shrubland. Comparing the cropland and abandoned land, the vertical trends of soil C:N and N:P ratios were similar, while there was a significant difference in the vertical trend of the soil C:P ratio. The C:N, C:P, and N:P ratios in abandoned land gradually approached the values of shrubland (18.64, 9.91, and 0.54, respectively), suggesting that the abandoned farmland, with reduced human activity, is transitioning towards natural soil conditions. However, the recovery of nutrient content levels and the balance of ecological stoichiometric ratios in abandoned land is a slow and fragile process. Thus, it is crucial to adopt measures, such as planting drought-resistant plants, to improve soil quality and prevent land desertification or promote the ecological restoration of abandoned farmland.

This study highlights the importance of sustainable land management. Local farmers should be encouraged to adopt intermittent cultivation and use balanced fertilization combined with moderate organic matter incorporation (e.g., straw return) to mitigate the negative impacts of agriculture on soil health and ecosystem functions. Future efforts should focus on restoring the soil quality of abandoned farmland and adopting sustainable practices in cropland to ensure long-term ecological stability and sustainability in the desert oasis region.

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