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Abstract

Alluvial fans possess diverse geomorphological features and have a significant impact on soil characteristics and variations in ecological stoichiometry. However, it remains unclear how alluvial fans in arid mountainous areas influence the changes in ecological chemical stoichiometry and, consequently, indirectly affect ecosystem function. Alluvial fan, with its diverse topographical features, exerts a multifaceted influence on soil formation and characteristics. Limited information exists regarding the ecological stoichiometric characteristics of the alluvial fan in arid mountainous areas. This study investigated the soil physical-chemical characteristics, enzyme activities, soil ecological stoichiometries, and its driving factors of four types of micro-topographies (alluvial mesas, high floodplain, groove beach, and striated groove) in the foothills of eastern Helan Mountains, China. Results showed that soil physical and chemical properties in the 0–20 cm soil depth was consistently higher than those in the 20–40 cm soil depth, with no changes in pH, total nitrogen, and total potassium. C:P and N:P ratios in alluvial mesas, high floodplain, and striated groove were significantly higher than those in groove beach. Redundancy analysis showed that soil nutrients played the most significant role in the variation of soil ecological stoichiometry characteristics. Topography influenced soil stoichiometry indirectly, primarily through impacts on enzyme activity and soil nutrient elements. These findings elucidate the intricate interplay between soil ecological stoichiometric characteristics and environmental factors across diverse micro-topographies in alluvial fan, contributing to our understanding of the formation and development of soil in dryland.

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Preamble

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Soil ecological stoichiometry in varied micro-topographies of an alluvial fan at eastern Helan Mountains, Northwest China

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Abstract: Alluvial fans possess diverse geomorphological features that significantly impact soil characteristics and ecological stoichiometry variations. However, it remains unclear how alluvial fans in arid mountainous areas influence ecological chemical stoichiometry changes and consequently affect ecosystem function indirectly. With its diverse topographical features, the alluvial fan exerts a multifaceted influence on soil formation and characteristics, yet limited information exists regarding the ecological stoichiometric characteristics of alluvial fans in arid mountainous areas. This study investigated soil physical-chemical characteristics, enzyme activities, soil ecological stoichiometries, and their driving factors across four types of micro-topographies (alluvial mesas, high floodplain, groove beach, and striated groove) in the foothills of the eastern Helan Mountains, China. Results showed that soil physical and chemical properties in the 0–20 cm soil depth were consistently higher than those in the 20–40 cm soil depth, with no changes in pH, total nitrogen, and total potassium. C:P and N:P ratios in alluvial mesas, high floodplain, and striated groove were significantly higher than those in groove beach. Redundancy analysis showed that soil nutrients played the most significant role in the variation of soil ecological stoichiometry characteristics. Topography influenced soil stoichiometry indirectly, primarily through impacts on enzyme activity and soil nutrient elements. These findings elucidate the intricate interplay between soil ecological stoichiometric characteristics and environmental factors across diverse micro-topographies in alluvial fans, contributing to our understanding of soil formation and development in drylands.

Keywords: enzyme activity; soil layer; topography; soil physical-chemical property; dryland

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1 Introduction

Soil, as the primary source of water and essential nutrients for plant growth, reflects a dynamic interplay of factors including soil parent material, topography, climate, and human activities [?, ?]. Notably, alterations in topography can induce spatial disparities in soil water content, thermal properties, nutrient availability, and other characteristics, thereby giving rise to environmental heterogeneity and niche differentiation among plant species [?, ?, ?]. Micro-topography, characterized by subtle surface fluctuations [?, ?, ?], plays a pivotal role in redistributing local resources such as soil water, nutrients, light, and heat [?, ?, ?, ?], consequently causing significant variations in soil attributes across distinct locations.

These distinct soil characteristics exhibit a discernible spatial regularity as they respond to micro-topographical fluctuations [?, ?, ?, ?], ultimately contributing to heterogeneity in characteristics and functions among different micro-topographies and native plant communities [?, ?]. For instance, Moser et al. (2009) elucidated the connection between micro-topography and soil nutrients through a comparative analysis of natural non-tidal freshwater mitigation wetlands and reference wetlands, also exploring the influence of mesoscale micro-topography on biomass production and plant species diversity. Consequently, the relationship between micro-topography at varying scales and ecological environmental features has become a focal point for numerous researchers, with findings highlighting the predominant role of topographic transformation and external erosion processes [?, ?, ?].

Most micro-topography studies have focused primarily on changes in soil moisture content, with less exploration into aspects such as soil temperature, physical, and chemical properties related to micro-topography. Current research has found that micro-topography significantly alters soil carbon pools [?, ?] and reduces vegetation diversity and biomass [?, ?], thereby exerting significant impacts on soil microbial community structure [?, ?]. Additionally, studies have found that micro-topography indirectly affects soil vegetation changes by altering soil moisture content [?, ?], thus significantly impacting soil ecosystem function [?, ?]. However, there is currently no definite conclusion on the effects of different micro-topographies on soil and vegetation characteristics. The ecological stoichiometry ratio of micro-topography, expressed as carbon:nitrogen:phosphorus (C:N:P), is often used to determine the degree of nutrient limitation in ecosystems [?, ?]. As an important indicator of soil quality, the ecological stoichiometry ratio of micro-topography has attracted researchers' attention regarding its relationship with environmental factors [?, ?, ?, ?]. Natural factors are the main sources and intrinsic drivers of soil properties, while topography is a major factor influencing changes in soil nutrient content and its proportional composition [?, ?]. Therefore, studying soil ecological stoichiometry characteristics and their driving factors across different micro-topographies is crucial for understanding plant growth dynamics and community development.

According to the topographic relief grading in China, terrain within an elevational difference of 0–30 m belongs to the micro-topography category, which can be divided into three types: plane, slope, and uneven terrain [?, ?]. An alluvial fan, a unit of slope micro-topography and geomorphology formed by fan-shaped accumulation, presents an optimal site for investigating the influence of micro-topography on soil characteristics. Due to the combined effects of flooding and sedimentation, different micro-topographies such as gully, alluvial mesas, groove beach, and striated groove are formed in alluvial fans, with differences in soil characteristics among these micro-topographies. According to Bahrami and Ghahraman (2019), the physical and chemical properties of soil are higher in riverside than in gully bed, the end of fan is higher than the fan top, and riverside gully in alluvial fan is higher than the alluvial fan itself. Oliveira Junior et al. (2019) researched the differences between soils affected by salinity at different locations of an alluvial fan in northern Brazil and found that pH, cation exchange capacity, and exchangeable sodium percentage at the foothills of the alluvial fan were lower than those at the fan top. Researchers have conducted extensive studies on the physical and chemical properties of soil at the top, middle, and edge of the alluvial fan [?, ?, ?]. However, most of these studies divide the alluvial fan into top, middle, and edge from the perspective of geomorphology and only focus on the impact of different landforms on soil ecological stoichiometry [?, ?]. Furthermore, relevant research on the nutrient content and ratio change characteristics of different micro-topographies of the alluvial fan, particularly on the response relationship between C:N:P ratio and environmental factors, has rarely been conducted.

The Helan Mountains, situated in Northwest China, serve as a crucial natural geographic boundary and ecological protection area. The mountain range exerts a pivotal influence on climate distribution and ecological patterns across vast areas, including the Huanghuai region and the ecotone between Ningxia Hui and Inner Mongolia autonomous regions [?, ?]. As a notable geomorphic feature within the eastern foothills of the Helan Mountains, the alluvial fan has abundant biodiversity and represents a vital water conservation zone. Predominantly characterized by desert grassland vegetation, the Helan Mountains play pivotal ecological roles in climate regulation, air purification, water and soil maintenance, and protection against wind and sand erosion [?, ?]. However, the ecological equilibrium of desert grassland within the alluvial fan at the eastern Helan Mountains has been disrupted in recent years, attributed to multiple factors including rapid development of ecotourism in the Helan Mountains, expansive growth of grape cultivation in the eastern foothills, and recurrent seasonal mountain floods. These disturbances have led to a cascade of ecological challenges encompassing water and soil loss, grassland degradation, and deterioration of the soil environment [**?**, **?**].

Regrettably, ecological stoichiometric characteristics of the alluvial fan in this area, particularly the interplay between ecological stoichiometric features within different micro-topographies and their associated environmental factors, have received little attention. In light of this knowledge gap, the aim of this study was to unravel the underlying reasons behind variations in vegetation community characteristics. We examined soil parameters including soil moisture (SM), pH, soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), hydrolyzable nitrogen (HN), available phosphorus (AP), and available potassium (AK) within the alluvial fan at the eastern Helan Mountains. In addition, we systematically investigated ecological stoichiometric variations and their correlation with environmental factors across distinct micro-topographies. By shedding light on these ecological intricacies, our research endeavors to elucidate the mechanisms governing vegetation community assembly, thereby establishing a theoretical framework for future studies on alluvial fan development, ecological restoration, and agricultural sustainability within the eastern foothills of the Helan Mountains.

2.1 Study Area

The study area is located within the eastern foothills of the Helan Mountains in Ningxia Hui Autonomous Region, China (38°27 -39°30 N, 105°41 -106°41 E). This area exhibits a distinctive southwest-northeast orientation and has an average elevation of approximately 2000 m a.s.l., as depicted in Figure 1 [Figure 1: see original paper]. Terrain within the eastern foothills of the Helan Mountains primarily comprises alluvial fans. It exhibits higher elevations in the western sector gradually sloping down towards the east, encompassing altitudes between 1120 and 1150 m. Annual average precipitation is 426 mm, with 255 mm in mountainous areas and 181 mm in sloping areas. From November to March of the following year, precipitation is relatively low, generally accounting for 20.0% of annual totals. Precipitation mainly occurs during the flood season from June to September, with higher altitudes experiencing more evenly distributed precipitation. In the middle section (>2000 m) of the Helan Mountains, 60.0%-70.0% of precipitation occurs. The study area predominantly comprises ordinary calcareous gravel and aeolian sandy soil. Vegetation resources in the alluvial fan are dominated by vascular plants, with the most abundant families being Compositae and Gramineae, followed by Fabaceae, Rosaceae, Chenopodiaceae, Ranunculaceae, Cyperaceae, Cruciferae, Caryophyllaceae, and Liliaceae. Wild plants under second-level national protection include *Glycine soja* Sieb. et Zucc., the endemic species *Ephedra rhytidosperma* C. Y. Cheng, *Prunus mongolica* (Maxim.) Ricker, *Tetraena mongolica* Maxim., *Ammopiptanthus mongoli-*

cus (Maxim. ex Kom.) Cheng f., *Tugarinovia mongolica* Iljin, and *Glycyrrhiza uralensis* Fisch.

2.2 Site Selection

The Suyukou alluvial fan, centrally located within the study area and extending from Dawukou in the north to Gangoukou in the south, was chosen as our primary sampling site (Fig. 1). In the southern region of the Helan Mountains, this well-developed alluvial fan is predominantly shaped by the sedimentation of water and non-viscous debris flow, resulting in a diverse landscape. Over time, this area has experienced continuous influence of perennial flood scouring and sedimentation, leading to the formation of gravel dams intermingled with gravel deposits in the older section of the fan. In line with classification methods established by Bahrami and Ghahraman (2019) in Iran and micro-topography classification utilized in the alluvial fan of the Qinghai-Xizang Plateau, we used a multidimensional approach for micro-topographical differentiation. This method involved unmanned aerial vehicle (UAV) imagery in conjunction with field surveys and analytical techniques, enabling us to categorize the micro-topography of Suyukou alluvial fan into four distinct types based on surface morphology, relative elevation, gravel pebble size, and vegetation composition. The following four types of micro-topography were identified: alluvial mesas, high floodplain, groove beach, and striated groove. Further information for each type is shown in Table 1 .

Micro-topography	Photograph Feature	Community Composition
Alluvial mesas	Difference in relative height is the greatest; mainly distributes coarse gravel and boulder sediments, flat terrain, well-developed fan soil; vegetation is mainly small shrubs.	*Sophora laricifolia* Maxim., *Elymus rhytidosperma* (Hook. f.) Pilg., *Caragana tragacanthoides* (Pall.) DC., *Lespedeza davurica* (Laxm.) Schindl., *Caragana arborescens* Lam., *Stipa breviflora* Griseb., and *Glycyrrhiza glabra* L.
High floodplain	Difference in relative height is significant; irregularly distributes fine gravel and coarse gravel sediments; fan area is in early stages of soil development; vegetation is mainly small shrubs.	*C. spinifera*, *Sophora laricifolia* Maxim., *Euphorbia maculata* L., and *Stipa breviflora* Griseb.

Micro-topography	Photograph Feature	Community Composition
Striated groove	Relatively low and flat terrain with fine-grained gravel sediments in narrow strips and thick soil layer; vegetation is mainly herbs.	*S. breviflora*, *Caragana inermis* Kom., *Polygonatum multiflorum* (L.) All., *Camellia japonica* L., and *Allium leek* L.
Groove beach	Low and flat terrain; vegetation is mainly herbs.	*S. breviflora*, *Reaumuria alashanica* Maxim., and *Ammopiptanthus mongolicus* (Maxim. ex Kom.)

2.3 Soil Sampling

In late June 2022, soil sampling was conducted within the study area, encompassing the upper, middle, and lower areas of the alluvial fan. Six distinct replicate sampling sites were established for each type of micro-topography, ensuring a representative sampling strategy. Spatial intervals between two sampling sites ranged from 5.0 to 10.0 km, and each sampling site covered a 4.5 m × 5.0 m area, situated at intervals of approximately 5.0 m. Surface litter and extraneous materials were removed during the soil sampling process. Subsequently, soil samples were collected from two depths: 0–20 cm and 20–40 cm. Soil samples derived from the same depth were homogenized to create composite samples, thereby ensuring sample uniformity. Larger stones were removed manually, followed by use of a 2-mm mesh sieve to extract smaller stones and plant roots. Each soil sample was stored in a labeled plastic bag and transported to the laboratory for further analysis, yielding a total of 96 soil samples. The collected soil samples were air-dried and subsequently ground to a fine consistency to facilitate assessment of physical and chemical properties.

2.4 Measurement of Physical and Chemical Properties

Physical and chemical properties of the soil were determined using conventional analytical methods [**?**, **?**]. A PHS-3G pH meter (INESA Scientific Instrument Co., Ltd., Shanghai, China) was used for pH measurement, potassium chromate volumetric method for soil organic carbon (SOC), semi-micro Kjeldahl method for total nitrogen (TN), molybdenum-antimony colorimetry for total phosphorus (TP), NaOH melt and flame photometry for total potassium (TK), alkali-hydrolyzed diffusion method for hydrolysable nitrogen (HN), 0.5 mol/L $NaHCO_3$ method for available phosphorus (AP), and flame photometry after

NH_4OAc extraction for available potassium (AK). Soil samples were dried at 105°C to a constant weight to measure soil water content (SWC). The activities of alkaline phosphatase, urease, catalase, and peroxidase in soil samples were determined using colorimetric methods as described by Tabatabai and Bremner (1969), Kandeler and Gerber (1988), Alef and Nannipieri (1995), and Kar and Mishra (1976), respectively.

2.5 Data Analysis

Stoichiometric ratios considered in this study involved the mass ratios of total soil nutrients. Multivariate analysis utilized C:N:P ratios as the response variable and topographic factors along with comprehensive soil nutrient content as explanatory variables. These topographic factors included slope (SLO), slope aspect (ASP), terrain curvatures (TC), relief degree of land surface (RDSL), surface roughness (SRL), stream power index (SPI), topographic wetness index (TWI), and elevation (ELE). Extraction of micro-topography was facilitated through remote sensing imagery and digital elevation models provided by UAV, with the assistance of ArcGIS v.10.2 software. Terrain factors were subsequently extracted using terrain analysis and grid calculator functions within spatial analysis software. Topographic factors were quantified with the formula α=cosβ, where β is the actual slope in degrees and α is the slope code value, with larger values of α indicating sunnier slopes.

One-way and two-way analysis of variance tests and Duncan' s multiple range test were performed using JMP Pro v.13.0 software (SAS Institute, Cary, USA) to analyze differences among treatments (4 micro-topographies, 2 soil depths, and 6 replicates). The impacts of topographic factors, soil physical-chemical characteristics, and soil enzyme activity on ecological stoichiometry of soil C:N:P were analyzed using redundancy analysis (RDA) and variance decomposition analysis (VPA) with Canoco v.5.0 software. A partial least squares structural equation model (PLS-SEM) was used to construct a path analysis of the effects of topographic factors, soil physical-chemical characteristics, and soil enzyme activity on changes in soil C:N:P ratio.

3.1 Soil Nutrient Contents and Ecological Stoichiometry

Soil nutrient analysis showed notable differences for SWC, gravel content, pH, TK, HN, AK, SOC, TN, TP, C:P, and N:P ratios in the 0–20 cm depth among different micro-topographies ($P<0.050$); however, no significant differences were detected for AP and C:N ratio (Table 2).

In the 0–20 cm soil depth, striated groove exhibited the lowest values for SOC, TN, C:P, and N:P ratios, being 10.80 (\$$\pm 0.56)mg/kg, 1.31(\pm 0.06)mg/kg, 16.66(\pm 1.07), and 2.04(\pm 0.13), respect$
$0.050; Fig.2[Figure2 : seeoriginalpaper]).However, whenanalyzingsoilsamplesinthe20–40cmsoildepth, nutrie$

$topographiesdifferedfromthoseinthe0–20cmsoildepth.Forinstance, whileTKdidnotsignificantlydifferam$
$topographiesinthe0–20cmsoildepth, itwassignificantlylowerinthe20–40cmsoildepthingroovebeachthaninothe$
$topographies, andithadthehighestvalue(2.31±$0.03%)) in striated groove (P<0.050; Fig. 2).

Subsequent two-factor analysis of variance indicated that both sampling depth and micro-topography significantly influenced soil nutrients and ecological stoichiometry ratios (Table 2). Notably, HN, AK, SOC, TN, C:N, and N:P ratios displayed significant differences at different soil depths. The remaining indicators, except AP and C:N ratio, also exhibited significant differences among different micro-topographies. However, the interaction between micro-topography and soil depth did not have a significant effect on any soil nutrient or chemical stoichiometric index (Table 2).

Figure 2 presents variations in ecological stoichiometry among different micro-topographies and soil depths. Overall, the interactions between micro-topographies and soil depths were not significant (P>0.050). However, other variables exhibited distinctive trends. Specifically, there were no significant differences among different micro-topographies for C:N ratio, but differences between soil depths were significant (P<0.050), with all micro-topographies showing lower C:N ratio in the 0–20 cm soil depth than in the 20–40 cm soil depth. In terms of C:P ratio, values in striated groove were significantly lower than in other micro-topographies, while differences between soil depths were not highly significant (P>0.050). For N:P ratio, all micro-topographies had higher values in the 0–20 cm soil depth than in the 20–40 cm soil depth, with differences between micro-topographies and soil depths being highly significant, and striated groove having markedly lower N:P ratio in the 0–20 cm soil depth.

3.2 Soil Enzyme Activity

Significant variations in peroxidase activity among different micro-topographies in the 0–20 cm soil depth were found, with groove beach having the highest values (P<0.050; Fig. 3 [Figure 3: see original paper]). In contrast, catalase activity significantly differed among different micro-topographies only in the 20–40 cm soil depth, with groove beach having the highest values at P<0.050 level. Additionally, in the two-factor analysis, all enzymes except alkaline phosphatase differed significantly among different micro-topographies (P<0.050). However, soil enzyme activity did not differ between soil depths and no interaction between micro-topography and soil depth was observed (P>0.050).

3.3 Micro-Topographic Factors in the Alluvial Fan

To investigate the correlation between soil ecological stoichiometry in different micro-topographies within the alluvial fan of the Helan Mountains and environmental factors (Fig. 4 [Figure 4: see original paper]), we conducted variance decomposition and RDA ranking. Figure 4 shows significant differences in terrain factors among different micro-topographies. Various topographic factors differed among different landforms, with RDSL and SLO exhibiting significant differences among different micro-topographies, both being highest in alluvial mesas ($P<0.050$). ELE and TWI also showed significant differences among different micro-topographies, and TWI was lowest in alluvial mesas ($P>0.050$).

3.4 Factors Influencing Soil Ecological Stoichiometry

Factors influencing soil ecological stoichiometry characteristics in different micro-topographies were categorized into three types: topographic factor (Fig. 5a [Figure 5: see original paper]), enzyme activity (Fig. 5b), and nutrient element (Fig. 5c). RDA results indicated that these three types of factors explained approximately 0.0%, 0.1%, and 52.1% of the variations in soil ecological stoichiometry, respectively (Fig. 5d). Interactions among these three types of factors accounted for 40.0% of the variation in soil ecological stoichiometry (Fig. 5d). In RDA analysis, RDSL, SLO, ELE, SRL, and ASP exhibited strong positive correlations with C:P ratio (Fig. 5a). URE activity was positively related to N:P and C:P ratios but had a negative correlation with C:N ratio (Fig. 5b). Among contributing factors, soil nutrient played the most significant role in the variation of soil ecological stoichiometry. Specifically, SOC made the largest contribution to C:P ratio and had a positive correlation, while TP and C:N ratio had a positive correlation (Fig. 5c). The response of soil ecological stoichiometry to different influencing factors varied. Among these factors, neither topographic factors nor enzyme activity had a significant impact, and their interaction did not exhibit a significant influence ($P>0.050$; Table 3). However, the overall influence of all influencing factors and their interactions on soil ecological stoichiometry was significant ($P<0.050$).

By constructing the PLS-SEM, we found the effects of interaction among topographic factor, enzyme activity, SWC, pH, and soil nutrient on soil ecological stoichiometry (Fig. 6 [Figure 6: see original paper]). Soil nutrient had an extremely significant and positive effect on ecological stoichiometry ($P<0.001$), while enzyme activity had a marginally significant and positive effect on soil ecological stoichiometry ($0.050<P<0.100$). Changes in enzyme activity affected soil nutrient cycling with a significantly positive effect ($P<0.001$), indirectly affecting soil ecological stoichiometry. SWC changes could exert a negative impact on soil nutrient, subsequently affecting soil ecological stoichiometry. Topographic factors had an extremely significant positive impact on soil nutrient ($P<0.001$), leading to changes in ecological stoichiometry. Furthermore, topographic factors, as well as SWC, had significantly negative impacts on pH.

We divided these factors into two categories: direct factors and indirect factors. Topographic factor, SWC, and pH influenced ecological stoichiometry indirectly by exerting positive or negative effects on enzyme activity and soil nutrient, thereby altering ecological stoichiometry; consequently, they were considered indirect factors. In contrast, enzyme activity and nutrient element had a direct positive impact on ecological stoichiometry and were considered direct factors (Fig. 6).

4.1 Factors Influencing Soil Nutrient

Limited variation in altitude and absence of distinct vegetation zonation in the alluvial fan area highlight the importance of micro-topography in explaining soil spatial heterogeneity. The unique morphological characteristics of different micro-topographies play a pivotal role in redistributing environmental factors such as solar radiation, precipitation, litter accumulation, and mineral elements [**?**, **?**, **?**], which have a significant impact on the physical and chemical properties of the soil [**?**, **?**, **?**]. In our study, we also observed marked differences in the vertical distribution of soil physical and chemical properties among different micro-topographies. The physical and chemical attributes within the 0–20 cm soil depth consistently surpassed those observed in the 20–40 cm soil depth, with some exceptions noted for pH, TN, and TK. This observation underscores the influence of plant root systems on the vertical distribution of soil properties and corroborates research by Tian et al. (2017), who attribute this phenomenon to the progressive translocation of organic matter from the soil surface to deeper strata, driven by litter decomposition and aided by precipitation and surface runoff processes.

Variation in nutrient content across different micro-topographies showed distinct trends. For instance, the order of AP content was groove beach, alluvial mesas, high floodplain, and striated groove. Groove beach displayed slightly higher AP content than alluvial mesas, while SOC, TN, HN, and AK exhibited descending order: alluvial mesas, groove beach, high floodplain, and striated groove. These variations could be explained by several factors. First, gravel content differed among different micro-topographies, with high floodplain, alluvial mesas, groove beach, and striated groove showing a decreasing order. The presence of fine gravel particles in groove beach soils, albeit in smaller quantities, had an effect, while the larger gravel size in alluvial mesas and high floodplain limited water erosion, retaining nutrients in the soil [**?**, **?**, **?**, **?**]. Second, influenced by the "fertilizer island effect" of shrubs, vegetation on alluvial mesas and high floodplain is predominantly shrub-based. Robust root systems of these shrubs enable them to absorb water and nutrients over a wide range, turning these areas into enrichment zones for soil moisture and nutrients [**?**, **?**, **?**]. This creates a positive feedback loop between shrub growth and soil morphology. Shrubs also intercept wind-transported materials such as litter and dust, absorbing and depositing these substances which enrich the soil [**?**, **?**]. Organic matter from atmospheric dust intercepted by the canopy is carried into the soil through rainfall and runoff from shrubs. Additionally, the milder microclimate created by shrubs serves as animal habitat, and resulting animal excrement contributes to soil nutrient levels, increasing soil heterogeneity in different micro-topographies [?, ?, ?].

Furthermore, these areas are influenced by the combined effects of wind and water erosion. Wind erosion occurs during windy winter and spring seasons, while water erosion predominates during summer and autumn with concentrated rainfall and short-duration rainstorm events [?, ?, ?]. These erosional processes impact the surface materials of the alluvial fan, affecting different micro-topographies in distinct ways. Alluvial mesas and high floodplain areas, with relatively higher elevation and larger gravel particle size, have stable vegetation communities that limit water and soil loss. In contrast, striated groove is relatively low-lying and prone to hydraulic erosion during the rainy season, resulting in lower soil SOC content than alluvial mesas and high floodplain. In this study, significant differences were observed in soil pH, TK, and TP contents among different micro-topographies ($P<0.050$), while differences among different soil depths were not significant ($P>0.050$). The pH values in soils of alluvial mesas, high floodplain, striated groove, and groove beach were weakly alkaline, gradually increasing with soil depth. This pattern is likely associated with arid and low rainfall conditions in the alluvial fan, where precipitation occurs primarily as heavy rainstorms. High evaporation rates and distribution of plant communities with herbaceous companion species in the soil surface layer contribute to this trend [?, ?, ?]. TP and TK elements mainly originate from gravel differentiation and mineral formation [?, ?]. Given the similarity in soil parent material within a specific area, there were minor differences in P and K contents between different soil depths and micro-topographies. Therefore, micro-topography plays a critical role in shaping soil nutrient distribution across the alluvial fan, with many factors including gravel content, vegetation, and erosion processes contributing to observed variations. Understanding these dynamics is vital for effective land management and soil conservation efforts in similar areas.

4.2 Ecological Stoichiometric Characteristics

Soil C:N:P ratio is a critical indicator of soil fertility [?, ?]. In this study, C:P and N:P ratios exhibited significant differences among different micro-topographies ($P<0.050$). All parameters showed a decrease with increasing soil depth. Difference in C:N ratio between different micro-topographies was not significant ($P>0.050$), but significant differences were observed among different soil depths ($P<0.050$), where C:N ratio increased with soil depth. Average C:N ratios in striated groove, high floodplain, alluvial mesas, and groove beach were 8.73, 8.71, 8.36, and 8.76, respectively, all lower than the average C:N ratio of 11.38 for Chinese soil and 13.30 for global soil [?, ?]. The rate of SOC mineralization between different micro-topographies in the alluvial-proluvial fan of the Helan Mountains was high [?, ?], indicating a relatively high decomposition rate of soil organic matter and SOC mineralization. Limitations imposed by C:N ratio on SOC accumulation were consistent with findings from Zhou et al. (2019). Moreover, the lack of significant difference in C:N ratio between different micro-topographies suggests a stable response between SOC and TN to environmental factors. This stability in accumulation and consumption of both components supports previous research demonstrating the relative stability of C values across various ecosystems [?, ?]. As known from prior studies, soil C:N ratio inversely correlates with the rate of soil organic matter decomposition; i.e., lower C:N ratio implies faster soil organic matter decomposition and a thicker soil layer [?, ?]. In our study, high floodplain displayed the lowest C:N ratio, while groove beach had the highest. Variation in soil layer thickness observed during field survey might be attributed to topographical factors at sampling sites.

Soil C:P ratio is a crucial indicator for assessing P mineralization and the release of soil organic matter [?, ?]. A low C:P ratio indicates strong ability of microorganisms to decompose soil organic matter and leads to an increase in soil AP content, as confirmed in this study. Average C:P ratio for different micro-topographies in the alluvial fan of the Helan Mountains was 212.26, significantly higher than the average ratio (81.90) of global forest soil [?, ?]. This finding suggests that P content in the alluvial fan was relatively low. In particular, C:P ratio revealed the following pattern: groove beach and alluvial mesas had higher values than high floodplain, which in turn exceeded values found in striated groove. This pattern suggests that striated groove underwent more pronounced microbial decomposition of soil organic matter in the alluvial fan of the Helan Mountains.

Soil N:P ratio is a key indicator for studying N saturation and nutrient supply for plant growth [?, ?, ?] and plays a quantitative role in influencing plant growth. An N:P ratio in soil exceeding 16.00 indicates P limitation [?, ?]. However, the average soil N:P ratio in the alluvial fan of the Helan Mountains was 27.91, significantly higher than 16.00 and the N:P ratio average of 6.60 for global forest soil [?, ?]. This high N:P ratio suggests limited P content in the study area. Soil TP content averaged 0.59 g/kg, slightly higher than the Chinese average of 0.56 g/kg [?, ?]. Soil TN content in the study area was 1.42 g/kg, lower than the Chinese average of 2.10 g/kg. In summary, P and N limitations affect plant growth in the alluvial fan of the Helan Mountains.

4.3 Factors Influencing Soil Ecological Stoichiometry

Micro-topography, a key indicator of terrain fluctuation, is pivotal in shaping soil nutrient dynamics, water flow, temperature, and other ecological factors in semi-arid areas. Our results indicate that topography influences soil ecological stoichiometry indirectly, primarily through impacts on enzyme activity and soil nutrient elements. While topographic factors alone did not account for significant variations in ecological stoichiometry, they had strong positive correlations with factors like slope and elevation, suggesting that topography alters ecological stoichiometry indirectly. Similarly, soil enzyme activities such as urease were positively related to C:N ratio, but their overall contribution to ecological stoichiometry was small (0.1%). However, enzyme activity plays a key role in nutrient cycling. Variations in SWC significantly affected enzyme activity and soil nutrient. As soil nutrient was the dominant factor driving variation of ecological stoichiometry (52.1%), this pathway indirectly affects chemical ratios by altering enzyme activity and nutrient transformations, which are influenced by topography and soil moisture.

The PLS-SEM analysis demonstrated the indirect effects of topographic factors on ecological stoichiometry. While soil nutrient had a direct positive impact, topography had an indirect positive effect mediated through increases in soil nutrient. SWC indirectly affected ecological stoichiometry by negatively influencing enzyme activity. Enzyme activity indirectly altered stoichiometry through positive impacts on nutrient cycling. In summary, the results suggest that topographic factors and soil moisture influence ecological stoichiometry ratios indirectly by modifying soil enzyme activity and nutrient level, resulting in significant alterations to elemental ratios and chemical composition indirectly. These results highlight the need to consider both direct and indirect mechanisms when evaluating landscape controls over ecological stoichiometry.

Previous studies have demonstrated that topography and micro-topography significantly influence soil properties and nutrient dynamics [**?**, **?**, **?**]. For example, topographic position affects SOC and nutrient distribution in tropical forests through indirect pathways such as soil moisture and enzyme activity [**?**, **?**]. Additionally, micro-topography shapes microbial communities and enzyme activities in semi-arid areas, which in turn affects soil nutrient cycling and stoichiometry [**?**, **?**]. In our study, we focused on several factors, particularly natural elements such as elevation and altitude that influence soil ecological stoichiometry. However, the impact of human activities on the environment in the eastern foothills of the Helan Mountains remains unclear, prompting the need for a more comprehensive approach in future research. It is crucial to thoroughly investigate the complex relationships between natural factors such as elevation and micro-topography and anthropogenic activities including land use and pollution. Future research could explore the combined effects of these factors on soil types and ecological stoichiometric ratios, especially in alluvial fan areas. By investigating these dynamics, valuable insights could be gained into how both natural and human-induced changes influence the soil environment, contributing not only to understanding underlying processes but also to promoting grassland community growth and protecting the fragile ecological environment in arid alluvial fan areas.

5 Conclusions

In summary, our study reveals significant variations in soil fertility and ecological stoichiometric characteristics across different micro-topographies within the study area. Specifically, alluvial mesas had the highest soil fertility, promoting robust vegetation growth compared with other micro-topographies. We observed a descending trend in SOC, HN, and TN contents from alluvial mesas to groove beach, high floodplain, and striated groove. Furthermore, our analysis identified variations in N:P and C:P ratios among different micro-topographies, with high floodplain exhibiting the greatest nitrogen-releasing potential. Despite relatively uniform water conditions, significant differences were observed in SOC content across different micro-topographies. However, the presence of low levels of TP and TN suggests limitations in plant growth due to P and N deficiencies. RDA results further emphasized the influence of topographic and nutrient factors on soil ecological stoichiometric characteristics, specifically that topography indirectly influenced soil chemical stoichiometry ratios through its impacts on enzyme activity and soil nutrient. These findings underscore the crucial role of environmental factors including topography and nutrient availability in shaping soil ecological stoichiometry. Moreover, our study highlights the intricate relationship between soil characteristics in small watersheds, particularly micro-topography. Further analysis and exploration of this relationship are needed to better understand the complex dynamics between soil properties and anthropogenic influences. Overall, our findings contribute to understanding soil fertility and ecological stoichiometric variations across different micro-topographies, providing valuable insights for soil management and ecosystem conservation in similar areas.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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