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Stoichiometric relationships between soil organic carbon and available phosphorus along soil profiles and landscape positions in mountain soils

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ABSTRACT

This study examined the stoichiometric relationships between soil organic carbon (SOC), phosphorus (P_2O_5), and pH in mountain-brown soils of the Hisar and Turkestan ranges (Central Asia). Soil profiles were sampled across watershed, slope, and footslope positions to assess vertical and regional patterns. SOC and available phosphorus (expressed as P_2O_5) decreased with depth across all soil subtypes, whereas pH and carbonate content increased concurrently along the profiles. Although surface SOC concentrations were comparable between regions, significant differences were observed in phosphorus availability and related stoichiometric indices (C:P_2O_5 and N:P_2O_5). The soils of the Hisar range showed indicators of stronger phosphorus-related constraints, expressed by steeper declines in available P fractions and higher N:P_2O_5 ratios. These findings suggest that phosphorus availability and soil chemical conditions, rather than SOC concentration alone, play a key role in shaping stoichiometric conditions potentially associated with SOC stabilization in mountain ecosystems. The results emphasize the importance of integrating nutrient stoichiometry into assessments of SOC dynamics in carbonate-dominated mountain soils.

Keywords: soil organic carbon, environmental stoichiometry, available phosphorus, mountain soils, carbonate content.

INTRODUCTION

Soil organic carbon (SOC) is a crucial component of the terrestrial carbon cycle and serves as an important indicator of ecosystem resilience, especially in mountainous landscapes characterized by high spatial variability under soil-forming conditions. Over the past few decades, the understanding of how SOC accumulates and remains stable has evolved. Instead of adhering to the traditional view that emphasized the chemical "refractory" nature of humic compounds, contemporary concepts see SOC as a continuum of organic compounds. The stability of these compounds is now understood to be influenced by environmental conditions, interactions with the mineral matrix, and landscape dynamics, rather than the inherent properties of the organic matter itself (Schmidt et al., 2011; Lehmann and Kleber, 2015). In this modern perspective, SOC is perceived as the result of a balance between organic carbon input, its transformation, and its fixation within the soil matrix.

In this context, the stoichiometry of carbon, nitrogen, and phosphorus (C:N:P) is a crucial factor. A mismatch between the incoming carbon and the availability of nitrogen (N) and phosphorus (P) can disrupt the balance of soil organic carbon accumulation and loss, particularly in mountain mosaic environments (Cleveland and Liptzin, 2007; Tipping et al., 2016). In this study, phosphorus was represented by its mobile, agrochemically available forms, defined as P_2O_5. Additionally, mass indices of available phosphorus based on oxides ($C:P_2O_5$ and $N:P_2O_5$) were calculated using a standardized approach.

Soil ecological stoichiometry indicates that imbalances in the C:N:P ratios can hinder the transformation of incoming organic carbon into more stable forms (Cleveland and Liptzin, 2007; Tipping et al., 2016). Global syntheses reveal that in the soils with low SOC, especially within mineral horizons, organic matter tends to be richer in nitrogen and phosphorus. This enrichment is attributed to the selective stabilization of nutrient-rich organic compounds on mineral surfaces (Tipping et al., 2016; Lavallee et al., 2020).

Stoichiometric limitations are especially important in mountainous regions. While SOC pools are generally associated with lower temperatures and slower decomposition rates, the studies examining altitudinal gradients reveal that increases in SOC pools at higher elevations do not always result in greater stability. Factors such as changes in organic matter quality, soil acidity, and nutrient availability can lead to the formation of less stable carbon pools, even when total SOC levels are high (Djukic et al., 2010; Budge et al., 2011; Mayor et al., 2017). This highlights the distinction between the SOC content and the stability of carbon; these two processes are not the same.

Phosphorus plays a crucial role in limiting the stabilization of soil organic carbon in mountain soils. During the weathering process, secondary minerals-primarily iron (Fe) and aluminum (Al) (hydr)oxides-are formed, which can convert a significant amount of phosphorus (P) into forms that are tightly bound or "occluded," making them less available to living organisms (Walker and Syers, 1976).

The reduction in P availability depends on the geochemical conditions of the soil. In acidic and weathered soils, the sorption and occlusion by Fe- and Al-(hydr)oxides are the dominant processes. In contrast, in carbonate and slightly alkaline soils, P is mainly bound in calcium (Ca) forms due to precipitation and the control of solubility by pH.

Therefore, for mountain brown carbonate soils, analyzing both pH and available phosphorus (P_2O_5) is particularly insightful. In some ecosystems, the total phosphorus stock can remain relatively high while the proportion of available phosphorus is low, primarily due to chemical fixation and the formation of secondary minerals (Yang et al., 2013). This situation exacerbates the imbalance: when the ratios of carbon to available phosphorus ($C:P_2O_5$) and nitrogen to available phosphorus ($N:P_2O_5$) are high, the risk of phosphorus limitation on microbial processing of organic matter increases. This limitation affects the processes that convert carbon into more stable, mineral-associated forms (Penn and Camberato, 2019).

Furthermore, changes in the availability of phosphorus can influence the dynamics of SOC. Increased phosphorus availability may accelerate mineralization by promoting the desorption of organic compounds and stimulating microbial activity. However, in long-term experiments, phosphorus fertilization in the context of nitrogen limitation can lead to a decrease in SOC stocks, even with increased productivity (Poeplau et al., 2016).

Along with vertical profile differentiation, the landscape-wide redistribution of nutrients is fundamentally important in mountainous regions (Doetterl et al., 2016; Berhe et al., 2018; Djalilova et al., 2021). Slope erosion and sediment accumulation in lower elevations lead to the redistribution of soil organic carbon and nutrients, creating contrasting stoichiometric conditions within a single landscape (Zhang et al., 2006). Reviews indicate that erosion can simultaneously cause SOC losses on slopes while promoting its stabilization in accumulation zones through processes such as burial and enhanced organic-mineral interactions (Van Oost et al., 2012; Doetterl et al., 2016; Nadeu et al., 2012).

The composition of transported organic matter and the carbon:nitrogen:phosphorus (C:N:P) ratios affect whether carbon is primarily mineralized or incorporated into more stable pools (Berhe et al., 2018; Kirkels et al., 2014; de Nijs and Cammeraat, 2020). Empirical data demonstrate that the organic matter preserved in mineral horizons often contains relatively higher amounts of nitrogen (N) and phosphorus (P) compared to plant detritus. This observation aligns with the idea of selective fixation of N- and P-containing components onto mineral surfaces (Spohn, 2024).

Consequently, an increase in the $C:P_2O_5$ and/or $N:P_2O_5$ ratios along a profile or between different terrain positions can act as an indicator of a potential increase in phosphorus (P) limitation. This limitation may influence processes associated with the formation and maintenance of more stable forms of SOC.

Recent studies of mountain soils are moving beyond the simplistic "higher → colder → more soil organic carbon" model. Instead, they emphasize that the factors influencing SOC storage and stability can vary, as hydrothermal regimes, vegetation, soil matrix properties, and nutrient availability all change with altitude (Bonfanti et al., 2025). Research on carbon fractions and aggregate structure along elevation gradients reveals changes not only in total SOC, but also in the distribution between "more active" and "more protected" pools, which is essential for understanding stabilization (Cao et al., 2024). In recent years, there has been growing interest in the role of phosphorus as a driver of the persistence of mineral-associated organic matter (MAOM) and SOC dynamics overall (Lieberman et al., 2025). For the field profiles of mountain soils, this suggests that a joint analysis of total phosphorus, available phosphorus (P_2O_5), and pH is practically valuable.

Manipulation experiments involving N and P illustrate the complexities of soil organic carbon responses. Nutrient additions can boost productivity and carbon inputs, but they may also trigger the decomposition of some previously accumulated SOC. The outcome of these processes depends on initial nutrient ratios, soil conditions, and the composition of organic matter (Ma et al., 2025; Dai et al., 2025).

When considering erosion and re-deposition, comprehensive reviews indicate that landscape transport significantly influences which fractions of carbon are mineralized or preserved through burial (Van Oost et al., 2012; Doetterl et al., 2016; Berhe et al., 2018). In mountainous regions, recent studies linking erosion, SOC, and carbon losses highlight the importance of incorporating topography into the landscape-based "stoichiometric constraints" model (Raj et al., 2025). This provides a strong rationale for designing a comparative study of uneroded watersheds, eroded slopes, and reclaimed aprons to analyze the combined variability of SOC, nitrogen, phosphorus, mobile phosphorus, and pH levels.

In this paper, the term "conditions potentially associated with SOC stabilization" is used in a provisional, operational sense and does not imply a direct measurement of carbon turnover time or the proportion of stable fractions (e.g., MAOM or POC). Stabilization is understood as a set of soil-chemical and stoichiometric conditions that, according to modern concepts, can facilitate the formation and preservation of mineral-associated forms of organic matter. SOC was not separated into fractions, but phosphorus availability, pH, and mass stoichiometric indices ($C:P_2O_5$ and $N:P_2O_5$) were used as operational indicators of the chemical prerequisites for stabilization.

This study aimed to evaluate the relationship between the carbon-to-nitrogen (C:N) ratio, indicators of available phosphorus supply (measured through mobile phosphorus forms, expressed as P_2O_5), soil acidity, and soil organic carbon content, and their potential stabilization conditions in mountain ecosystems. This analysis was conducted along soil profiles and across different relief positions.
The study tested the following hypotheses:

1. An increase in the $C:P_2O_5$ and $N:P_2O_5$ ratios (along with a decrease in phosphorus availability) is linked to the conditions that may limit the formation of stable organic-mineral SOC forms in mineral horizons.
2. Differences between erosional and accumulative relief positions create a more distinct gradient of stoichiometry and SOC than the altitudinal factor alone.
3. Indicators of mobile phosphorus and soil pH show more consistent associations with SOC and stoichiometric indices within the landscape than differences based solely on soil subtypes or relief positions.

The findings of this study will clarify the role of phosphorus limitation and landscape distribution in creating the spatial heterogeneity of SOC in mountain soils.

In this study, the term "stoichiometric ratios" is used to refer specifically to the ratios between soil organic carbon, nitrogen (N), and agrochemically available phosphorus (P_2O_5), rather than adhering to the strict elemental stoichiometry of carbon to phosphorus (C:P). From an ecological engineering perspective, it is particularly important to use straightforward and reproducible indicators to assess the functional state and limitations of soils, especially in situations with limited field data. Recent reviews highlight that integrating indicators of soil organic carbon, environmental response, and nutrient status is an effective strategy for diagnosing soil degradation and planning restoration measures across various ecosystems (Bünemann et al., 2023).

MATERIALS AND METHODS

Research area

The object of the study corresponded to mountain-brown soils (carbonate, typical, and leached), formed in the mountain ecosystems of the Hisar Range, including the territory of Baysun

(Surkhandarya region), as well as the Turkestan Range, within the Zaamin (Jizzakh region) of the Republic of Uzbekistan (Figure 1).

The topography of both regions is dominated by slope surfaces, which determine contrasting moisture conditions and the intensity of lateral soil transport (Gafurova et al., 2024). On the Turkestan range, slopes of 7–15° account for 5.1%, 15–25° for 22.4%, and slopes steeper than 30° account for more than 45% of the area. The slopes within the study area predominantly face west and northwest, with shaded slopes accounting for approximately 33% and sunny slopes for 67%. For the Hisar Range, the slope distribution by steepness is: 0–3° – 6.1%, 3–5° – 7.8%, 5–10° – 22.0%, 10–15° – 20.9%, 15–20° – 15.9%, >20° – 27.3%; the largest share of exposures is southern area (15.9%) and southeastern area (15.2%), the share of shady slopes (northern, northeastern and northwestern exposures) is ≈33.0%, sunny (southern, southeastern and southwestern) - ≈43.0%, and eastern and western exposures – ≈24.0%. The studied slopes show distinct topographic positions, including the watershed, upper slope, middle slope, and foot (accumulative surfaces). Large areas of the foothills and lowlands are made up of Upper Cretaceous and Paleogene marine sediments. The lower layers consist of sandstones and conglomerates, while the upper layers are composed of Paleogene limestones (Mirkhaydarova and Sodikova, 2020). The specific characteristics of the parent rocks, along with the noticeable climatic zonation at different altitudes, influence the natural vegetation in the study area (Gafurova et al., 2020). In the foothills and lowlands, perennial vegetation types, such as *Phlomis, Cousinia, Ferula, Crambe,* and *Eremurus* are predominant, with occasional thickets of pistachio and almond. In the low- and mid-mountain zones, the vegetation is characterized by the communities containing essential oil and tannin-producing species (Gafurova et al., 2020).

Topographic and vegetation characteristics of soil pits

Before sampling, each soil pit was morphologically described in situ. For every profile, slope position (watershed, slope, footslope), slope gradient, exposure, vegetation type, and degree of erosion were recorded. Slope gradients ranged from 5° to 25°. Watershed sites were located on gentle surfaces (0–5°) and classified as non-eroded. Slope positions showed moderate sheet erosion, expressed by reduced thickness of humus horizons. Footslope sites (<7°) represented accumulative positions with thicker humus layers and signs of colluvial deposition. All studied sites were covered by natural mountain vegetation (phytocenosis), dominated by perennial herbaceous species (*Phlomis, Cousinia, Ferula, Eremurus*). No active agricultural use was observed. These landscape characteristics were considered when interpreting the vertical and lateral patterns of SOC and available phosphorus.

Sampling design

Soil pits were excavated and soil samples were collected during the field campaigns conducted in June-July 2024 (Hisar range) and July 2023 (Turkestan range), during the dry season to minimize short-term moisture variability. The sampling was conducted in two mountainous regions of Uzbekistan – the Hisar and Turkestan ranges – focusing on three subtypes of mountain brown soils: leached, typical, and carbonate. In each range, sampling pits were established according to the

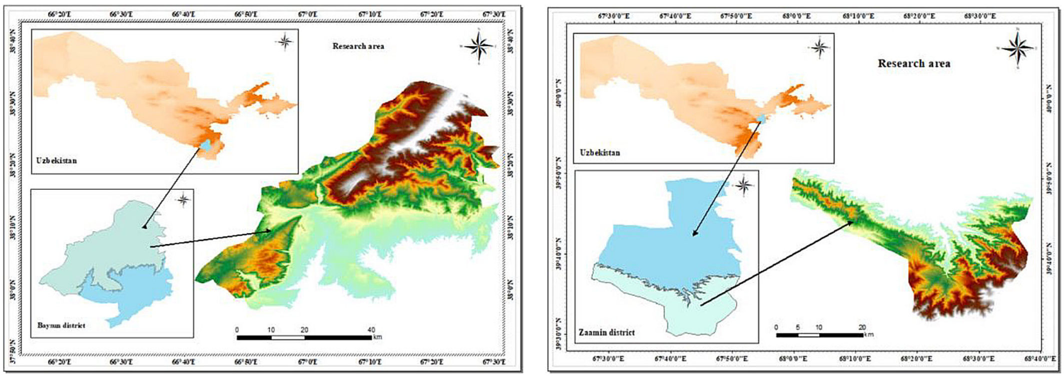

Figure 1. Layout of study sites on the Hisar and Turkestan ranges

main topographic positions of the slope profile: watershed positions (uneroded soils), slope positions (eroded soils), and accumulative surfaces at the foot (reclaimed soils). On the Hisar range, fifteen pits ($n = 15$) were sampled. In the Turkestan range, twelve profiles ($n = 12$) were established. Slope exposure was recorded during field description but was not treated as an independent analytical factor due to limited sample size within individual soil subtypes. Sampling was conducted along genetic horizons (4–6 per profile) to a depth of approximately 80–120 cm, depending on soil subtype and relief position. In total, 27 profiles were examined (15 Hisar and 12 Turkestan), comprising 114 horizons (61 in Hisar and 53 in Turkestan). For interregional comparisons, the upper horizon of each profile was used (n = number of profiles). For vertical differentiation analysis, all horizons were considered (n = number of samples), allowing comparison between upper and deepest horizons while avoiding pseudoreplication.

Laboratory analysis of soils

Air-dried soil samples were homogenized and sieved prior to laboratory analysis. For most analyses, the soil samples were passed through a 1-mm mesh sieve. For total phosphorus determination, the samples were passed through a 2-mm sieve and subjected to acid digestion according to standard procedures.

SOC was determined using the Tyurin wet oxidation method, based on oxidation with potassium dichromate in a sulfuric acid medium. Results were expressed as percentage by weight (%). For reporting purposes, humus content was calculated from SOC using the Van Bemmelen factor (Humus, % = SOC × 1.724). When necessary, SOC values were converted to g/kg (1% = 10 g/kg). This study focused on the concentrations of soil organic carbon (Corg) across different horizons; however, soil organic carbon stocks (measured in Mg C ha^{-1}) were not calculated, since the measurements needed for bulk density and skeletal fraction proportions – essential for accurate stock calculations – were not performed. Hence, the term “content” in this study refers to differences in SOC concentrations between horizons or terrain positions, rather than to stocks. Total nitrogen (N) was determined using the Kjeldahl method and expressed as a mass percentage (%). The pH of the medium was measured potentiometrically in an aqueous suspension with a soil-to-solution ratio of 1:2.5. The available forms of phosphorus and potassium were determined using the Machigin method, which involved extraction with an ammonium carbonate solution. Following this, phosphorus was measured photometrically through the formation of a phosphorus-molybdenum blue complex, and potassium was quantified using flame photometry. The results were expressed as P_2O_5 and K_2O (mg/kg). In this study, the P_2O_5 values represent available phosphorus determined using the Machigin extraction method and expressed in oxide form according to standard agrochemical practice. Here, P_avail was derived from the mobile phosphorus P_2O_5, converted to elemental phosphorus using the equation: P_avail (mg/kg) = 0.43662 × P_2O_5 (mg/kg). The carbonate content was estimated from the CO_2 content (%) using a gasometric method, which measures the volume of CO_2 released during the acid treatment of the sample. All determinations were performed with at least two analytical replicates. If the discrepancy between parallel measurements exceeded the acceptable laboratory criteria, the analysis was repeated. On the basis of the obtained values, stoichiometric parameters, including C:N, C:P_2O_5, and other derived ratios, were calculated. The ratios of C:P_2O_5 and N:P_2O_5 were determined to assess the stoichiometric conditions for agrochemically available phosphorus. These ratios were calculated using mass indices on an oxide basis as follows: C:P_2O_5 = (SOC, g/kg) / (P_2O_5, g/kg) and N:P_2O_5 = (N, g/kg) / (P_2O_5, g/kg). In these equations, SOC (soil organic carbon) and N (nitrogen) were converted from percentage to grams per kilogram (by multiplying by 10), while P_2O_5 was converted from mg/kg to g/kg (by dividing by 1.000). This can also be expressed as: C:P_2O_5 = SOC (%) × 10,000 / P_2O_5 (mg/kg); N:P_2O_5 = N (%) × 10.000 / P_2O_5 (mg/kg). Higher index values indicate a lower concentration of P_2O_5 per unit of carbon (C) or nitrogen (N) and are interpreted as operational indicators of the relative availability of phosphorus in relation to organic matter. This interpretation should be seen as indicative, without making direct assumptions about phosphorus limitation. In this study, it serves as an operational indicator of available phosphorus, rather than a universal stoichiometric equivalent for elemental phosphorus. To assess the vertical differentiation of carbonate content, the ΔCO_2 indicator was employed. This indicator is calculated as the difference between the CO_2 content in the upper and deepest horizons of the soil profile (ΔCO_2 = CO_2(upper) - CO_2(deep)). Negative ΔCO_2 values signify an increase in the carbonate content deeper in the profile. All stoichiometric ratios (C:N, C:P_2O_5, and N:P_2O_5) were calculated separately for each profile or horizon. The tables and accompanying text present the median values of these ratios, rather than the ratios derived from median element concentrations. It is important to note that the C:P_2O_5 and N:P_2O_5 indices should not be interpreted as universal representations of elemental ecological stoichiometry in the traditional sense (C:P). Instead, they serve as operational indicators of the availability of agrochemically accessible phosphorus in organic matter within carbonate mountain soils, where the P_2O_5 index is standardized and comparable across different profiles. The interpretation of these indices is indicative and does not imply any direct conclusions about the physiological limitations of the biota.

Statistical analysis

To compare the characteristics of the upper soil layer between the Hisar (n=15 profiles) and Turkestan (n=12 profiles) ranges, the nonparametric Mann-Whitney test was employed. The paired Wilcoxon test was used to assess vertical differences between the upper soil layer and the deeper soil layer. To analyze associations between parameters, Spearman's rank correlation, with statistical significance set at $p < 0.05$ was applied. Due to the limited number of soil profiles in individual subtypes (n = 4–5), the statistical results were interpreted as indicators of consistent trends and associations rather than definitive quantitative assessments of effects. Nonparametric methods were specifically chosen for this research design. No correction for multiple comparisons was applied, as the analysis aimed to identify consistent patterns of changes in soil organic carbon (SOC), pH, and phosphorus availability within the profiles and across the landscape.

RESULTS

A summary of the characteristics of the upper horizon of mountain-brown soils in the two ranges (SOC, P_2O_5, pH, CO_2, and stoichiometric indices) is presented in Table 1. Detailed comparisons for each soil subtype are given in Table 1.

Mountain brown carbonate soils – in the upper soil layer (along the profiles), the SOC contents did not differ statistically between the ranges: Hisar – 19.84 (18.45–22.39) g/kg (n=5) vs. Turkestan – 15.93 (12.99–20.53) g/kg (n=4); Mann–Whitney test, p=0.413. Available phosphorus (expressed as P_2O_5) in the upper soil layer was higher in Hisar– 29.88 (22.58–32.68) mg/kg, than in Turkestan – 17.30 (16.25–19.70) mg/kg, but the difference was not significant (p=0.190). Moreover, the

Table 1. Soil agrochemical properties and stoichiometric indices in the upper horizon (upper horizon of each profile) of mountain soils in the Hisar and Turkestan ranges.

Soil subtype	n (number of profiles)	SOC (g kg^{-1})	N, %	P_2O_5 (mg kg^{-1})	pH	CO_2, %	C:N	C:P_2O_5	N:P_2O_5
Mountain-brown carbonate soils (Hisar)	5	19.84 (18.45–22.39)	0.294 (0.22–0.36)	29.88 (22.58–32.68)	7.70 (7.70–7.80)	9.10 (8.30–9.60)	6.22 (6.15–6.49)	664	120.50 (101.00–132.90)
Mountain-brown carbonate soils (Turkestan)	4	15.93 (12.99–20.53)	0.13 (0.070–0.165)	17.30 (16.25–19.70)	7.00 (6.97–7.03)	6.49 (4.84–8.31)	12.56 (11.13–14.63)	921	76.32 (60.44–87.44)
Mountain-brown typical soils (Hisar)	5	22.51 (21.81–23.90)	0.36 (0.30–0.43)	36.68 (31.38–36.88)	6.80 (6.80–6.90)	1.80 (1.70–1.90)	6.13 (6.06–6.17)	640.6 (626.5–651.5)	100.1
Mountain-brown typical soils (Turkestan)	4	26.75 (20.38–31.67)	0.29 (0.128–0.415)	22.40 (19.80–24.50)	6.20 (6.20–6.20)	0.80 (0.79–0.80)	8.91 (8.39–9.55)	1189.0 (1013.1–1290.8)	134.0
Mountain-brown leached soils (Hisar)	5	25.81 (23.84–27.61)	0.4 (0.32–0.48)	25.88 (19.38–28.28)	6.80 (6.80–6.90)	Not determined	6.38 (6.28–6.44)	997	155.60 (153.00–201.20)
Mountain-brown leached soils (Turkestan)	4	30.52 (23.78–39.69)	0.32 (0.23–0.42)	46.45 (44.77–47.65)	6.25 (4.79–6.33)	Not determined	9.95 (9.59–10.44)	657	70.31 (56.11–84.55]

Note: Values are presented as median (interquartile range, IQR). n represents the number of soil profiles in each subtype. Units are given in parentheses. P_2O_5 represents available phosphorus expressed in oxide form.

pH was higher in Hisar – 7.70 (7.70–7.80) compared to Turkestan – 7.00 (6.97–7.03), p = 0.017. No differences in the carbonate content (CO_2, %) were found in the upper layer: Hisar – 9.10 (8.30–9.60) %, Turkestan – 6.49 (4.84–8.31) % (p = 0.219). The C:N ratio for the surface horizon (upper boundary 0 cm) was higher in Turkestan – 12.56 (11.13–14.63) compared to Hisar – 6.22 (6.15–6.49), p = 0.016. In both ranges, a decrease in SOC and available phosphorus (expressed as P_2O_5) with depth was observed, while pH and CO_2 increased; with a small number of pairs, statistical significance most often manifested itself as a trend (Wilcoxon: p=0.062 for Hisar and p=0.125 for Turkestan). The decrease in the proportion of available phosphorus along the profile was more pronounced in Hisar: ΔP_avail_frac = 0.0040 (0.0030–0.0048) versus 0.0017 (0.0012–0.0019) in Turkestan (p=0.049). The N:P_2O_5 index in the upper layer was also higher in Hisar – 120.50 (101.00–132.90) compared to Turkestan – 76.32 (60.44–87.44), p=0.032 (Figure 2).

Typical mountain-brown soils – in the upper soil layer, the SOC content did not differ statistically between the ranges: Hisar – 22.51 (21.81–23.90) g/kg (n=5) vs. Turkestan – 26.75 (20.38–31.67) g/kg (n=4), p=0.556. Moreover, available phosphorus (expressed as P_2O_5) in the upper layer was higher in Hisar– 36.68 (31.38–36.88) mg/kg compared to Turkestan – 22.40 (19.80–24.50] mg/kg, the difference is significant (p=0.016). In Turkestan, a higher C:N ratio was observed for the surface horizon – 8.91 (8.39–9.55) compared to Hisar – 6.13 (6.06–6.17), p=0.016. The C:P_2O_5 index in the upper layer was higher in Turkestan 1189.0 (1013.1–1290.8), compared to Hisar – 640.6 (626.5–651.5); p=0.032. The proportion of available P was also higher in Hisar – 0.0102 (0.0091–0.0105) compared to Turkestan – 0.0063 (0.0058–0.0066), p=0.016. Along the profile, SOC and P_2O_5 decreased with depth, and pH – 6.80 (6.80–6.90) vs. 6.20 (6.20–6.20) in the upper layer; p=0.013 and CO_2 – 1.80 (1.70–1.90) % vs. 0.80 – (0.79–0.80) %; p=0.019 increased; Wilcoxon paired tests for vertical changes most often yield the following: p=0.062 (Hisar) and p=0.125 (Turkestan) (Figure 3).

Leached mountain–brown soils – in the upper layer, SOC did not differ statistically between the ranges: Hisar – 25.81 (23.84–27.61) g/kg (n=5 vs. Turkestan – 30.52 (23.78–39.69) g/kg (n=4), p=0.556. Available phosphorus (expressed as P_2O_5) in the upper layer was higher in Turkestan– 46.45 (44.77–47.65) mg/kg compared to Hisar – 25.88 (19.38–28.28) mg/kg, p=0.016. The C:N ratio for the surface horizon was higher in Turkestan – 9.95 (9.59–10.44) vs Hisar – 6.38 (6.28–6.44), p=0.016. Index N:P_2O_5 in the upper layer was higher in Hisar – 155.60 (153.00–201.20) compared to Turkestan – 70.31 (56.11–84.55), p = 0.016. In the upper layer, pH was higher in Hisar – 6.80 (6.80–6.90) compared to Turkestan – 6.25 (4.79–6.33), p = 0.019. The increase in the carbonate content with depth, calculated as $\Delta CO_2 = CO_2$ (upper) – CO_2 (deepest), was more pronounced in Hisar (i.e. ΔCO_2 is more negative) compared to Turkestan: –7.90 (–8.60–7.90) vs –1.55 (–1.69–1.25) in Turkestan, p=0.019 (negative ΔCO_2 values reflect an increase in the carbonate content with depth). Correlation analysis by horizons within subtypes showed that in all six samples, SOC was positively related to P_2O_5 (ρ=0.851–0.959; p<0.001) and negatively related to pH (ρ=–0.892…–0.313; p<0.05) and CO_2 (ρ=–0.940…–0.487; p<0.05). In general, with comparable SOC levels in the upper layer, differences between the ranges were more often manifested in the acid-base balance and phosphorus

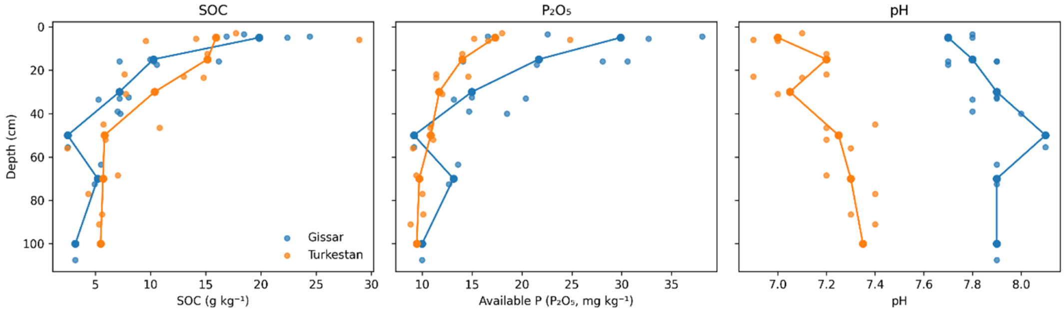

Figure 2. Vertical distribution of SOC (g kg^{-1}), available phosphorus (P_2O_5, mg kg^{-1}) and pH along soil profiles of mountain-brown carbonate soils sampled at watershed, slope and footslope landscape positions in the Hisar and Turkestan ranges

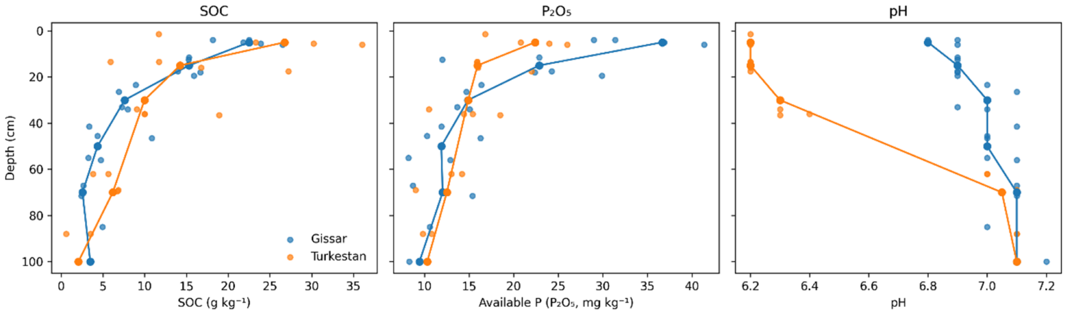

Figure 3. Vertical distribution of SOC (g kg^{-1}), available phosphorus (P_2O_5, mg kg^{-1}) and pH along soil profiles of typical mountain-brown soils sampled at watershed, slope and footslope landscape positions in the Hisar and Turkestan ranges

availability: in Hisar, the upper layer is generally more alkaline, and for individual subtypes (typical and leached), contrasting levels of P_2O_5 and associated C:P_2O_5 and N:P_2O_5 indices were observed. In the "phosphorus block" differences depend on the subtype: typical soils of the Turkestan range exhibit a higher C:P_2O_5 ratio (less available P per unit of SOC), while leached soils of the Turkestan range, conversely, have a significantly higher P_2O_5 (and therefore a lower C:P_2O_5 ratio). The profile contrast in available P and the carbonate content varies between ranges and may create different preconditions for SOC stabilization in mineral horizons (Figure 4).

DISCUSSION

It is important to clarify that this study focused on analyzing soil organic carbon concentrations, rather than carbon stocks, as the data on bulk density and skeletal fraction content were unavailable. Consequently, the discussion regarding the impacts of erosion and accumulation primarily relates to the chemical and stoichiometric conditions in soil horizons, rather than providing a quantitative assessment of carbon balance at the landscape level.

The results indicate that although the concentrations of soil organic carbon in the upper horizon of mountain-brown soils are comparable between the Hisar and Turkestan ranges, the regions exhibit notable differences in phosphorus (P_2O_5) availability, acid-base balance, and related stoichiometric indices (C:P_2O_5 and N:P_2O_5). This aligns with the current understanding that the SOC content and its stabilization are influenced by various factors, particularly in mountain ecosystems. Similar patterns have been reported in mountain ecosystems, where soil chemical properties, including pH and phosphorus availability, are considered important regulators of SOC distribution (Djukic et al., 2010; Mayor et al., 2017). In carbonate soils, increasing pH has been shown to influence phosphorus solubility and nutrient interactions (Penn and Camberato, 2019; Spohn, 2024). The obtained findings are consistent with these conceptual frameworks and provide additional regional evidence from Central Asian mountain soils.

Many studies on altitudinal gradients and different mountain systems have demonstrated a similar disparity between SOC stocks/concentrations and the conditions necessary for its stability. For instance, Djukic et al. (2010) and Mayor et al. (2017) found that an increase in SOC with altitude does not always correlate with increased stability. Chemical and nutrient limitations can counteract the impact of climate. The obtained data contribute to these findings, highlighting that phosphorus availability can be a significant chemical constraint, even when the SOC levels are similar.

Vertical stoichiometric patterns along soil profiles

Across all soil subtypes, a consistent decrease in soil organic carbon and available phosphorus (expressed as P_2O_5) was observed with increasing profile depth, while pH and carbonate content increased. Similar vertical trends have been widely reported for mountain and foothill soils, reflecting fundamental processes in the pedogenesis of phosphorus and organic carbon. The classic model proposed by Walker and Syers (1976) describes the evolution of phosphorus in soil as a transition from mobile forms to fixed and

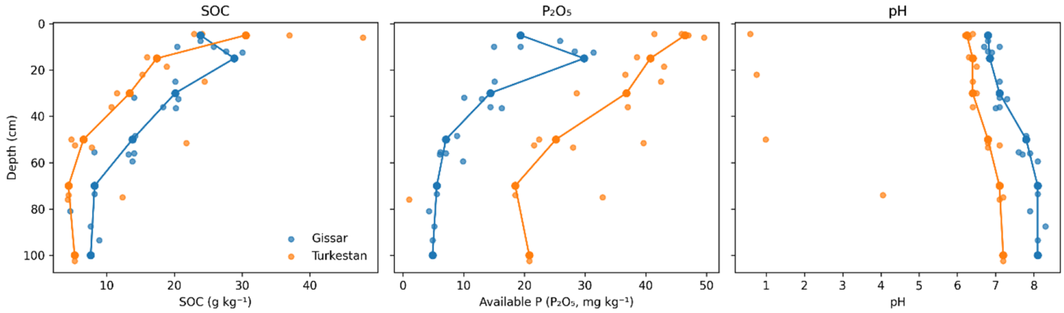

Figure 4. Vertical distribution of SOC (g kg^{-1}), available phosphorus (P_2O_5, mg kg^{-1}) and pH along the soil profiles of the leached mountain brown soils sampled at watershed, slope and footslope landscape positions in the Hisar and Turkestan ranges

occluded forms as the soil profile develops. The obtained findings support this model, particularly in carbonate soils, where rising pH and calcium carbonate ($CaCO_3$) content lead to decreased phosphate solubility and a reduction in the proportion of available phosphorus (Penn and Camberato, 2019). The more significant decline in the proportion of available phosphorus along the profile in the Hisar range soils suggests increased chemical limitations on phosphorus availability, which may hinder microbial recycling of organic matter and the formation of stable organomineral forms of SOC in deeper horizons. The influence of phosphorus availability on soil organic carbon is nonlinear and depends on various contexts. A short-term increase in phosphorus availability can enhance mineralization, but over the long term, changes in stoichiometry and organic matter transformation pathways can differently affect the formation of stable SOC pools.

Regional differences between the Hisar and Turkestan ranges

Despite comparable climatic conditions and soil subtypes, the soils in the Hisar and Turkestan ranges show consistent differences in pH, carbonate content, and available phosphorus (expressed as P_2O_5). The differences in available phosphorus vary by soil subtype: in typical soils, the P_2O_5 levels are higher in Hisar, while in leached soils, the P_2O_5 levels are higher in Turkestan. Similar regional contrasts have also been observed in other mountain systems, including Central Asia and the Tibet Plateau. In these areas, carbonate substrates and alkaline pH significantly limit phosphorus availability, despite relatively high total phosphorus stocks (Yang et al., 2013). The obtained data support the idea that soil chemistry – specifically pH and carbonate content – may have a more significant impact on SOC stoichiometric conditions than the formal classification of soil subtypes. The carbon to nitrogen (C:N) ratio in the upper horizon of soils across all subtypes was found to be higher in the Turkestan range compared to the Hisar range. In the context of the ecostoichiometric approach, high C:N values typically indicate a lower degree of microbial processing of organic matter or a greater presence of nitrogen-poor organic inputs. Global syntheses suggest that mineral-associated organic matter is generally enriched in nitrogen and phosphorus compared to plant detritus. This enrichment is likely due to the selective sorption of nitrogen- and phosphorus-containing compounds onto mineral surfaces (Tipping et al., 2016; Lavallee et al., 2020; Spohn, 2024). The lower C:N ratios observed in Hisar soils, along with higher nitrogen to phosphorus ($N:P_2O_5$) ratios, may signify more pronounced microbial transformation of organic matter and a greater influence of stoichiometric phosphorus limitations. Within specific soil subtypes (by horizon), a consistent positive relationship was identified between soil organic carbon and phosphorus (P_2O_5), while negative relationships were observed with pH and carbonate content. Similar patterns have been documented in studies of mountain soils and eroded slopes, where the distribution of SOC is closely linked to phosphorus redistribution and changes in the chemical environment (Zhang et al., 2006; Nadeu et al., 2012).

Implications for SOC stabilization and nutrient cycling

It is important to highlight that the identified correlations should not be seen as direct cause-and-effect relationships. Instead, they reflect the combined effects of soil formation processes, landscape transport, and the chemical limitations affecting phosphorus availability. This perspective aligns with contemporary views that consider soil organic carbon stability as a systemic property of the ecosystem, rather than solely a result of the chemical "refractoriness" of organic matter (Schmidt et al., 2011; Lehmann and Kleber, 2015).

Mountain soils develop under the influence of both vertical and lateral processes. Erosion and accumulation contribute to the redistribution of SOC and nutrients along slopes, resulting in varying stoichiometric conditions (Van Oost et al., 2012; Doetterl et al., 2016; Berhe et al., 2018).

The findings of this study are consistent with previous research conducted in mountain and high-altitude landscapes, which indicates that the transport and burial of soil materials can exacerbate chemical limitations in phosphorus availability. This, in turn, influences the conditions for SOC stabilization (Zhang et al., 2006; Nadeu et al., 2012). These results confirm that the landscape context is a crucial factor in shaping SOC stoichiometric conditions, alongside soil formation processes and climate.

It is important to note that the differences found in stoichiometric indices and phosphorus availability should not be interpreted as direct evidence of limitations on microbial processes or actual stabilization of soil organic carbon. Rather, these relationships reflect a combination of pedogenetic, geochemical, and landscape factors that influence the chemical conditions for processing organic matter. Therefore, the parameters used in this study should be regarded as indicators of potential limitations, rather than direct mechanistic drivers of SOC dynamics.

These results reinforce the significance of stoichiometric limitations in SOC accumulation and stabilization in mountain soils, highlighting the importance of available phosphorus and the acid-base balance of soil. However, the limitations of this study should be acknowledged, particularly the relatively small number of profiles per subtype and the use of P_2O_5 as an operational indicator of available phosphorus.

In conclusion, the sample size in this study (n=4–5 profiles per subtype) restricts the generalization of the results. Nonetheless, considering the difficulty of accessing high-altitude areas and the labor-intensive nature of detailed layer-by-layer analyses, the data collected are valuable as a pilot assessment. The patterns identified – specifically the relationships between SOC, pH, and phosphorus – are statistically significant ($p<0.05$) and align with global trends documented for mountain soils (as referenced by Djukic et al., 2010; Mayor et al., 2017). This underscores the reliability of the observed patterns, despite the limited number of replicates.

A comparison of the obtained data with the findings from other studies indicates that the identified patterns align well with the current understanding of how phosphorus, pH, and landscape processes contribute to spatial heterogeneity of SOC in mountain ecosystems.

From a practical perspective, the stoichiometric parameters obtained can be incorporated into an operational framework for assessing the condition of mountain soils. High ratios of carbon to phosphorus ($C:P_2O_5$) and nitrogen to phosphorus ($N:P_2O_5$), when combined with high pH and carbonate content, may suggest the areas where phosphorus is limiting for organic matter transformation processes. These areas should be prioritized for monitoring and for planning restoration and management measures within mountain ecosystems.

CONCLUSIONS

In the mountainous brown soils of the Hisar and Turkestan ranges, both regions exhibit similar concentrations of soil organic carbon in the upper horizon. However, the primary differences between the regions are seen in the available phosphorus (P_2O_5) content, the acid-base balance, and associated stoichiometric indices ($C:P_2O_5$ and $N:P_2O_5$). These differences suggest variations in soil chemical conditions that may influence the content and stabilization of organic carbon.

All soil subtypes demonstrate significant vertical differentiation: as soil profile depth increases, both SOC and available phosphorus (expressed as P_2O_5) decrease, while pH and carbonate content rise. Additionally, the proportion of available phosphorus relative to total phosphorus declines, reflecting heightened chemical constraints on phosphorus availability in the mineral horizons.

The reduction in the proportion of available phosphorus is particularly pronounced in the soils of the Hisar range, especially within carbonate subtypes. This suggests that phosphorus-limiting conditions may be more severe for processes related to the transformation and fixation of organic matter in the deeper soil layers.

Interregional differences in stoichiometric parameters vary according to soil subtype. Typical soils of the Turkestan range are associated with higher $C:P_2O_5$ values, while the leached soils in Turkestan tend to have a greater supply of available phosphorus. This highlights that the impact of phosphorus on SOC is context-dependent.

The consistent positive relationship between soil organic carbon and available phosphorus (expressed as P_2O_5), along with the negative relationships between SOC and both pH and carbonate content, observed in various soil subtypes, highlights the combined influences of pedogenetic, geochemical, and landscape processes on the spatial variation of SOC in mountain ecosystems.

These findings confirm the effectiveness of the stoichiometric approach in interpreting SOC distribution patterns in mountain soils. Additionally, they indicate that indicators of available phosphorus and acid-base balance can serve as valuable tools for assessing the conditions that promote the potential stabilization of organic carbon.

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