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ORIGINAL ARTICLE

Soil Properties and Stoichiometry as Influenced by Land Use, Enclosures and Seasonality in a Semi-arid Dryland in Kenya

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Abstract

Agropastoralism and nomadic pastoralism constitute the main land use systems in semi-arid drylands in Kenya. However, limited studies have investigated how land use and management practices and seasonality affect soil properties that alter C, N, and P biogeochemical cycling in African drylands systems. Thus, this study was conducted to determine effects of: (1) sedentary agropastoral land-use system (SAL), (2) semi-nomadic pastoral land-use system (SNL)), (3) pasture enclosures and (4) seasonality on selected soil chemical properties and total C, N, and P stoichiometry in a semi-arid landscape in Kenya. Land use, enclosures, and seasonality affected chemical properties of soils and C, N, and P stoichiometry. Generally, Na, K, Ca, Mg and cation exchange capacity were higher in the dry than wet period. Soil C:N ratios were less than 5, while N:P and C:P ratios were 5–56 and 16–177, respectively. However, ratios of C:N, N:P and C:P were significantly higher in SNL than SAL. The C:P and N:P ratios in both land use systems were highly correlated ($r^2 > 0.70$). During the wet season, C:N ratios of soils were higher inside enclosures in both land uses. Higher soil N:P and C:P ratios were observed during dry compared to wet seasons. The N:P and C:P ratios of soils were higher inside and outside enclosures in SAL and SNL, respectively. Land use, enclosures and seasonality exhibited different effects on chemical properties of soils and C:N:P stoichiometry ratios. Perennial vegetation cover in enclosures has a great potential to enhance soil health necessary to support pastoral land-use systems in semi-arid African drylands.

Keywords Enclosures · Grasses · Pastoralism · Rangelands · Restoration · Soil Health

1 Introduction

African pastoral systems sustain livelihoods of approximately 100 million people and contributes on average 40% of the regions' agricultural GDP, largely in form of meat for both local markets and exports (Semplici and Campbell 2023). In the eastern African drylands, pastoralism remains a key and economically viable land use system (Davies et al. 2015). It is broadly characterized by varying aspects of production forms and strategies including mobility and sedentarization, livestock diversity, reliance of livestock for food and revenue, and is a major production system in arid and semi-arid regions in Kenya. In Kenya, drylands support an estimated 30% of the human population, 70% of livestock (cattle, goats, sheep and camels) and most of the wildlife (Amwata et al. 2016).

Livestock production constitutes the major economic activity among pastoralists who occupy 75% of the arid and semi-arid lands and own 80% of sheep and goats and 60% of cattle (Amwata et al. 2016). These contribute about 10%

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of Kenya's gross domestic product (GDP) (Amwata et al. 2016; Nyariki et al. 2009). These drylands are often characterized by threshold dynamics that alternate between different highly resilient and stable states. Moreover, pastoralists inhabiting these resilient ecosystems have a detailed understanding of their grazing land environment, gained through experienced herding and augmented by wealth of knowledge gained from past land use (Angassa and Oba 2008). However, interaction of heavy livestock grazing in marginal areas and climate variability that typify African drylands can cause massive land degradation in the absence of effective governance system.

Overgrazing often results from a complex interaction of increased livestock numbers, limited grazing land, depletion of vegetation cover, curtailed mobility mainly due to agricultural expansion into semi-arid rangelands, fragmentation of grazing areas and water development e.g. inappropriate citing of watering points leading to sedentarization (Kimiti et al. 2018). Converting semi-arid rangeland ecosystems for agricultural use has been cited in many studies as a contributing factor to soil degradation attributed to a large decrease in C additions in soil, fast mineralization of soil organic matter (SOM) and soil erosion (Mganga and Kuzyakov 2014). Degraded soils negatively affect livelihoods and the production and supply of important ecosystem goods and services, e.g. water, the most limiting resource in the drylands. Soil degradation is the most evident form of land degradation in the Kenyan arid and semi-arid drylands. Physical (e.g. compaction due to grazing livestock hoof action, erosion (wind and water)), biological (e.g. loss of soil biodiversity) and chemical (e.g. depletion of SOM and fertility) are the major forms of soil degradation in these dryland ecosystems.

Rangeland enclosures, representing grazing areas closed off from livestock for a specific period, have been used by pastoralists as a way of responding to the scarcity of forage both in quantity and quality, especially for vulnerable livestock classes e.g. newly born calves, sick and weak animals, especially during the lean dry seasons. These enclosures provide a considerable plant species diversity (Angassa and Oba 2010). They also present an excellent chance to establish a resource management system that is more intensive, communal and mimics traditional wet–dry season grazing patterns common in African drylands (Angassa and Oba 2008). Additionally, enclosures are renowned for rehabilitation and restoration of degraded dryland ecosystems. This is because enclosures enhance biodiversity, soil health and increases water availability and reduces soil loss through erosion (Verdoodt et al. 2010).

Cycling of soil N and P in terrestrial ecosystems are closely linked to C cycling, mainly via impacts connected to primary production of C in ecosystems. Land use and associated management strategies in African semi-arid rangelands negatively impacts soil structure and properties that change C, N, and P cycling and ecosystem processes and regulate ecosystem nutrient pools within the vegetation-soil system (Pabst et al. 2013; Mureithi et al. 2014Mganga et al. 2016). This has major implications for relevant biogeochemical processes of C and nutrients in African semi-arid rangelands.

The C:N ratio in soils is a very good indicator of the potential source of organic matter (OM), its state of decomposition and possible contribution to soil health. High C:N ratios (>25) is indicative of faster SOM accumulation than decomposition, between 12 and 16 demonstrate significant breakdown of SOM and below 10 suggest rapid mineralization and increased N availability (Bui and Henderson 2013). High (C:P >300) and low (C:P <200) soil C:P ratios suggest net immobilization and mineralization effect on P in soil by bacteria, respectively (Zhang et al. 2014). Soil C:P ratio in the range of 200 and 300 suggest minimal changes in available P (Bui and Henderson 2013). N:P ratio in soils is particularly sensitive to fertilization (Peñuelas et al. 2012). This is because increased N deposition e.g. via livestock manure, can change availability of nutrients or transform fragile systems to P-limitation (N:P >16) from N-limitation (N:P <14) or to both N and P co-limitation (Sardans et al. 2012; Shen et al. 2019).

Despite the adoption of rangeland enclosures among pastoralists inhabiting semi-arid drylands in Kenya, few studies have investigated how land use, enclosures and seasonality affect chemical properties of soils and C, N and P stoichiometry. Subsequently, our knowledge and understanding of how land use, rangeland enclosures and seasonality affect soil properties and ecosystem functioning in these dryland systems is limited. Thus, the main objective of this study was to investigate and better understand land use effect (semi-nomadic pastoral land-use system (SNL) and sedentary agro-pastoral land-use system (SAL)), enclosures and seasonality (wet and dry season) on soil properties (pH, CEC, K, P, Ca, Na, Mg, C, N, P,) and soil stoichiometric ratios (i.e. C:N, C:P, and N:P) in a typical semi-arid landscape in northern Kenya.

2 Materials and Methods

2.1 Study Area, Site Selection and Soil Sampling

The study was set-up and conducted in the semi-arid Njemps Flats, Baringo County, Kenya. Njemps flats range unit, covers an area of approximately 305 km^2 and located in agro-climatic zones IV and V, between latitude 00º 30N and longitude 36º 00E (Fig. 1). Rainfall is spatiotemporally unreliable, low and erratic (Kipkorir 2002). On average, the Njemps Flats rises to an altitude of 900 m and receives between 300 and 700 mm annual rainfall spread over two seasons (Karaya et al. 2021). The monthly rainfall

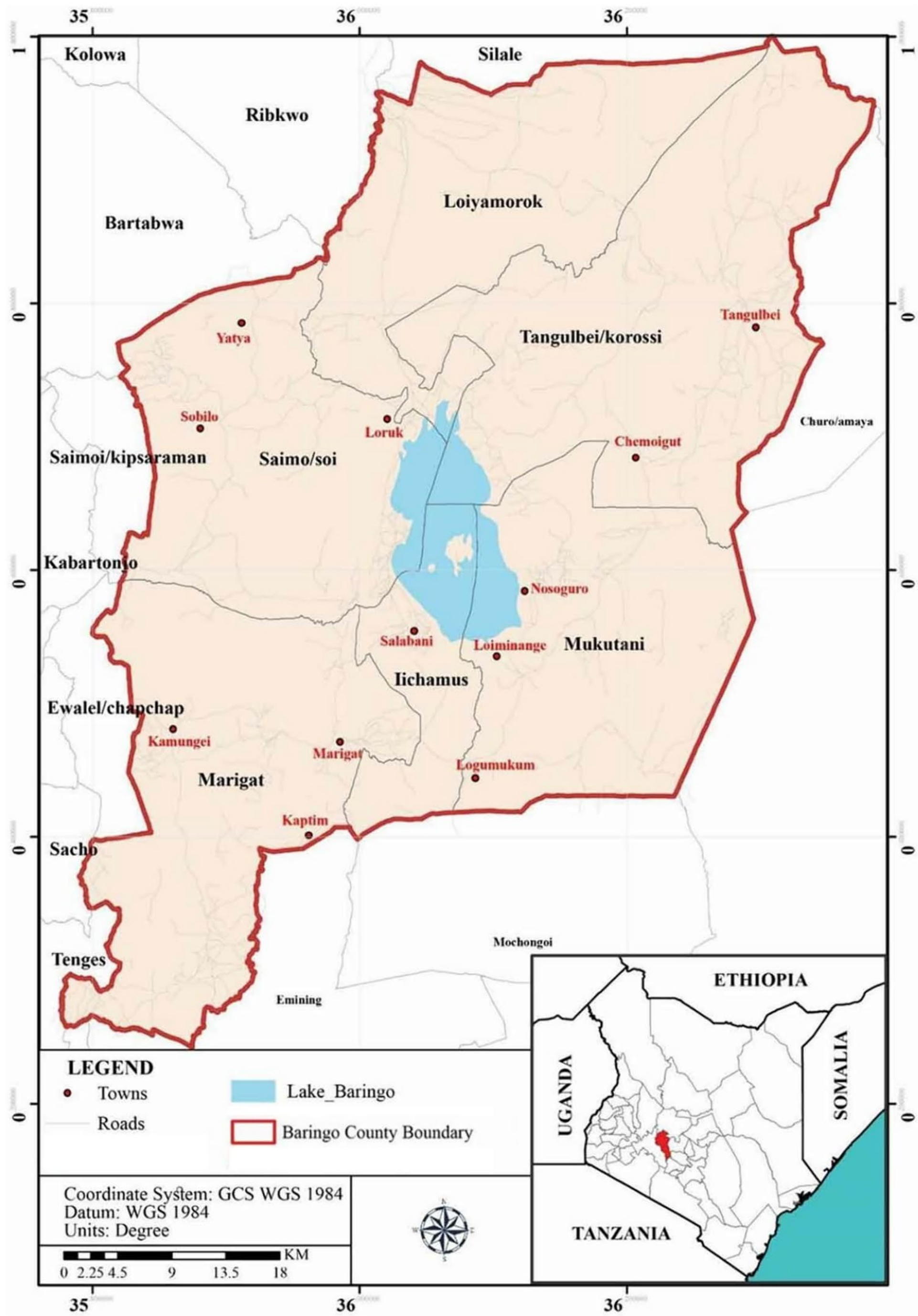

Fig. 1 Map of the study area, Baringo County, Kenya

distribution pattern is bimodal with short rains (SR) in October–November and long rains (LR) in April–August. Two major peaks characterize the long rains, one in April–May and the other one in July–August. Njemps Flats is characterized by hot and dry climate, with average minimum temperature of 20 °C and maximum temperature of 35 °C (Kaimba et al. 2011).

Soils have a low organic matter content with a shallow silt loam to clay loam texture. The soils are closely linked to alluviums and sedimentary lake deposits and often very stony in steep areas (Verdoodt et al. 2010). They have a weakly developed structure including Eutric or Calcaric Cambisols and Eutric or Calcaric Fluvisols, with few sodic phases (Snelder and Bryan 1995). The clay loam textures soils are normally formed on old (Pliocene) rocks of volcanic origin. The relatively fertile soils of coarser loam and clay occur in the very flat southeastern parts of Lake Baringo.

Major vegetation types are woodlands dominated by leguminous *Acacia* species, permanent Loboi swamp dominated by *Cyperus papyrus,* a shrub grassland and grassland that is seasonally flooded (Mureithi et al. 2014). *Acacia reficiens* and *A. mellifera* bushland with some colonization of *A. nubica* dominate the perennial woody vegetation. The northern part of the Njemps Flats and riverine areas are predominantly covered by semi-deciduous woodland vegetation. Along the riparian and flatter areas are dominated by the tall *A. tortilis* and *A. xanthophloea* trees. *Prosopis juliflora* is the most common exotic species in the area (Karaya et al. 2021). Sedentary agro-pastoral land-use system (SAL) and semi-nomadic pastoral land-use system (SNL) are the key land-use systems in the Njemps flats.

The main land-use practice and system in the study area is livestock production categorized into two pastoral land-use systems i.e. (1) semi-nomadic pastoral land-use system (SNL) and (2) sedentary agro-pastoral land-use system (SAL). The SNL is dominant on the northern part of Njemps Flats and is characterized by extensive livestock rearing based on strategic and flexible herd mobility. The SAL, dominant on the southern parts of Njemps Flats, is characterized by combined livestock rearing and crop cultivation by sedentary agropastoralists. Maize is the main and most productive crop, though more susceptible to drought than sorghum and millet which were the dominant crop pre-colonial period. The Marigat-Loruk road in the area was used to lay down a belt transect traversing the two pre-determined sites (SNL and SAL), where soil sampling was conducted.

Six enclosures within the belt transect were selected in each land-use system. These were statistically representative of the enclosures in the study area. Each enclosure was paired with an adjacent open plot to allow comparison of soil attributes. The paired plots were radiating southwards and northwards from the centre of each of the two land-use sites. Thus, a total of twelve pairs (open and closed plots, 2 acres) were sampled during the study period. Soil sampling was done at 0–30 cm depth at four points in each of the six paired plots, inside and outside the enclosures, in the two sites (SNL and SAL). Soils were sampled at the peak of the wet (April) and dry (January) seasons, and at the end of wet (June) and dry (February) seasons. A summary of the rainfall amount and seasons corresponding to the sampling period during the study period is as presented in Fig. 2.

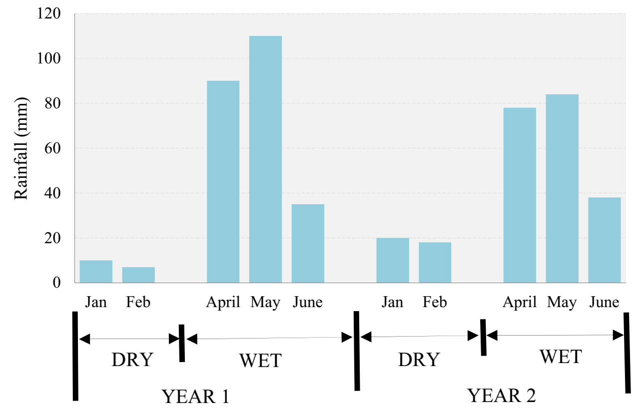

Fig. 2 Summary of the bimodal seasonal rainfall pattern (wet and dry) during the study period

2.2 Laboratory Chemical Analyses of Soil Samples

Air dried soil samples were used for chemical analyses. Soil pH was measured in Milli-Q water (ratio of 1:2.5) using a pH meter. The exchangeable ions (Na^+, K^+, Ca^{2+} and Mg^{2+}) were measured using atomic absorption spectrophotometry (Ca^{2+} and Mg^{2+}) and flame photometry (Na^+ and K^+) after extraction of the soils with a natural ammonium acetate ($NH_4CH_3CO_2$) solution. Total N and P were determined by digestion followed by colorimetry. The Walkley–Black Method was used to determine total C.

2.3 Statistical Analysis

The normality and homogeneity of variance were checked by the Shapiro–Wilk test ($P > 0.05$) and Levene test ($P > 0.05$) before statistical analysis, respectively. Factorial analysis of variance (ANOVA) was used to determine the differences in the measured soil characteristics as influenced by land-use systems (SNL and SAL), enclosures (inside and outside), and seasonality (wet and dry seasons). Significant differences of means at ($P < 0.05$ significance level) between treatments were compared using paired t-test (Stat Soft. STATISTICA. V 10.0.). We used linear regression analysis to understand how soil pH and CEC affect C, N and P stoichiometry. Pearson's correlation analyses were conducted to explore relationships between C, N, P and stoichiometric ratios C:N, C:P and N:P.

3 Results

3.1 Land Use, Enclosures and Seasonality Effect on Soil pH

Soil pH in both land use systems ranged between 8.47 ± 0.16 and 8.73 ± 0.18 (Table 1). Soil pH was significantly ($P < 0.05$) influenced by season (wet and dry) both in SNL and SAL. In SNL, soil pH values were higher in the dry than wet season. However, in SAL, soil pH was much higher in the wet than the dry period. In SNL, lowest pH value was 8.47 ± 0.16 inside the enclosure during the wet season and highest pH was 8.70 ± 0.19 outside the enclosure during the dry season (Table 1). In SAL, lowest pH value was outside enclosures during the dry season (8.47 ± 0.16), while the

Table 1 Soil chemical characteristics depending on land use, seasonality and enclosure in a typical semi-arid dryland environment in Kenya

Land use	Season	Enclosure	pH	CEC (me/100 g soil)	Sodium (mg g^{-1} soil)	Potassium (mg g^{-1} soil)	Calcium (mg g^{-1} soil)	Magnesium (mg g^{-1} soil)	Ca:Mg ratio
SAL	Wet	IN	8.73 ± 0.2	30.33 ± 3.1	0.43 ± 0.1	0.39 ± 0.04	4.57 ± 0.69	0.50 ± 0.11	11.26 ± 3.8
SAL	Wet	OUT	8.60 ± 0.2	27.37 ± 6.3	0.37 ± 0.2	0.31 ± 0.03	4.15 ± 0.31	0.54 ± 0.11	10.01 ± 4.9
SAL	Dry	IN	8.55 ± 0.2	33.90 ± 4.8	0.58 ± 0.1	0.57 ± 0.12	5.18 ± 0.88	1.44 ± 0.55	7.17 ± 4.3
SAL	Dry	OUT	8.47 ± 0.3	30.03 ± 4.9	0.47 ± 0.2	0.85 ± 0.31	5.49 ± 0.04	1.51 ± 0.60	8.77 ± 5.4
SNL	Wet	IN	8.47 ± 0.2	30.87 ± 4.2	0.17 ± 0.1	1.33 ± 0.52	3.18 ± 0.33	1.04 ± 0.32	4.37 ± 1.4
SNL	Wet	OUT	8.52 ± 0.2	26.97 ± 3.6	0.20 ± 0.1	1.08 ± 0.40	2.56 ± 0.34	1.10 ± 0.36	3.53 ± 1.4
SNL	Dry	IN	8.60 ± 0.2	31.23 ± 3.8	0.15 ± 0.1	2.05 ± 0.32	3.22 ± 0.50	1.66 ± 0.14	1.99 ± 0.3
SNL	Dry	OUT	8.70 ± 0.1	26.00 ± 2.1	0.26 ± 0.1	1.19 ± 0.37	2.87 ± 0.41	1.66 ± 0.37	2.73 ± 0.6

Where SAL represents sedentary agro-pastoral land-use system and SNL semi-nomadic pastoral land-use system. Values represent means ± SE

highest value was inside enclosures during the wet season (8.73 ± 0.18).

3.2 Land Use, Enclosures and Seasonality Effect on Potassium and Sodium

Potassium content in soils was much higher ($P < 0.05$) in SNL, ranging between 1.19 and 2.05 mg g^{-1} soil, compared to SAL with between 0.31 and 0.85 mg g^{-1} soil. Moreover, in SNL, K content was much higher inside than outside pasture enclosures in both dry and wet seasons. In SNL, K content inside pasture enclosures ranged between 1.33 and 2.05 mg g^{-1} soil compared to 1.08 and 1.19 mg g^{-1} soil outside enclosures. In both land use systems, K content was lower during the wet than dry season (Table 1).

Conversely, significantly higher amounts of Na were observed in soils under SAL (0.37–0.58 mg g^{-1} soil) compared to SNL (0.15–0.26 mg g^{-1} soil). Sodium content was higher inside than outside pasture enclosures in SAL but not in SNL. Seasonality i.e. wet and dry seasons did not have a significant effect ($P > 0.05$) on Na content inside and outside pasture enclosures in the studied land use systems (Table 1).

3.3 Land Use, Enclosures and Seasonality Effect on Calcium and Magnesium

Calcium content was higher in SAL than SNL and higher in dry than wet season in both land use systems (Table 1). Significantly higher ($P < 0.05$) values between dry and wet season were observed in SAL but not in SNL (Table 1). Generally, Ca content was higher inside enclosures in both land use systems. Both land use systems displayed significantly higher Mg content in dry than wet season. Generally, Mg content was higher in SNL compared to SAL. The Ca:Mg ratios were higher in SAL (4.53–11.26) than in SNL (1.78–5.94) and also higher in the wet compared to the dry season (Table 1).

3.4 Land Use, Enclosures and Seasonality Effect on Cation Exchange Capacity (CEC)

Cation exchange capacity ranged between 27 and 40 me/100 g soil and 26 and 31me/100 g soil in SAL and SNL, respectively (Table 1). Generally, in both SNL and SAL, CEC was higher inside than outside enclosures in dry and wet seasons. However, CEC values were not significantly different ($P > 0.05$) between seasons and inside and outside of enclosures. In both land use systems, higher CEC values were largely observed during the dry than wet season.

3.5 Land Use, Enclosures and Seasonality Effect on Carbon, Nitrogen and Phosphorus

Land use, enclosure and seasonality effect on total soil C, N and P are as shown in Fig. 3. Total soil C content was comparable inside and outside enclosures but was higher in SNL (4.88–6.73 mg g^{-1} soil) than SAL (4.13–4.78 mg g^{-1} soil). Total soil N content was 2.12–3.52 mg g^{-1} soil in SAL and 1.48–2.30 mg g^{-1} soil in SNL and mostly higher inside than outside enclosures. Total soil P ranged between 0.28 and 0.33 mg g^{-1} soil and 0.05 and 0.14 mg g^{-1} soil in SAL and SNL, respectively. Total P content in SAL was comparable inside and outside enclosures but was higher during the wet than dry season.

3.6 Land Use, Enclosures and Seasonality Effect on Total Soil C, N and P Stoichiometry

Land use, enclosure and seasonality effect on soil C:N, N:P and C:P ratios are as shown in Fig. 4. Soil C:N, N:P and C:P

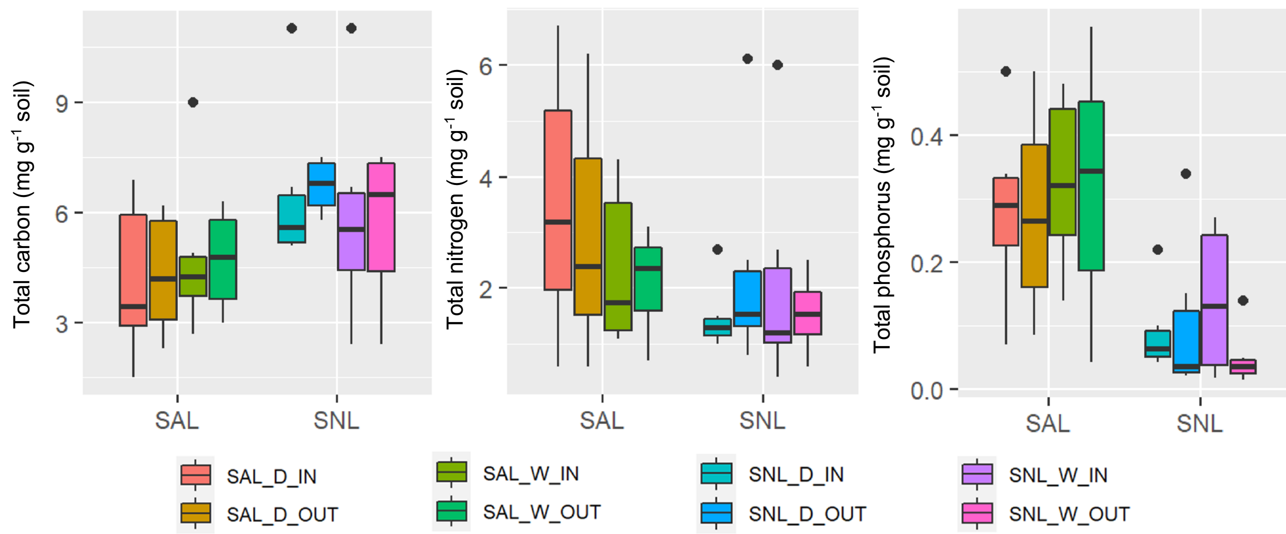

Fig. 3 Total soil carbon, nitrogen and phosphorus (mg g^{-1} soil) depending on land use (SAL and SNL), enclosure (IN and OUT) and seasonality (WET and DRY). Where SAL represents sedentary agro-pastoral land-use system and SNL represent semi-nomadic pastoral land-use system

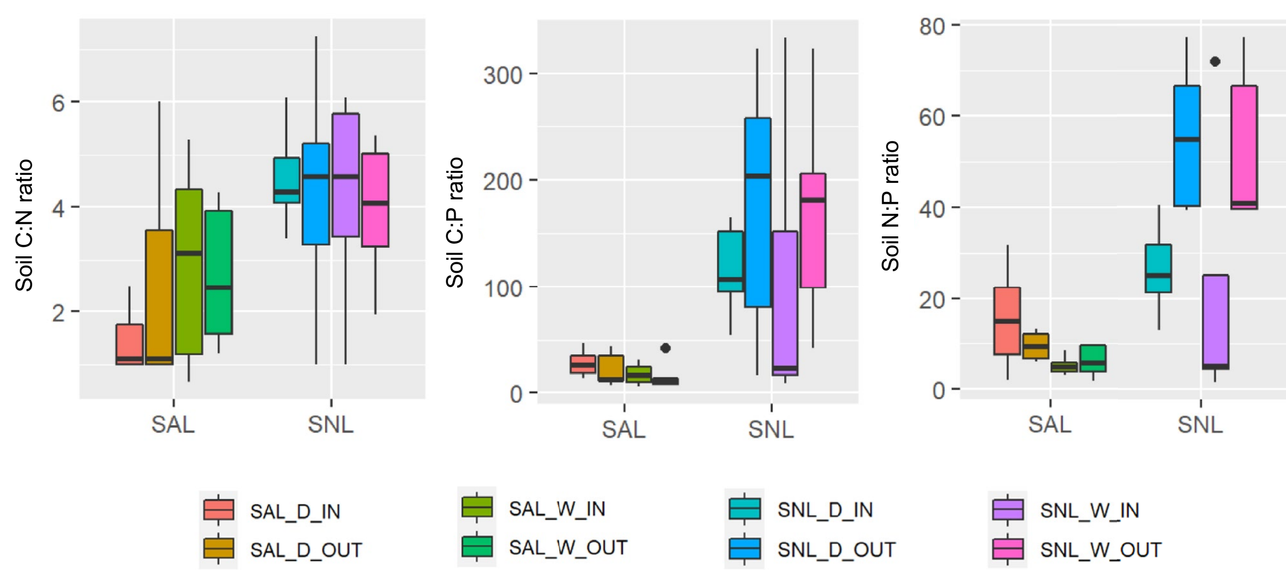

Fig. 4 Soil C:N, C:P and N:P stoichiometric ratios depending on land use (SAL and SNL), enclosure (IN and OUT) and seasonality (WET and DRY). Where SAL represents sedentary agro-pastoral land-use system and SNL represent semi-nomadic pastoral land-use system

ratios were much higher in SNL than SAL. In the studied systems, differences in N:P and C:P ratios were larger compared to C:N ratio. In SAL, soil C:N ratios were lower in the dry than wet season, while the N:P and C:P ratios were higher in the dry than wet season. In SNL, soil C:N, N:P and C:P ratios were higher in the dry than wet season. C:P ratios were higher inside than outside enclosures in SAL. However, in SNL, C:P ratios were lower inside than outside enclosures. N:P ratios were much higher outside than inside enclosures in SNL but lower in SAL, especially in the dry season. Generally, C:N ratios were higher inside the enclosures, except during the dry season in SAL where C:N ratio was higher outside than inside the enclosure.

Results from the linear regression analysis (Fig. 5) demonstrated that the correlation between pH and CEC and C, N, P, C:N, C:P and N:P ratios were weak (positive and negative) and the r^2 coefficients were very low and generally below 0.25 in both land use systems (Table 2).

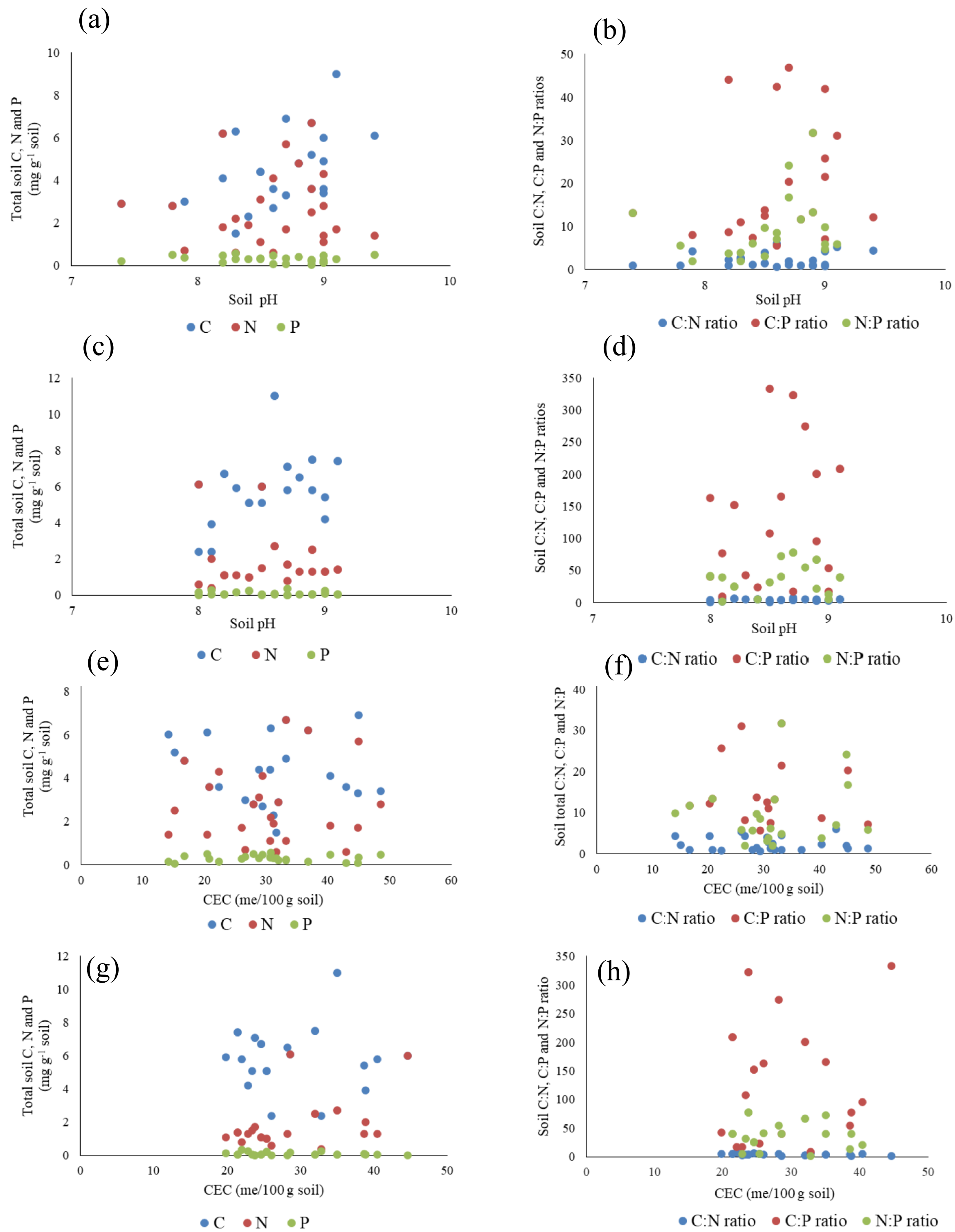

Fig. 5 Scatterplots showing the relationship between soil total carbon, nitrogen, phosphorus, C:N, C:P, N:P and soil pH and cation exchange capacity (CEC) depending on land use systems. Where **a**, **b**, **e**, **f** represent SAL (sedentary agro-pastoral land-use system) and **c**, **d**, **g**, **h** represent SNL (semi-nomadic pastoral land-use system). r^2 coefficients were low and less than 0.25 in both land use systems

Table 2 Correlation matrix of Pearson correlation coefficients

	Carbon	Nitrogen	Phosphorus	C:N ratio	C:P ratio	N:P ratio
Carbon	1					
Nitrogen	0.1489	1				
Phosphorus	− 0.4002*	0.0899	1			
C:N ratio	0.3241*	− 0.7547*	− 0.2934*	1		
C:P ratio	0.4781*	− 0.0527	− 0.6838*	0.2606	1	
N:P ratio	0.5754*	− 0.0253	− 0.6010*	0.2644	0.7249*	1

*Correlation is significant at the 0.05 level (2-tailed test)

4 Discussion

4.1 Land Use, Enclosures and Seasonality Effect on Soil pH

Similar to other dryland ecosystems, soil pH in the studied semi-arid land ranged between slightly alkaline (pH 7.53) and moderately alkaline (pH 8.36). Dryland soils are often characterized by neutral to alkaline pH. This is mainly because rainfall received is low and inadequate to wash out basic cations required to release acidic anions from clay fractions. Thus, drylands ecosystems, compared with wetter regions, tend to have higher pH attributed to the accumulation of soluble salts and carbonates in soil (Moreno-Jiménez et al. 2019). Leaching of Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} may also occur during periods of high amounts of rainfall. Leaching during wet rainy season is one of the factors contributing to lower pH levels in soils (Huang et al. 2020). This partly explains low soil pH values observed during the wet season in both land use systems. Also, ash deposits from prescribed burns typical of in semi-arid African rangelands returns enough base cations which contribute to higher soil pH (Parwada et al. 2020).

Alkaline conditions of the studied soils suggest that they might be deficient of nutrients such as zinc (Zn), copper (Cu), boron (Bo), cobalt (Co) and manganese (Mn). Moreover, calcium (Ca) can tie up phosphorous, making it less available to plants. Deficiencies in Zn and Co lead to stunted plants, poor growth and reduced yields in grazed pastures. Enclosures in semi-arid drylands promote species richness, recovery of herbaceous species and higher basal grass cover compared to openly grazed rangelands (Verdoodt et al. 2010). Higher water uptake by vegetation in enclosures during the wet season might have contributed to less leaching and subsequently relatively higher soil pH compared to outside enclosures, characterized by less vegetation cover.

4.2 Land Use, Enclosures and Seasonality Effect on Cation Exchange Capacity (CEC)

High CEC values observed in both SAL and SNL can be attributed to alkaline soil pH and clays and clay loams present in the studied sites. The high CEC observed in both land use systems suggest that the studied soils have a high capacity to hold cations thus influence soil structure stability and nutrient availability. Also, soil CEC vary depending on clay type and SOM quality and content. Clay minerals are often characterized by a large specific surface area that carries a charge necessary to chemically bind and stabilize native SOM (Islam et al. 2022). Higher soil pH values result to additional negative charges, leading to higher CEC values.

High CEC inside enclosures during the dry and wet season can largely be attributed to SOM content. Perennial vegetation cover and accumulation of plant litter inside enclosures may have facilitated the buildup of SOM. In terrestrial ecosystems, amount of plant litter amount, its characteristic features and composition, are key factors controlling SOM formation (Córdova et al. 2018). Also, rhizodeposition by plant roots contribute a substantial amount of SOM in soil (Villarino et al. 2021). Soils with a high CEC are less prone to leaching and thus unlikely to be deficient in cations. Our results suggests that enclosures in pastoral dryland systems can enhance soil health and fertility through SOM accumulation which increase soil water holding capacity (WHC) and reduce leaching. Soils that are highly negatively charged retain more positively charged cations such as sodium (Na^{+}) which can occupy an important portion of the CEC in similar dryland environments and potassium (K^{+}), magnesium (Mg^{2+}) and calcium (Ca^{2+}), needed to support primary production.

4.3 Land Use, Enclosures and Seasonality Effect on Potassium and Sodium

Potassium plays a key physiological and biochemical role in plants e.g. N metabolism, phloem loading, storage processes and assimilation. However, K is also a mobile cation (Lu et al. 2022). Thus, K in soil can easily be leached beyond plant roots. Potassium leaching in terrestrial ecosystems is regulated by clay content, soil texture, (Rosolem and Steiner 2017) climatic conditions and land use (Rashmi et al. 2017). High amounts of K in SNL during the dry season and inside enclosures can be attributed to reduced K losses which can occur through percolation after the rainy season.

Soil moisture affects diffusive flux of K in soil solution (Lu et al. 2022). Thus, low soil moisture availability in drylands during the dry season restricted the diffusive flux of K in soil. Humification of plant residues inside enclosures produced OM with a high CEC that plays a key role in holding soil K in exchangeable form. This is significant in tropical soils with OM rich in kaolinitic clays and low CEC, thus contributing to higher retention capacity. Our results demonstrate the significant contribution of rangeland enclosures in increasing SOM in dryland soils and maintaining soil health. This is because SOM promotes aggregate formation and stability, thus enhancing soil WHC and aeration.

Higher K content in SNL than SAL can be attributed to K inputs from manure deposited by large grazing livestock herds, which play a major role in K-cycling in soil–plant-animal terrestrial systems. Deposition of excreta (faeces and urine) by grazing livestock enhances semi-arid rangeland soils fertility. Most (70–90%) of the K excreted by livestock is soluble in water (ionic form) making it readily available for plants. Potassium input at urine patches has been estimated as being equivalent to 500–1000 kg K ha^{-1} which exceeds by far the necessary plant requirements (Kayser and Isselstein 2005).

Similarly, saturation level of Na in the studied soils was influenced by climate and land use. Agropastoral production in SAL resulted to higher Na concentration compared to SNL. Sustainable agricultural production in marginal arid and semi-arid drylands is under threat due to salinization (Perri et al. 2022). Salinization linked to agricultural crop production occurs when salts accumulate in the root zone because water drainage from the sub-soil is insufficient to stop salty water from reaching the rhizosphere. The wet and dry cycles in soil explains the variation in Na content in the dry and wet periods. Evaporation is a dominant process affecting the chemistry of arid and semi-arid dryland soils. Most of the water from the rainstorms in these dryland systems evaporates from the soil and does not percolate to the deeper soil horizons. Although leaching of salts in drylands is low due to little rainfall, irregular heavy rain downpours partially dissolves accumulated salts in the vadose zone. Sodium chloride and sulphate are particularly leached very rapidly compared to K chloride and sulphate and Ca and Mg carbonates (Ordóñez et al. 2013).

4.4 Land Use, Enclosures and Seasonality Effect on Calcium and Magnesium

Calcium and Mg are categorized as secondary nutrients and together with K are referred to as the basic cations. Calcium weathers easily as a soluble cation. This enables Ca^{2+} to be readily transported in soil solution where it can be absorbed onto the CEC, assimilated by plants and soil microbes or leached through the soil profile (Wei et al. 2019). This characteristic explains the lower Ca concentration during the wet than dry season. Moreover, movement of Ca from exchange sites in soil and degradation of SOM associated Ca also contributed to Ca fluxes. Like other cations, humification of plant residues inside enclosures probably produced OM with high CEC for holding exchangeable Ca and Mg in soil. Perennial natural vegetation cover in SNL minimized Mg losses through leaching because less water passed beyond the rhizosphere. Furthermore, Mg brought up from lower horizon and deposited in OM maintained a high Mg content in the upper 0–30 cm soil horizons. Higher Mg content in SNL compared to SAL can also be attributed to 'hot spots' of manure deposited by grazing livestock herds in SNL (Marshall et al. 2018).

Calcium has a positive effect on soil health as it improves soil structure, thus improving infiltration of water and creating a conducive environment in the soil for root development and growth of soil microorganisms. Calcium and Mg effects on clay flocculation and soil aggregate stability during the rainy season has also been supported by differences in infiltration and erosion between Ca and Mg treatments on soil (Zhang and Norton 2002). Higher Ca:Mg ratios inside than outside enclosures during the wet season in both land use systems, demonstrates that rangeland enclosures enhance soil physical characteristics, thus facilitating water infiltration, reducing nutrient losses through erosion. However, unlike Ca, Mg is not an effective cation to precipitate P in soils. The contribution of exchangeable Mg in minimizing Ca-P precipitate formation could result to increased P availability in soils characterized by low Ca:Mg ratios similar to those occurring in SNL land use system (Wadu et al. 2013).

4.5 Land Use, Enclosures and Seasonality Effect on Total Carbon, Nitrogen and Phosphorus

Higher total soil C content observed in SNL than SAL is consistent with other studies that have demonstrated that intensive cultivation accelerates soil C losses in the long-run (Fu et al. 2021; Okolo et al. 2020). Semi-arid natural rangelands where SNL is practiced store large amounts of SOC due to high root residue input from native perennial drought tolerant grasses. This can mainly be attributed to reduced turnover and gradual senescence of belowground biomass especially in lean dry periods (Mganga and Kuzyakov 2014). Agropastoral production in SAL led to a substantial decrease in soil C additions by roots and shoot biomass and rapid SOM degradation. Furthermore, tillage practices increases soil aeration and often lead to rapid decomposition of SOM (Mehra et al. 2018). Similar total soil C content inside and outside enclosures probably suggests their recent establishment (< 10 years old). Our results compare well with a study conducted in Ethiopian drylands that demonstrated

6–10 years of enclosure establishment is a short period to observe changes in soil C (Okolo et al. 2020).

Conversely, total N was generally higher in SAL than SNL land use system. This is mainly attributed to the use of livestock manure as a biofertilizer among agropastoral farmers in SAL (Kosgey et al. 2008). This is consistent with what has been observed in a previous study in dry rangelands (Melero et al. 2007). Additionally, total N was generally higher inside than outside enclosures. Perennial vegetation of leguminous plant species inside enclosures could have contributed to the significant increase of total soil N content. Incorporation of leguminous livestock fodder species and native N-fixing trees (e.g. *Acacia tortilis*) inside enclosures enhance total soil N (Mureithi et al. 2014).

African drylands soils are P-deficient forcing agropastoral farmers with limited resources to rely on available organic inputs e.g. the use of livestock manure as a biofertilizer (Kosgey et al. 2008; Mafongoya et al. 2000). Livestock manure recycled to cropland supply valuable quantities of nutrients and OM, to meet plant growth and production requirements and maintain soil health (Sileshi et al. 2019). Continuous P accumulation in SAL is attributable to long-term livestock manure biofertilization. Application of manure has several effects notably increasing available, soluble and total soil P levels in upper and deeper soil horizons and accelerates rates of biologically driven organic P turnover due to activation of microbial and enzyme activity (Melero et al. 2007; Motavalli and Miles 2002). Low total P content in SNL compared to SAL also suggest a continuous uptake of available by the perennial vegetation cover consisting of diverse plant species than few annual crops that only persist during the growing season in SAL. Increase in P content in the wet season in both land uses suggest the probable interaction of livestock manure and soil surface water runoff. Phosphorus fractions, especially soluble P can play a major role in dictating the forms of available P present in runoff water and top soil (Kleinman and Sharpley 2003).

4.6 Land Use, Enclosures and Seasonality Effect on Total Soil C, N and P Stoichiometry

Soil C:N, N:P and C:P stoichiometric ratios are indicators of soil health, biological activities and provide valuable information on the mineralization potential of SOM (Boudjabi and Chenchouni 2022). Generally, both land use systems had very low soil C:N ratios (less than 5) but was higher in SNL than SAL. Low C:N ratios are common in drylands soils (Delgado-Baquerizo et al. 2013). Higher soil C:N ratio in SNL than SAL is indicative of higher SOM mineralization rate in SAL than SNL. Agricultural practices e.g. tillage, in SAL might have accelerated SOC and N mineralization, leading to lower C:N ratios. This is because C losses as CO_2 fluxes are normally higher than N losses (Zinn et al. 2018). Less variation in soil C:N ratio observed in both land use systems, suggest that soil C:N ratio responses to land use are more constrained than those of soil N:P and C:P stoichiometric ratios. This pattern is consistent to what has been observed in previous studies (Zhang et al. 2021; Zhou et al. 2018). Slightly higher C:N ratios inside enclosures can be associated to more litter and root inputs than outside enclosure leading to a SOM pool consisting mainly plant biomass in the initial stages of breakdown. An alternative explanation is that plant litter inside enclosures is dominated by recalcitrant materials. Recalcitrant plant litter inside enclosures may degrade slowly yielding higher soil C:N ratios. Less plant litter input in the dry lean seasons in SAL lead to a reduction in C:N ratios, compared to SNL with more perennial vegetation cover even during the dry season.

Soil C:P and N:P ratios were higher in SNL compared to SAL than C:N ratios. The substantial difference suggests that changes in soil C:P and N:P ratios due to land use are less constrained than soil C:N ratios. The C:P high ratios in SNL system (range 106–177) are comparable to those obtained in an African semi-arid steppe rangeland (range 43–582) (Boudjabi and Chenchouni 2022). Soil C:P and N:P ratios exhibited high correlation ($r^2 > 0.70$), demonstrating that C and N in soils are generally tightly coupled even in response to land use (Delgado-Baquerizo et al. 2013). Higher soil N:P and C:P ratios in SNL suggest that P limitation in the land use system could be contributing to an augmented mineralization and absorption which led to the unproportional buildup of P than C and N in the top (0–30 cm) soil. This also partly explains higher soil N:P and C:P ratios outside than inside enclosures in SNL compared to SAL and during the dry season in both land use systems. Much lower soil C:P and N:P ratios in SAL compared to SNL can be attributed to probable P accumulation due to organic manure fertilization in SAL system. Thus, our results compare well with other studies that show organic amendments decrease N:P and C:P imbalances and lower soil N:P and C:P ratios (Huang et al. 2021).

Our findings demonstrate that land use, seasonality and enhanced vegetation cover in enclosures can adjust soil stoichiometric characteristics in African dryland systems. Soil factors, e.g. CEC and pH, affects availability and interactions of different elemental pools and subsequently C:N:P stoichiometry ratios. Results presented showed that soil factors (CEC and pH) were generally weakly correlated with C, N, P and C:N:P stoichiometric ratios. Results obtained from this study show that land use, enclosures, seasonality and soil affect C:N:P ratios differently. Thus, these findings can provide a fundamental framework for model building and adjustment suitable for African drylands.

5 Conclusions

Land use was the main factor that regulated the measured soil properties and soil health indicators. Establishment of enclosures in semi-arid dryland environments is majorly a response by the pastoral communities to dwindling forage resources and degradation of grazing lands. Established rangeland enclosures enhanced soil health. This can largely be linked to the perennial vegetation cover. Moreover, soil chemical characteristics and C:N:P stoichiometry ratios were strongly affected by seasonality, a key characteristic of African dryland environments. Overall, this study demonstrate that land use, enclosures, seasonality affected soil chemical characteristics and C:N:P stoichiometry ratios differently. The pronounced soil C:P and N:P ratios changes observed in the studied semi-arid dryland suggest that decoupling of the P cycle from C and N cycles is common. This decoupling can greatly alter C, N, and P biogeochemical cycle and processes in global dryland systems.

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Data Availability All data generated or analysed during this study are included in this published article and are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no conflicts of interest.

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