Hindawi
Applied and Environmental Soil Science
Volume 2019, Article ID 6874268, 15 pages
https://doi.org/10.1155/2019/6874268

*Research Article*

# Land Cover and Soil Properties Influence on Forage Quantity in a Semiarid Region in East Africa

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Received 15 August 2018; Revised 13 November 2018; Accepted 25 November 2018; Published 8 April 2019

Academic Editor: Claudio Cocozza



Soil properties contribute to the widely recognised resilience of semiarid areas. However, limited attention has been given in providing a scientific basis of how semiarid soil properties in the various land covers occur and how they influence forage quantity. This study investigated the influence of different soil properties and land cover types on herbaceous biomass quantity in the Karamoja subregion of Uganda. A completely randomized design in three land cover types (thickets and shrublands, woodlands, and savannah grasslands) was implemented. In each vegetation type, 50 × 40 m plots were demarcated with nested plots to facilitate clipping of the herbaceous layer. Composite soil samples at two depths (0–15 cm, 15–30 cm) were obtained from each plot. The results showed that soil properties varied across land cover types. Soil pH ranged between 6.9 and 8.1 and SOM, N, P, and K were generally low in all land cover types. Soil hydraulic properties revealed the existence of rapid to very rapid permeability in thickets/shrublands, grasslands, and woodlands. Percent change in soil properties (0–15 cm to 15–30 cm) was highest in P, Ca, Mg, Na, and SOM. In the grasslands, P positively ($p \leq 0.01$) influenced herbaceous biomass, whereas pH, K, Na, % sand, and % clay, N, and SOM had a negative relationship with herbaceous biomass ($p \leq 0.05$). Herbaceous biomass in the thickets/shrublands was negatively influenced by P, Ca, and Mg and % clay and positively by N and % silt ($p \leq 0.05$). Only N and SOM were significant determinants of herbaceous biomass in the woodlands ($p \leq 0.05$). The low level of soil nutrients observed in this study reveals the fragility of semiarid soils, indicating the need for sustainable landscape management.

## 1. Introduction

Land plays an important role in providing food and water security and building resilience to climate change. It further contributes to climate change mitigation, through carbon sequestration and helping to meet energy needs [1]. However, land degradation and its manifestations have emerged as serious challenges facing the global community. The degradation is jeopardizing livelihoods and environmental health and is triggering a knock-on effect on the prevalence of diseases for plants, animals, and humans. These effects are subsequently disrupting human welfare and wellbeing by negatively affecting food production and sustainable development [2–4]. The United Nations Convention to Combat Desertification (UNCCD) indicated that the world is facing a "perfect storm," with a number of huge problems converging around land issues. The poor, whose survival greatly depends on land, are at the center of this global challenging storm. However, they have limited capacity to tackle the marshaling "storm" clouds [5]. Several studies [3, 6–9] have analyzed the causes of land degradation with the appreciation of biophysical processes in combination with human-induced drivers occurring at different spatio-temporal scales. The causes often range from the level of the individual land user, whose management practices may be destructive, exploitative, short-sighted or negligent, to the policy level at which land use and management across larger (administrative) areas are governed and may be ill-conceived, inequitable, discriminatory, and/or simply ineffective [3, 10].

Despite the on-going degradation discourse, soil properties still contribute to the widely recognised resilience of semiarid rangelands because they provide a degree of suppleness that prevents any shifts in ecological competitive dominance [11]. For example, the high hydraulic conductivities associated with semiarid soils facilitate rapid water movement from the topsoil to the subsoil, thereby reducing direct evaporative losses that are often restricted to the upper 50 cm soil layer [12]. Such patterns in semiarid soils lead to high water use efficiency owing to accelerated infiltration of incident rainfall, rapid movement of water beyond the topsoil, and the rapid plant uptake of the topsoil water [11]. Soil properties are affected by the human use and abuse of soils; this can easily disturb the resilience of semiarid soils due to associated degradation [13]. In a study conducted in northern Gadarif region of Sudan, land use/cover changes had significant influence on physical and chemical soil properties leading to land degradation [14]. Research on soil properties changes due to land use/cover management is critical to understanding land degradation processes, sustainable use and resource dynamics in semiarid areas. Semiarid resource dynamics, in particular, forage and water, are critical in sustaining pastoral and agropastoral livelihoods as they directly influence livestock production, a key food security holding [15].

Like other pastoralists in Eastern Africa and the Horn of Africa such as the Borana [16], Afar [17], Maasai [18], and Orma [19] who depend on native and natural pastures to feed their livestock, the Karamojong are no exception. In these locations, grasses and woody plants provide the bulk of fodder to animals [16]. The availability of fodder in these areas depends on complex relations and interactions between ecosystem components including among others: soil, water, plant, climate, and animals [20]. Comprehensive understanding of social, ecological, and economic sustainability of rangelands is dependent on full knowledge of these ecosystem conditions and their impact on forage-including herbaceous productivity. Rangelands vary in herbaceous forage availability and production across landscapes. This in itself has not received judicious investigation [21]. Meanwhile, in pastoral Karamoja, pasture status is perceived by the pastoralists in terms of plant growth taking into consideration three growth phases: the early regeneration that occurs soon after the initial rainfall showers, the maturing and flowering stages of grasses, and the standing dry hay [19].

The Karamoja pastoralists understand the critical role that soil and landscapes have on livestock grazing and management by exerting control on vegetation dynamics. In their classification, the Matheniko, for example, know of "hot" and "cold" soils with the "hot" soils being undesirable for night cattle kraaling. The Karamojong also have observed that sandy landscapes tend to be heavily grazed compared to black soil landscapes arising from differences in land cover types as well as herbaceous species [19]. However, these observations are only based on the traditional ecological knowledge and thus lack scientific explanations. In other rangeland areas such as in Benin, forage species tolerance to low soil fertility has been observed. Legumes have been observed to grow in sandy to clay soils with a better performance in medium textured soils [22]. In contrast, [23] identified nitrogen (N), phosphorus (P), potassium (K), and soil pH as four primary soil components important in forage production. Karltun et al. [24] showed a high positive correlation between nitrogen and biomass production in Ethiopia. Further, Juice et al. [25] established that the abundance, species composition, and nutrient content of vegetation are influenced by changes in concentration of cations and nutrient availability in soils. In a three year study conducted in a forest and watershed ecosystem in Pennsylvania, Pabian et al. [26] established that forage biomass availability was positively related to soil pH, calcium, and magnesium.

Several researchers [17, 27] attempted detailed investigations of rangeland status. A number of these studies have focused on rangeland conditions, with emphasis towards understanding "rangeland degradation" [28, 29]. Fewer studies have focused on rangeland productivity; a notable example is [30] who addressed the effect of bushland encroachment on grassland productivity. Pickup [31] discussed the role of climate on rangeland forage production. The effect of grazing and trampling on forage productivity has also received some attention [32]. Further, others have focused on the attendant effects of land use [33] and associated practices such as grazing [34], fire, and cultivation on soil properties in the rangelands [28]. As such, the understanding that soil characteristics contribute to the widely recognised resilience of semiarid rangelands has been overlooked [11]. There is an urgent need to investigate how land management and its modifications impact soil and soil properties in rangelands with a view of affirming how man might be "a destructive agent" of the rangelands. The missing link in most of these studies has been the scientific basis of semiarid soil properties in the different land cover types and how they influence semiarid forage production. Bridging this knowledge gap is important in East Africa where semiarid areas have traditionally been considered "wastelands" [35] whose inhabitants live in a state of "chaos" [36] and whose environments and practices are beyond development [37]. This study therefore determined the influence of different land cover types and soil properties on forage quantity in a semiarid Karamoja region of East Africa.

## 2. Materials and Methods

*2.1. Study Area.* This study was conducted in Karamoja subregion located in the north eastern Uganda (Figure 1). Karamoja subregion is occupied by the Karamojong people who are part of the Karamoja cluster in the Greater Horn of Africa (GHA). The area is a semiarid with variable rainfall ranging from 500 to 1000 mm per annum and is poorly distributed. Rainfall is often characterised by storms that

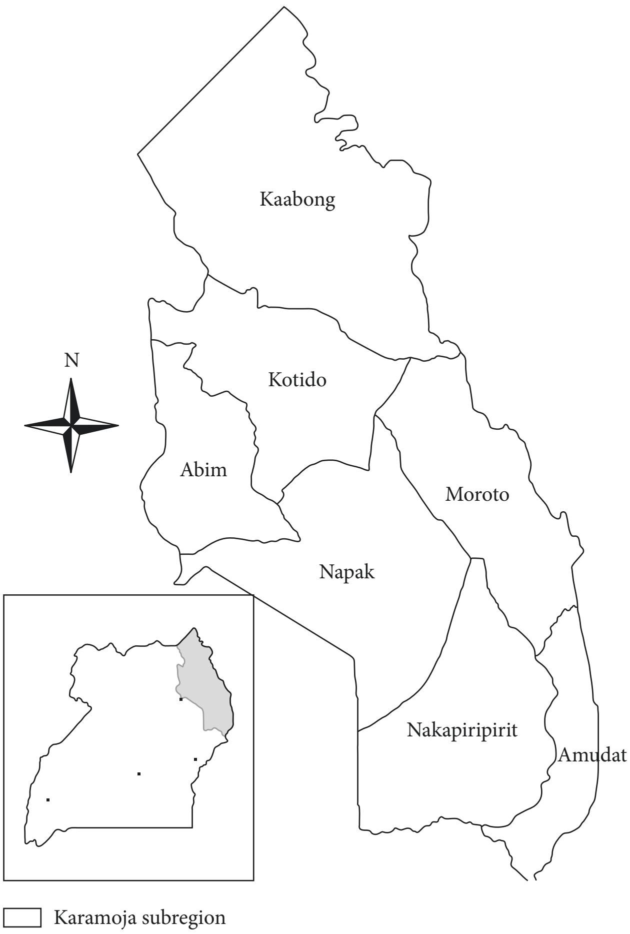


Figure 1: Geographical location of Karamoja subregion.

build up in the afternoons with velocities in the region of 13–18 km/h and with storm diameters of 32 to 48 km thereby producing intense rainfall of up to 25 mm/h [38, 39]. This pattern of rainfall is not surprising given the high temperatures and associated evapotranspiration averaging 28°C–33°C for minimum and maximum temperature and annual potential evaporation (PET) of 1800–2200 mm/annum, respectively [18, 40, 41]. The subregion is dominated by C4 grasses characterised by acacia/cymbogon/themeda complex [42]. Thus, the subregion is generally a savanna ecosystem that is made up of bushlands, woodlands, and thickets/shrublands [43]. Geologically, Karamoja consists of plains and isolated volcanic highlands including Mount Moroto, Mount Zulia, Mount Kadam, Mount Iriiri, and Mount Labwor and a series of other inselbergs (e.g., Kogwele, Kanamerinjor, Katipus, Morutit, Kapernakori in Kotido district and Koromwae, Napakgngaran, Turusuk, Nyanga, Thane, Arakas, Kolung, Nakithilet hills in Kotido-Kaabong). The subregions' soils originate from the Precambrian basement complex. Western Karamoja generally consists of carbonatites with deeply dissected agglomerates, tuffs, and silica unsaturated flows of lava overlying the Precambrian basement. The soils in the plains and valleys of the subregion are dominated by dark grey to dark brown calcareous clays which are noteworthy for their extreme stickiness when wet and for their aridity shrinkage (tendency to form large deep cracks when dry). These clays are derived both from wind and water deposits [44]. The soils in the northern Karamoja are part of the ferruginous tropical soils that are freely drained and weakly developed lithosols. Karamoja' soils are in general characterised by black cracking clays classified as vertisols under the FAO soil classification scheme [45].

*2.2. Consultation with Local Stakeholders.* Prior to undertaking forage quantification exercise, a previsit to the subregion was undertaken. During the previsit, an exercise to identify forage monitoring sites was conducted with elders, youth, scouts, and herders who have detailed knowledge of the land cover types in the region. Three land cover types were identified including: grasslands, thickets/shrublands, and savannah woodlands. These land covers were identified through consultative discussions that matched vegetation growth forms to land cover type. The local stakeholders also identified three vegetation growth forms. First is *eparat echalichal* which describes early regeneration after early and initial rainfall. This was indicated to occur around late February through to early April depending on the timing of rainfall onset. Second is *akelebat/ekelebat/kelebat* which describes the period when the herbaceous vegetation flowers and matures. This was indicated to occur between the months of June and July. Third is *athakan* which describes the standing dry hay that was indicated to often occur between the months of October and November. In order to corroborate the growth forms and periods as identified by local stakeholders, long-term monthly normalized difference vegetation index (NDVI) data were utilised. The National Oceanic and Atmospheric Administration-Advance Very High Resolution Radiometer (NOAA-AVHRR, 1981–2008) and Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI (2000–2012) time series NDVI data were used for this purpose. Mean monthly NDVI deviations were computed. Computing the mean monthly NDVI deviations allowed us to identify vegetation growth periods (Figure 2).

*2.3. Establishing Monitoring Sites.* In this study, the identified land cover types (grasslands, thickets and shrublands, and woodlands), phenological stages, and periods (seasons: wet and dry) were considered as treatments/independent variables. Forage assessment monitoring sites were established based on three criteria. These criteria jointly developed by the scientific team and local stakeholders. First, the land cover had to be fairly stable in with the minimum grazing effect observed. A fairly stable land cover was taken to be that with a good balance of desirable forage species. Second, the land cover had to be fairly secure from potential raiders that paused insecurity in the subregion. Third, the land cover had to be fairly accessible that it could be reached on foot. A 15 km walkable distance from the last point a vehicle could access was considered. This was essential because some areas could experience sporadic rains. In addition, armed security guards provided by the Uganda

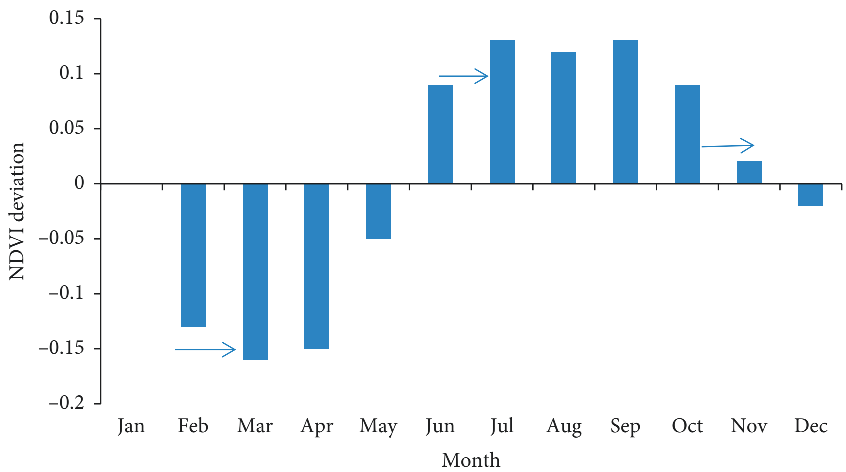


FIGURE 2: Long-term monthly NDVI deviations revealing vegetation growth patterns in Karamoja.

People's Defense Forces (UPDF) had to be back at the base before 6:00 pm.

*2.4. Forage Quantification and Soil Sampling.* In this study, forage was taken to mean the edible herbaceous parts of plants, other than separated grain, that can provide feed for grazing animals and/or can be harvested for feeding livestock [46]. In order to determine the influence of different land cover types and soil properties on forage quantity, a completely randomized design established in three land cover types (grasslands, woodlands, and thicket/shrublands) was used. Eight plots measuring 50 × 40 m were demarcated in each land cover unit in Moroto and Kotido districts. Plots of 50 × 40 m have been recommended when measuring above-ground biomass [47]. In the 50 × 40 m plots, nested plots were established for herbage clipping. Five nested plots of 5 × 5 m were established in the woodlands, 10 plots of 5 × 5 m in the thickets/shrublands, and 20 plots of 1 × 1 m in the grasslands. Clipped herbage was freshly weighed, and a 0.5 kg composite sample (all edible parts of plants) was taken for dry matter determination in the Makerere University Soil Science Laboratory. The assessment was conducted in three periods during January/February, June/July, and October/November in respect to vegetation growth periods identified with the local stakeholders.

The soil physical and chemical properties investigated included soil texture, soil structure, total nitrogen (TN), available phosphorus (Av. P), total potassium (TP), magnesium (Mg), sodium (Na), calcium (Ca), soil pH, and soil organic matter (SOM). Composite soil samples were collected using a soil auger of 50 mm diameter for soil texture, SOM, TN, Av. P, soil pH, Mg, Na, and Ca determination. Undisturbed soil samples (100 $cm^3$) were taken for saturated hydraulic conductivity, and bulk density analysis using a core method by driving a core sampler into the soil to a desired depth. All the soil samples were taken at soil depths 0–15 cm and 15–30 cm from the same plots where forage was clipped. Soil samples were taken at these depths because they represent active root zone [48]. Further, these sampling depths have previously been applied in the semiarid areas of Mongolia [49].

*2.5. Forage and Soil Samples Processing.* Quantity of forage was determined through dry matter processing. Herbaceous forage samples taken to the laboratory were oven dried at 60° C until a constant weight. Following [50]; dry matter was determined gravimetrically as the residue remaining after oven drying. The gravimetrical results of different sampling plots were then pulled together by land cover type and averaged to obtain dry matter weight (kg/ha).

Soil available phosphorus was determined using spectrophotometry (Bray-1). Total nitrogen was determined by digestion and titration. For extractable bases (P and Na), flame photometry method was used after extraction with natural ammonium acetate. Ca and Mg were determined using atomic absorption spectrophotometry after extraction of the soils with a natural ammonium acetate solution. Further, saturated hydraulic conductivity was analyzed through a constant head method [51]. Soil organic matter (SOM) was determined using the Walkley–Black method. All these methods of analysis are detailed described in [52]. Soil structure was determined by the dry sieving technique and the results are expressed as mean weight diameter (MWD) of the aggregates [53]. Soil samples were passed through a 10 mm sieve [54], thereafter passed through a nest of concentric rings of progressively declining sieve sizes: 6.36, 4.75, 2.36, 1.18, 0.425, and 0.212 mm. A vibratory sieve shaker-FRITSCH analyzette 3E was set at amplitude 5 for 30 minutes during the processing of soil aggregates. Lastly, available water content (AWC) was computed following the approach described by [55]. Soil samples to determine available water content and bulk density were oven-dried at 105°C for a minimum of 24 h.

## 3. Data Analysis

In this study, four classical statistical techniques were utilised to analyze for associations between soil properties and forage availability. Descriptive statistics of soil properties from the different land covers (woodlands, grasslands, and thicket and shrublands) were generated to ascertain their patterns and trends. Correlations were thereafter conducted to test for the relationship between soil properties and forage quantity expressed in biomass (kg/ha). Analysis of variance (ANOVA) was performed to test for the significances in the mean differences related to soil properties and land covers during the two rainfall seasons. Prior to the ANOVA test, soil properties data were subjected to normality distribution test following the approach by [56]. Significant differences in ANOVA tests were determined at $p < 0.05$ and land cover and soil properties means were compared by Fisher's protected least significant difference (LSD) test. In addition, a principal component analysis (PCA) and generalized linear model (GLM) regression were acquired for determining the relationship and influence of soil properties on forage quantity in the land covers. Also, regression analysis was performed for each land cover type to identify landscape specific determinants. Classical statistical analysis was conducted using GenSTAT12 portable version [57].

## 4. Results

*4.1. Variability of Soil Properties across Land Cover Types.* The observed variability of soil properties across the land cover types in the study area are presented in Table 1. According to the USDA soil texture classification [58], all soils in the grasslands and thickets/shrublands are predominantly sandy clay loam while woodlands have sandy loam. However, soils generally depicted variability across the land cover types. Soil organic matter varied from 1.23 to 1.84% across the land cover types. The mean SOM values across the land cover types were below the critical value of 3.0%. The soil pH across the land cover types was neutral to alkaline. The mean soil pH was 7.7 for both soil depths across the land cover types. The minimum and maximum soil pH values were 6.9 and 8.4, respectively. The soil pH values observed are conducive for vegetation growth. The mean N and Av. P values across the land cover types for both soil depths were below their respective critical values (0.2% and 15 ppm, respectively). Among the selected soil properties analyzed, available P had the largest decline (88%) and increase (283%) from top soil (0–15 cm) to the subsoil (15–30 cm) across all the land cover types. Furthermore, grassland land cover type had the largest depletion and increment of available $p$. When the results were subjected to the ANOVA test, the observed mean differences for the soil properties were significantly ($p < 0.05$) different across the land cover types, except total nitrogen, soil organic matter, available water content, and potassium (at 15–30 cm depth) (Table 1).

In terms of physical soil properties, Ksat and bulk density experienced variations within and between land cover types. Grasslands had Ksat mean of 17.5 ± 10.1 (mm/h), thickets/shrublands 17.4 ± 11.1 (mm/h), and woodlands 39.4 ± 25.5 (mm/h). Bulk density showed an overall mean of 1.3 ± 0.1 (g/cm$^3$) for all land covers with a minimal variation between land cover types. At 1.38 (g/cm$^3$), the bulk density in the woodlands varied significantly from that in the grasslands and thickets and shrublands. Although there were differences in the wilting point, field capacity and the available water content (AWC) in the different land cover types (Figure 3), these differences were nonsignificant.

## 5. Relationship between Soil Properties and Biomass

The correlation coefficients between individual soil properties and biomass are reflected in Tables 2–4. A few soil properties and biomass showed positive and negative dependence at 5% significance level. However, there were several soil properties that were closely associated with biomass at 10% significance level (Tables 2–4).

*5.1. Relationship between Soil Properties, Land Cover, and Season.* Soil physical and chemical properties in the grasslands, thickets and shrubs, and woodlands across the seasons are shown in Tables 5 and 6 for soil depths 0–15 cm and 15–30 cm, respectively. Top soil (0–15 cm) properties except percent silt content, SOM, TN, Av. P, K, and Mg differed significantly ($p < 0.05$) across land cover. Across seasons, soil properties (TN, Ca, and Mg) showed significant differences ($p < 0.05$). Albeit no significant differences across land cover for SOM, statistically, grasslands had higher SOM (1.84% in dry season and 1.45% in wet season), though this is below the critical value (3.0%).

Likewise, soil properties in the lower depth (15–30 cm) except TN, percent silt, and Na differed significantly ($p < 0.05$) across land cover. Comparing soil properties across the seasons, soil properties except percent clay and silt, exchangeable K, Av. P, Na, and soil pH differed significantly ($p < 0.05$). SOM was considerably higher (1.8%) in grasslands in the dry season while in the wet season, woodlands registered a slightly higher SOM. Like in the top soil, the mean SOM values across the land covers were below the critical values (3.0%).

Table 7 presents the effect of the soil properties on forage quantity across the land use cover types and seasons. Results showed that during the wet and dry seasons, woodlands had relatively higher dry matter at 42.3 Kg/ha and 31.7 Kg/ha, respectively. This was followed by 42.6 Kg/ha and 10.7 Kg/ha in the grasslands during the wet and dry seasons, respectively. On the other hand, thicket and shrublands land covers had 26.8 Kg/ha and 9.6 Kg/ha of biomass during the wet and dry seasons, accordingly. However, this pattern changed during the transitionary season with the thickets and shrublands having relatively higher dry matter 22.9 ± 9.6 Kg/ha, followed by grasslands and woodlands. Woodlands had a low biomass yield during the transitionary season because some of the plots had been interfered with by partial burning (use of fire).

*5.2. Influence of Soil Properties on Forage Quantity.* The principal component analysis (PCA) revealed a strong

Table 1: Summary of chemical and physical soil properties characteristics.

| Property | Depth (cm) | Grasslands | Thickets and shrublands | Woodlands | $p$ |
|---|---|---|---|---|---|
| pH | 0–15 | 7.89[a] | 8.18[a] | 6.89[b] | 0.001 |
| | 15–30 | 8.38[a] | 7.99[a] | 6.91[b] | 0.001 |
| | Avg. | 8.14 | 8.08 | 6.9 | |
| N (%) | 0–15 | 0.13 | 0.12 | 0.12 | ns |
| | 15–30 | 0.12 | 0.11 | 0.12 | ns |
| | Avg. | 0.125 | 0.115 | 0.12 | |
| SOM (%) | 0–15 | 1.84 | 1.33 | 1.37 | ns |
| | 15–30 | 1.61 | 1.23 | 1.38 | ns |
| | Avg. | 1.725 | 1.28 | 1.375 | |
| Av. P (ppm) | 0–15 | 2.75[a] | 0.06[b] | 26.91[c] | 0.027 |
| | 15–30 | 0.33[a] | 0.23[a] | 45.23[b] | 0.03 |
| | Avg. | 1.54 | 0.145 | 36.07 | |
| K | 0–15 | 0.84[a] | 0.34[b] | 0.22[bc] | 0.023 |
| | 15–30 | 0.63 | 0.48 | 0.51 | ns |
| | Avg. | 0.735 | 0.41 | 0.365 | |
| AWC ($cm^3/cm^3$) | 0–15 | 0.112 | 0.102 | 0.106 | ns |
| | 15–30 | 0.104 | 0.106 | 0.106 | ns |
| | Avg. | 0.108 | 0.104 | 0.106 | |
| Clay (%) | 0–15 | 29.26[a] | 33.68[a] | 13.11[b] | 0.001 |
| | 15–30 | 28.36[a] | 29.88[a] | 10.61[b] | 0.001 |
| | Avg. | 28.81 | 31.78 | 11.86 | |
| Sand (%) | 0–15 | 54.79[a] | 54.01[a] | 68.88[b] | 0.032 |
| | 15–30 | 58.11[a] | 54.57[a] | 77.06[b] | 0.001 |
| | Avg. | 56.45 | 54.29 | 72.97 | |
| Texture class | 0–15 | SCL | SCL | SL | |
| | 15–30 | SCL | SCL | SL | |

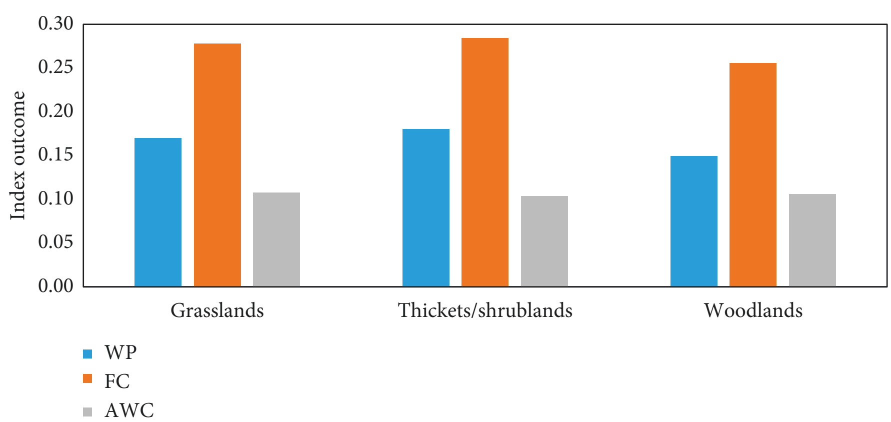


Figure 3: Shows wilting point (WP), field capacity (FC), and available water content (AWC) for the different land cover types in Karamoja.

Table 2: Relationship between soil properties and forage quantity in grasslands.

| | Biomass (kg/ha) | N | SOM | K | P (ppm) | Na | Mg | pH | % clay | % sand |
|---|---|---|---|---|---|---|---|---|---|---|
| Biomass (kg/ha) | 1 | | | | | | | | | |
| N | −0.486 | 1 | | | | | | | | |
| SOM | −0.375 | 0.509 | 1 | | | | | | | |
| K | −0.603 | 0.241 | 0.442 | 1 | | | | | | |
| P (ppm) | 0.077 | 0.5 | 0.112 | −0.219 | 1 | | | | | |
| Na | −0.204 | 0.233 | 0.49 | **−0.005** | 0.07 | 1 | | | | |
| Mg | 0.536 | −0.571 | −0.205 | −0.158 | −0.265 | 0.14 | 1 | | | |
| pH | −0.134 | 0.106 | **0.009** | −0.014 | −0.466 | 0.055 | 0.146 | 1 | | |
| % clay | −0.263 | **−0.038** | −0.403 | 0.32 | −0.337 | **0.032** | −0.135 | −0.085 | 1 | |
| % sand | 0.158 | 0.064 | 0.438 | −0.173 | 0.431 | **0.039** | 0.208 | −0.095 | −0.938 | 1 |

Table 3: Relationship between soil properties and forage quantity in thickets/shrublands.

| | % N | % clay | SOM | % sand | % silt | Biomass (kg/ha) | Ca | K | Mg | Na | P (ppm) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % N | 1 | | | | | | | | | | | |
| % clay | 0.132 | 1 | | | | | | | | | | |
| SOM | 0.632 | −0.395 | 1 | | | | | | | | | |
| % sand | −0.368 | −0.763 | 0 | 1 | | | | | | | | |
| % silt | 0.5 | −0.763 | 0.789 | 0.289 | 1 | | | | | | | |
| Biomass (kg/ha) | −0.564 | −0.667 | −0.154 | 0.359 | 0.308 | 1 | | | | | | |
| Ca | 0.289 | −0.553 | **0.026** | 0.553 | 0.526 | 0.205 | 1 | | | | | |
| K | 0.921 | 0.289 | 0.553 | −0.289 | 0.263 | −0.821 | 0.158 | 1 | | | | |
| Mg | 0.289 | −0.553 | 0.026 | 0.553 | 0.526 | 0.205 | 1 | 0.158 | 1 | | | |
| Na | −0.308 | 0.564 | −0.872 | −0.41 | −0.667 | 0.1 | **−0.051** | −0.359 | −0.051 | 1 | | |
| P (ppm) | 0.289 | 0.684 | −0.237 | −0.921 | −0.289 | −0.154 | −0.289 | 0.132 | −0.289 | 0.667 | 1 | |
| pH | 0.975 | 0.205 | 0.667 | −0.359 | 0.41 | −0.7 | 0.154 | 0.975 | 0.154 | −0.4 | 0.205 | 1 |

Table 4: Relationship between soil properties and forage quantity in the woodlands.

| | Biomass (kg/ha) | % clay | % N | SOM | % sand | % silt | Ca | K | Mg | Na | P (ppm) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biomass (Kg/ha) | 1 | | | | | | | | | | | |
| % clay | 0.51 | 1 | | | | | | | | | | |
| N | −0.425 | **−0.053** | 1 | | | | | | | | | |
| SOM | 0.222 | 0.423 | 0.47 | 1 | | | | | | | | |
| % sand | −0.341 | −0.812 | **−0.04** | −0.64 | 1 | | | | | | | |
| % silt | 0.152 | 0.333 | 0.074 | 0.276 | −0.41 | 1 | | | | | | |
| Ca | 0.49 | 0.682 | −0.232 | 0.09 | −0.626 | 0.52 | 1 | | | | | |
| K | −0.286 | 0.393 | 0.529 | 0.703 | −0.634 | 0.336 | 0.057 | 1 | | | | |
| Mg | 0.499 | 0.693 | −0.25 | 0.068 | −0.644 | 0.439 | 0.982 | 0.068 | 1 | | | |
| Na | 0.324 | 0.902 | **−0.004** | 0.295 | −0.698 | 0.249 | 0.65 | 0.308 | 0.661 | 1 | | |
| P (ppm) | −0.455 | −0.35 | 0.645 | 0.41 | −0.09 | 0.095 | −0.332 | 0.449 | −0.31 | −0.251 | 1 | |
| pH | 0.46 | 0.797 | −0.089 | 0.314 | −0.741 | 0.369 | 0.532 | 0.419 | 0.532 | 0.646 | −0.237 | 1 |

Table 5: Effects of land cover type on physical and chemical soil properties at 0–15 cm depth.

| Season | Land cover type | Sand | Clay | Silt | SOM | T N | Av. P | K | Ca | Mg | Na | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | % | | | ppm | | Cmol/Kg | | | |
| Dry | Grassland | 54.8 | 29.2 | 16 | 1.84 | 0.1 | 7.4 | 0.8 | 4.2 | 1.2 | 0.9 | 7.9 |
| | Thickets/shrublands | 54 | 33.7 | 14.3 | 1.3 | 0.1 | 0.5 | 0.7 | 4.7 | 1.3 | 1.6 | 8.2 |
| | Woodlands | 68.9 | 13.1 | 13.8 | 1.37 | 0.1 | 5.4 | 0.6 | 11.6 | 0.4 | 0.2 | 6.9 |
| Wet | Grassland | 53.2 | 31.9 | 15.1 | 1.45 | 0.1 | 0.75 | 0.7 | 24.0 | 4.1 | 0.9 | 7.9 |
| | Thickets/shrublands | 50.8 | 34 | 16.7 | 1.2 | 0.1 | 0.32 | 0.6 | 27.3 | 4.0 | 1.4 | 8.1 |
| | Woodlands | 57.6 | 26 | 22.9 | 1.3 | 0.1 | 3.06 | 0.6 | 9.6 | 3.3 | 0.4 | 7.0 |
| *Land cover* ($p \leq 0.05$) | | **0.03** | **<.001** | **Ns** | **Ns** | **Ns** | **Ns** | **Ns** | **<.001** | **Ns** | **<.001** | **<.001** |
| *Season* ($p \leq 0.05$) | | **Ns** | **0.047** | **0.049** | **Ns** | **0.02** | **Ns** | **Ns** | **<.001** | **<.001** | **Ns** | **Ns** |

Table 6: Effects of land cover type on physical and chemical soil properties at 15–30 cm depth.

| Season | Land use type | Sand | Clay | Silt | SOM | TN | *p* | Exch. K | Ca | Mg | Na | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | % | | | ppm | | Cmol/Kg | | | |
| Dry | Grassland | 58.3 | 28.0 | 15.8 | 1.8 | 0.2 | 1.2 | 0.7 | 4.6 | 1.1 | 1.4 | 8.3 |
| | Thickets and shrubs | 54.6 | 29.9 | 15.4 | 1.3 | 0.1 | 2.1 | 0.5 | 3.9 | 1.0 | 1.4 | 8.0 |
| | Woodlands | 76.4 | 16.1 | 13.8 | 1.4 | 0.1 | 4.7 | 0.5 | 1.5 | 0.3 | 0.2 | 6.9 |
| Wet | Grassland | 56.9 | 29.7 | 15.8 | 1.1 | 0.1 | 0.6 | 0.7 | 30.8 | 4.3 | 1.0 | 7.9 |
| | Thickets and shrubs | 56.0 | 28.5 | 18.0 | 0.9 | 0.1 | 1.0 | 0.5 | 20.7 | 3.6 | 1.5 | 8.0 |
| | Woodlands | 56.9 | 27.0 | 20.4 | 1.2 | 0.1 | 2.3 | 0.6 | 17.9 | 2.9 | 1.3 | 7.3 |
| *Land cover* ($p \leq 0.05$) | | **0.004** | **0.02** | **Ns** | **0.042** | **Ns** | **0.03** | **0.05** | **0.049** | **0.048** | **Ns** | **0.003** |
| *Season* ($p \leq 0.05$) | | **0.02** | **Ns** | **Ns** | **0.002** | **0.003** | **Ns** | **Ns** | **<.001** | **<.001** | **Ns** | **Ns** |

Table 7: Influence of soil properties on forage quantity in the land cover units.

| Land cover unit | Grasslands | | Thickets and shrublands | | Woodlands | |
|---|---|---|---|---|---|---|
| Soil property | Estimate | $p$ value | Estimate | $p$ value | Estimate | $p$ value |
| Intercept | 29.532 | 0.001 | 13.836 | 0.001 | −0.039 | 0.977 |
| pH | −1.261 | 0.001 | −0.618 | 0.001 | 0.254 | 0.013 |
| Nitrogen content (%) | 10.915 | 0.005 | 42.896 | 0.001 | −15.313 | 0.001 |
| SOM (%) | −0.724 | 0.003 | −0.806 | 0.001 | 0.926 | 0.001 |
| Phosphorus (ppm) | −0.019 | 0.001 | 3.771 | 0.001 | −0.014 | 0.661 |
| Potassium (cmol/Kg) | −3.14 | 0.001 | −10.46 | 0.001 | 1.146 | 0.332 |
| Ca | −0.008 | 0.644 | −0.16 | 0.001 | 0.048 | 0.001 |
| Mg | 0.514 | 0.001 | 1.402 | 0.001 | 0.001 | 0.001 |
| Na | 0.905 | 0.023 | 0.225 | 0.086 | −0.682 | 0.306 |
| Sand (%) | −0.173 | 0.001 | −0.026 | 0.512 | 0.031 | 0.006 |
| Clay (%) | −0.225 | 0.001 | −0.184 | 0.001 | −0.016 | 0.408 |
| Silt (%) | 0.01 | 0.991 | 0.074 | 0.045 | −0.036 | 0.019 |
| N : P ratio | 0.08 | | 0.004 | | 0.04 | |
| $R^2$ | 0.899 | | 0.844 | | 0.617 | |

correlation of six soil properties with the forage quantity (Figure 4). Results of the generalized linear regression model revealed different levels and patterns of influence soil properties have on forage quantity (Table 7). Soil pH, potassium and sodium, percent sand, and percent clay were observed to be inversely significant ($p \leq 0.05$) in the grasslands. This indicates that a decline in these soil properties potentially triggers an increase in forage quantity in the grasslands. A similar pattern was observed in SOM and phosphorus. Meanwhile, magnesium (Mg) and nitrogen had a positive significant effect on forage quantity in the grasslands.

In the thickets and shrublands, phosphorus, calcium, magnesium, and percent clay had a significant but inverse effect on forage quantity at 3.8%, 0.2%, 1.4, and 0.2% respectively. This indicates that a decline in these soil properties would result to an increase in biomass quantity in the thickets/shrublands land cover type. This trend was also observed in pH and SOM that had a 0.6% and 0.8% inverse influence rates on biomass, respectively. Notably, nitrogen was observed to have a relatively high positive significant ($p \leq 0.05$) effect on forage quantity at 42.9% in the thickets/shrublands, indicating that a unit increase in nitrogen in the thickets/shrublands would lead to a 42.9% increase in forage quantity. Meanwhile, a low N : P ratio (0.004) pertained in the thickets/shrublands; this indicated that phosphorus was a limiting soil nutrient in the thickets/shrublands. Nitrogen was found to a negative ($p \leq 0.05$) effect on forage quantity in the woodlands (Table 7). This revealed that a reduction in nitrogen in the woodlands would lead to an increased forage quantity in this land cover. However, calcium, pH, and percent sand showed a positive influence on biomass at 10% level. A lower N : P ratio (0.04) in the woodlands was identified revealing phosphorus limitations.

## 6. Discussion

*6.1. Soil Properties in Various Land Cover Types.* Soil pH is an important soil chemical property for healthy plant growth. This is because it controls the availability of nutrients most especially phosphorus [59]. At an average pH 7.7, the soils of Karamoja can be classified into moderately acidic to strongly alkaline category as described by [60]. Besides being high, the pH was variable across the three land cover types as well as with depth. The high pH observed in Karamoja is attributable to high calcium deposits within the subregion. The mining of calcium rich rocks (limestone and marble) in the subregion in Moroto and Amudat district provides evidence to the calcium rock deposits in the area. Further, the deep wells including boreholes in the subregion are characterised with hard water which is indication of high calcium compound deposits [61]. According to Perry [62], soils in semiarid and arid regions are generally characterised by neutral to high pH (7.0–8.7). Arshadullah et al. [63] have documented the presence of high alkaline pH in semiarid ecosystems of Pakistan. A high pH in semiarid environments is attributed to the fact that soils developing in these environments tend to retain the alkaline earth and alkali cations to a great extent. Thus, the hydroxides of these cations form, leading to an alkaline pH [64]. Further, this study has shown significant differences in pH of different land cover types. This variation in soil pH could be attributable to soil types [65], parent materials [66], and land use activities [67].

Nitrogen levels observed in the subregion as well as in respective land covers (grasslands, thickets/shrublands, and woodlands) were generally below the critical levels in [52]. However, they were relatively higher than those observed in semiarid Mulga lands of Australia [68]. Semiarid areas have been reported to have low nitrogen levels [69]. Albeit an exception to this pattern is found in the earlier study by [70] that revealed a relatively high nitrogen content of 5 to 8% in semiarid Senegal. Low N presence in the different land covers could be attributed to limited presence of leguminous plants in the land covers that could support N fixation. Notwithstanding low nitrogen across different land covers, Venkanna et al. [71] showed nitrogen variability with respect to land use/cover types in which grasslands often have relatively higher nitrogen compared to croplands.

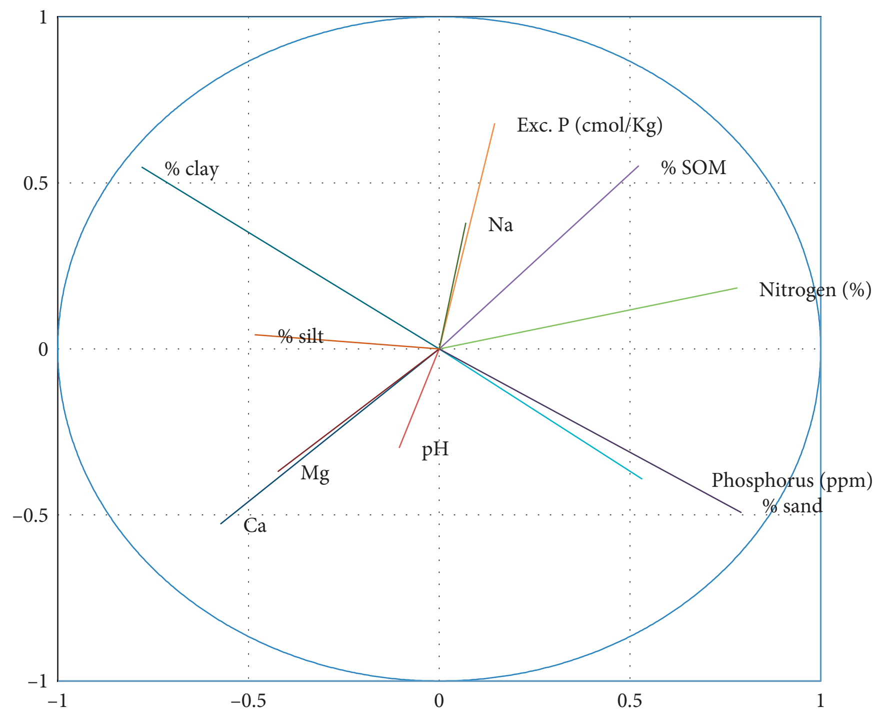


Figure 4: Principal component analysis of the relationship between forage quantity and soil properties.

The average soil organic matter (SOM) in this study was lower than the limit value suggested by Pradini et al. [72]. It is also far below the minimum level indicated by Smith and Elliot [73] as well as that documented by Arshadullah et al. [63] in the semiarid Pabbi, Pakistan. These low levels of SOM reveals a low soil fertility in the area. Yet, SOM is one of the important indicators of soil quality [74]. According to [65] semiarid areas are typified by relatively low SOM concentrations. This is often conspicuously low ranging between 0.5 and 3% and generally less than 1% [72, 73]. This presence of low SOM in semiarid areas has been attributed to inputs dominated by plant-derived organic matter, degradation processes regulated by microorganisms, and organomineral interactions [75]. Further, it is a result of low primary productivity and rapid SOM mineralization that often characterises semiarid regions [65]. Karamoja subregion is no exception to these patterns. This is because the quantified biomass as indicated by the results of this study is lower than in most grazing systems of the same rainfall regime. For example, Chen et al. [76] have shown evidence of herbaceous biomass quantity ranging between 518 kg/ha to 8075 kg/ha in the semiarid rangelands of Idaho. This is above the established herbaceous biomass quantified in the subregion. It is also important to note that in Karamoja, the frequent use of fire as a range management tool leads to limited ground litter cover that could potentially be decomposed into SOM.

The average phosphorus in the land covers was indicated at 3.4 ± 6.8 mg/kg with a range of 0.4 to 5.7 mg/kg. Thickets/shrublands were indicated to have the lowest average phosphorus content. These levels of phosphorus reveal severe deficiency because they are far lower than the critical limits (15 mg/kg$^{-1}$). But, phosphorus (P) has been observed as the second most limiting micronutrient for plant growth after N. This is because P makes up to 0.2% of the plant's dry weight and is a component of key molecules. Ample plant growth is dependent on a reliable supply of phosphorus [77]. Thus, P limitations observed in the subregion can quite well help to explain the low quantity of forage obtained per hectare in the different land covers. Further, the observed P in Karamoja was lower than that observed in semiarid northern Ghana [78] as well as in semiarid Argentina [79]. The cases of higher P levels identified by these two studies could be an exception in semiarid regions as several studies have shown P deficiencies in semiarid areas. Whereas, this study did not analyze the effect of phosphorus on livestock reproductive and growth performance, the apparently low levels offer insights into the likely livestock status performance.

The K content obtained in this study is slightly higher than that obtained by Chikuvire et al. [80] in semiarid Zimbabwe. Our results however show lower K levels compared to the results of [81] obtained in the Negev desert in Israel. This could be attributable to differences in land cover types as well as the geologies of the two places. The availability of potassium in the soil is generally attributed to the type of K-bearing minerals, the degree of weathering, and the intensity of soil forming processes [82]. Further, Paliwa and Sundaravalli [83] observed that burning in a semiarid ecosystem of Madurai positively influenced potassium availability. Given that burning is a management strategy that is applied on an annual basis in the Karamoja subregion, it is likely that in addition to parent material-related factors, it also contributes to relatively high K availability in the region. This is an issue that requires further investigation.

The bulk density observed in this study in the different land cover types was within the optimum value for arable soils. It also reveals that the land cover types had minimal levels of soil compaction. Based on the criteria for identification of monitoring sites, this result confirms the reliability of site selection criteria. Further, it shows that there is value in integrating traditional ecological knowledge when conducting rangeland monitoring studies. In an earlier study, Alderfer et al. [84] established that in nongrazed and lightly grazed landscapes, soil bulk density ranged between 1.09 and 1.51 $Mg/m^3$, and this study's results are within this range. Further, they had shown that for heavily grazed sites, soil bulk densities ranged from 1.54 to 1.91 $Mg/m^3$, indicating relatively high compaction. Similarly, Ayoubi et al. [85] in a study in semiarid western Iran have shown that under pasture, soil bulk density is significantly lower ($1.30\,g{\cdot}cm^{-3}$), which is in agreement with our findings. Considering that this study's results show minimal compaction of the land cover types, degradation in the monitoring sites is thus limited.

According to [19] in an ethnological study in Karamoja, the Matheniko pastoralists of Moroto district had characterised their land covers as moderately to minimally used. This could further explain the favorable bulk density values observed in this study. It also shows that there is minimal livestock trampling in the grazing land covers. This study's findings have further reinforced earlier findings by providing biophysical evidence from the grazing land covers within the subregion. However, in Oba's findings, the landscapes with poor status were those near settlements and security establishments. Similarly, during the field process, we observed considerable gradient effect existing in and around the waterholes and protected kraals with high grazing and trampling intensity, lose soil, and compact soil particles in others as well as existence of erosion signs.

The low bulk density associated with minimum compaction observed in this study could thus provide plausible explanation to the relatively high saturated hydraulic conductivity (Ksat) also observed in this study. However, compared to saturated hydraulic conductivity results reported in semiarid profiles in Tunisia ($4.84 \pm 3.33\,kg{\cdot}s{\cdot}m^{-3}$) and Senegal $3.93 \pm 2.24\,kg{\cdot}s{\cdot}m^{-3}$ [86], our results are slightly higher but lower than those reported in the semiarid Maireana shrubs of Australia [87]. It is important to note that there was considerable variation in Ksat values in the different land cover units with the highest values observed in the woodlands while the thickets/shrublands were within comparable range. Consequently, the land cover type was later found to have a significant effect on Ksat. This phenomenon is not unusual because it is not unusual to obtain variation in Ksat depending on the depth and the method in use [88], type of soil, for example, sandy versus clayey soils [86], land use practice [89], type of vegetation, and landform [90].

*6.2. Influence of Land Cover and Seasonality on Soil Properties.* A significant effect of land cover on soil properties was identified in this study. However, it varied with soil depth (0–15 cm and 15–30 cm). Land cover type had a significant influence on percent sand, percent clay, calcium content, and sodium and soil pH at 0–15 cm depth. At 15–30 cm depth, the range of influence expanded to include percent sand, percent clay, SOM, phosphorus, potassium, calcium, and magnesium and soil pH. Sodium and percent silt were not influenced by land cover type at this soil depth. Additionally, land cover had a significant impact on bulk density and saturated hydraulic conductivity (Ksat). Land cover alteration tends to influence bulk density and Ksat after conversion from one form to the other for example, from forested to nonforested-exposed lands [91]. Similarly, [14, 92] found a significant influence of land cover type on physical and chemical soil properties.

Changes in land cover led to land degradation in the Gadarif region of Sudan. Soil properties such as organic matter, interchangeable K, and available P showed degradation tendencies in the Trans-Mexican volcanic system of Mexico. Therefore, conversion of woodlands into grasslands will likely elicit a similar pattern as observed in the previous studies. Land cover changes have already been observed to be occurring in the subregion at an unprecedented rate with grasslands, thickets/shrublands, and woodlands being threatened by croplands [42]. Moreover, land cover types vary in their rooting characteristics; for example, forests and shrublands have been found to root deeper with better diameter, dispersion, and biomass than rooting systems of herbaceous plants (characteristic of grasslands) or cultivated crops [93]. Our results also reveal that soils under native vegetation cover often have low bulk density and high saturated hydraulic conductivity. This corroborates with the earlier findings of [94]. However, in the findings of Celik [95] and Li and Shao [96], soils exposed to human influence are often stripped of organic rich upper horizons, resulting in higher BD values and reduced infiltration rates.

Seasonality has a bearing on nutrient availability. Our results showed that season had significant influence on pH, bulk density, saturated hydraulic conductivity, soil organic matter, and nitrogen. This corroborates with findings of several researchers [97, 98] that reported the influence of season on various soil properties (SOM, total nitrogen, soil pH, available phosphorus, and exchangeable cations). Further, this study has reported a significant influence of season on saturated hydraulic conductivity and bulk density that are also significantly different across various land cover types. Additionally, the land cover type has been identified to influence saturated hydraulic conductivity, and this varies across seasons [99], as observed in this study.

*6.3. Effect of Soil Properties on Forage Quantity.* This study observed a positive relationship between nitrogen and forage quantity in thickets/shrublands and grasslands similar to the findings of other scientists [24, 100–102] that established a positive relationship between increased nitrogen and aboveground forage quantity in various parts of Africa such as Laikipia in Kenya and Northern Cape, South Africa. The influence of nitrogen on herbaceous biomass arises from the N fertilization that often leads to increased net primary production (shoot biomass) and thicker stands [8, 9, 103].

This perspective has similarly been shown in this study (Table 7). However, in the woodlands, an inverse influence of nitrogen on forage quantity was observed. This could be attributed to the fact that in woody land cover types, there is often a strong negative dependence of woody cover on soil nitrogen availability [104]. This result is however contrary to the findings of other researchers [105–107] that have showed that under conditions of increased nitrogen, the yield of biomass and dry matter are generally high. In the case of the current study, the result observed is attributable to the fact that nitrogen was not a limiting nutrient in the woodlands as results revealed phosphorus limitations. Phosphorus limitation on grass growth has been observed in semiarid Laikipia [108].

Potassium (K) is an essential macronutrient for normal plant growth. In a limited amount, it limits accumulation of crop/pasture biomass resulting tin stunting of crop/pasture as well as low yields [109–111]. In this study, potassium exhibited inverse relationship with forage quantity in all the land cover types (Table 7). This contrasts with the findings of [110, 112] that opined that potassium has an incremental effect on plant biomass accumulation. The inverse relationship observed in this study could be attributed to relatively elevated potassium levels (0–15 cm ($0.7 \pm 0.2$ cmol/kg) and 15–30 cm ($0.6 \pm 0.2$ cmol/kg) soil depth. This was higher was higher than the critical soil potassium (0.19 cmol/kg) needed to achieve a 90% maximum yield in crops such as sorghum and maize [113]. Sorghum and maize are closer to herbaceous grasses that were quantified in this study. We attribute the relatively high K concentrations in this study to ash accumulation from continuous burning that takes place in the subregion. Routine burning is used as a management tool to facilitate forage regrowth. Biomass burning and continuous livestock grazing have previously been found to lead to relatively high potassium content concentrations in the grassland savannas in Kenya [114].

The SOM was found to have negative relation with forage quantity in thicket/shrublands and grassland land covers while it increased forage quantity in the woodlands. This result is particularly intriguing because SOM is generally expected to have a positive association with above-ground biomass production [115]. However, the pattern observed could also suggest that greater SOM could be associated with higher clay content which in itself could be an active negative factor for perennial plant growth. Further, we opine that this outcome could be arising from the limited soil moisture in the grasslands and thickets/shrublands. This leads to limited decomposition of litter; as a result, the available SOM cannot be transferred into available nutrient for plant growth. It is important to note that this result contrasts the findings of [116] who reported that total above-ground biomass was influenced by soil organic matter. Owing to the complex nature of soil quality and/or soil health effects, we hold the maxim that "correlation is not causality" with regard to this study's findings.

## 7. Conclusions

This study has shown that soil nutrient levels in Karamoja are generally low confirming the notion of low nutrient availability in semiarid areas. However, instances of above average soil nutrient levels such as the case with potassium whose value was above the critical level determined as necessary to achieve a 90% yield in crops such as sorghum were observed. Secondly, nitrogen and phosphorus limitations varied in the different land cover types. Nitrogen was observed as a limiting nutrient in the grasslands while phosphorus was a limiting nutrient in the thickets/shrublands and woodlands. Thus, any improvement on pasture production as well as crop production (particularly sorghum that is commonly grown in the region) in these land covers ought to address these nutrient limitations. Thirdly, seasonality and differences in land covers influenced forage quantity; this strengthens the evidence of heterogeneity, a key attribute that has for long facilitated local level (land cover type) to regional level (landscape level) opportunistic livestock herd management among pastoralists and agropastoralists in the subregion. Besides seasonality and land cover type influence on forage quantity, soil properties both physical (bulk density and saturated hydraulic conductivity) and chemical (N, P, K, SOM) have a significant influence on forage quantity in the subregion. We recommend for long-term monitoring of soil properties and forage under different grazing regimes in Karamoja subregion. Further, it is vital that the identified soil nutrients that influence forage quantity be validated in the subregion.

## Data Availability

Primary data for this study and the results contained therein are available and can be made available on request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Anthony Egeru was involved in the study conceptualization, development, data collection, and manuscript write-up. Oliver V. Wasonga, provided technical backstopping in the study design and manuscript development and quality assurance processes in the study. Geofrey Gabiri provided support in data collection and data analysis. Laban A. MacOpiyo played a role in research design, data collection supervision, and field based monitoring for quality assurance. John Mburu supported the editorial components of the manuscript development process. Gilbert Jackson Mwanjalolo Majaliwa provided technical backstopping in data analysis, interpretation of results, and manuscript structuring.

## Acknowledgments

This study was funded in part by Carnegie Corporation of New York through Makerere University and Regional Universities Forum for Capacity Building in Agriculture. The funding agency did not take part in the design of the study neither in the collection, analysis, and interpretation of data thereof leading this paper.

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