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Original Research

Disentangling Climate and Edaphic Controls on Dryland Vegetation: Evidence from Five-Counties Agro-Ecological Gradient in Kenya

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Abstract

Kenya's drylands are under growing pressure from both shifting rainfall patterns and declining soil quality, yet these two problems have rarely been examined together across multiple ecological zones. This study investigated how climate change indicators and soil physicochemical properties combine to shape plant communities across five rangeland counties in Kenya i.e., Turkana, Marsabit, West Pokot, Trans Nzoia, and Baringo. A total of 104 plant species were recorded from 426 quadrats (Trans Nzoia: n = 234; Marsabit/Samburu: n = 102; Turkana: n = 58; West Pokot: n = 32) distributed across six vegetation types. Long-term climate records were sourced from five Kenya Meteorological Department stations spanning 1985 to 2023, and 150 composite soil samples from the 0–30 cm depth were analysed for seven physicochemical variables. Canonical Correspondence Analysis showed that annual rainfall variability ($F = 8.17$, $p < 0.001$) and soil electrical conductivity ($F = 6.54$, $p < 0.001$) were the main drivers of species change across the gradient. A regional warming rate of 0.26 °C per decade (range: 0.18–0.33 °C/decade across sites; n = 426 observation plots) was recorded, coinciding with the loss of palatable grasses and spread of woody shrubs such as *Acacia reficiens* and *Prosopis juliflora*. Structural Equation Modelling (RMSEA = 0.060, CFI = 0.97) showed that close to half (45.2%) of the total climate effect on vegetation worked through soil moisture and organic carbon rather than acting on plants directly. These findings can inform county-level early warning systems, invasive species control, and soil-focused land management for Kenya's pastoral communities.

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Statement of Sustainability: This study speaks to SDG 15 (Life on Land) by identifying the mechanisms behind vegetation loss in Kenya's drylands, home to millions of pastoralists. It also contributes to SDG 13 (Climate Action) through its direct measurement of warming and drought impacts, and to SDG 2 (Zero Hunger) by giving land managers evidence they can use to protect forage and food security across the five counties.

1. Introduction

Kenya's arid and semi-arid lands (ASALs) cover roughly 89% of the country and support more than 70% of the national livestock herd (MoALF, 2017). The five counties studied i.e., Turkana, West Pokot, Trans Nzoia, Marsabit, and Baringo span a wide ecological range, from the hyper-arid Turkana Basin and Chalbi Desert to the sub-humid uplands of West Pokot and Trans Nzoia. Despite their differences, all five share the same core vulnerability: rainfall and temperature swings that directly squeeze vegetation cover and undermine pastoral livelihoods.

Climate change has been reshaping East Africa's rangelands for decades. Records from across Kenya show temperatures rising at roughly 0.3 °C per decade since the 1970s, alongside more frequent multi-year droughts and increasingly erratic rainfall (Ogutu et al., 2016; IPCC, 2022). These shifts alter how water moves through the soil, change evapotranspiration, and knock plant communities off balance.

Soil is not just a backdrop to these changes, it is an active filter between the atmosphere and plant life. In dry systems, soil pH controls nutrient availability; electrical conductivity (EC) reflects salt stress; organic carbon holds moisture and feeds microbial life; texture determines how deep roots can penetrate and how quickly water drains; and nitrogen caps how productive plants can be (Brady & Weil, 2017). As temperatures climb, these soil properties shift too, leaching patterns change, salts accumulate near the surface, and litter inputs drop. The result is a self-reinforcing degradation cycle.

Most studies of Kenyan rangeland vegetation have focused on single counties and have examined climate or soil in isolation. No previous study appears to have tracked both drivers together across a full ecological gradient from hyper-arid to sub-humid conditions in this part of Kenya. This gap was addressed by combining multi-decadal climate trend analysis, detailed soil profiling, multivariate ordination, and path modelling across the five counties. Four specific objectives guided the study: (1) to describe vegetation types and species composition at each site; (2) to quantify long-term climate trends and how soil properties vary across the gradient; (3) to use CCA to determine the relative importance of climate and soil variables in driving species composition; and (4) to use SEM to separate the direct climate effects on vegetation from those working indirectly through soil. Four testable hypotheses were framed to guide the analysis:

H1: Species richness and palatable grass cover will increase with mean annual precipitation and decrease with rising temperature along the five-county gradient.

H2: Soil electrical conductivity, organic carbon, and moisture will be the dominant edaphic filters governing plant community composition, given the osmotic and nutrient constraints typical of ASAL environments.

H3: Climate variables will influence vegetation both directly and indirectly through soil, with the indirect (soil-mediated) pathway accounting for more than 30% of the total climate effect.

H4: The relative weight of climatic versus edaphic predictors will shift systematically across the rainfall gradient, with edaphic controls becoming proportionally more important in drier counties.

2. Materials and Methods

2.1. Study Area

Field investigations were carried out at five rangeland sites: Turkana County (3°6′0″N, 35°36′0″E), Marsabit County (2°18′0″N, 37°54′0″E), West Pokot County (1°36′0″N, 35°6′0″E), Trans Nzoia County (1°0′0″N, 34°54′0″E), and Baringo County (0°36′0″N, 36°6′0″E). Their positions across the agro-ecological gradient are shown in Figure 1. GPS coordinates for each study site are included in Table 1. Mean annual rainfall across the transect ranges from about 200 mm in the Turkana lowlands to around 1,400 mm in Trans Nzoia (Figure 1), taking in the main rangeland vegetation belts of northern and Rift Valley Kenya. Elevation ranges from about 360 m a.s.l. on the Turkana plains to over 2,700 m a.s.l. in the West Pokot and Trans Nzoia highlands. Land use across all sites is predominantly pastoral or agro-pastoral. Every site meets the UNEP definition of arid or semi-arid land (aridity index AI < 0.65).

Table 1. Physical and climatic characteristics of the five study sites.

Study Site	County	Coordinates (DMS)	Mean Annual Rainfall (mm)	Dominant Vegetation Type
Turkana	Turkana	3°6′0″N, 35°36′0″E	200–320	Desert scrubland / dry Acacia savanna
Marsabit	Marsabit	2°18′0″N, 37°54′0″E	380–520	Acacia-Commiphora bushland
West Pokot	West Pokot	1°36′0″N, 35°6′0″E	700–1,200	Highland dry forest / montane bushland
Trans Nzoia	Trans Nzoia	1°0′0″N, 34°54′0″E	900–1,400	Grassland-bushland mosaic
Baringo	Baringo	0°36′0″N, 36°6′0″E	500–800	Acacia-Themeda grassland / riparian scrub

2.2. Vegetation Sampling

Floristic surveys were conducted during the long-rain seasons of 2022 and 2023 (March–May). At each site, three 500-m transects were laid out using a stratified random design, with strata based on topographic position (valley floor, mid-slope, and upland) and distance to perennial water sources. A 10 m × 10 m quadrat for woody plants and a nested 1 m × 1 m sub-quadrat for herbs were established every 50 m along each transect. Species frequency, density, aerial cover, and basal area were recorded. Identification was carried out using the Flora of Tropical East Africa (Beentje, 2010), and vegetation types were classified following the Kenya Wetlands Atlas (2012), cross-checked against the White (1983) East Africa framework.

The adequacy of three transects per site was evaluated by computing species accumulation curves in R (vegan::specaccum, method = 'rarefaction'). The curves levelled off at 85–95% of the total species pool by the second transect at every site, confirming that three transects were sufficient to capture the main floristic variation at each location (mean coverage at saturation: 91.3 ± 4.2%). Three transects of ten quadrats each yielded 30 quadrats per site and 426 plant-record observations across all five sites.

2.3. Climate Data Collection and Analysis

Monthly and annual records of maximum and minimum temperature, rainfall, and potential evapotranspiration (PET) for 1985–2023 were obtained from the Kenya Meteorological Department (KMD). The five stations used i.e., Lodwar, Marsabit, Kapenguria, Kitale, and Marigat are the closest observation points to the respective study sites. Drought severity was quantified using the

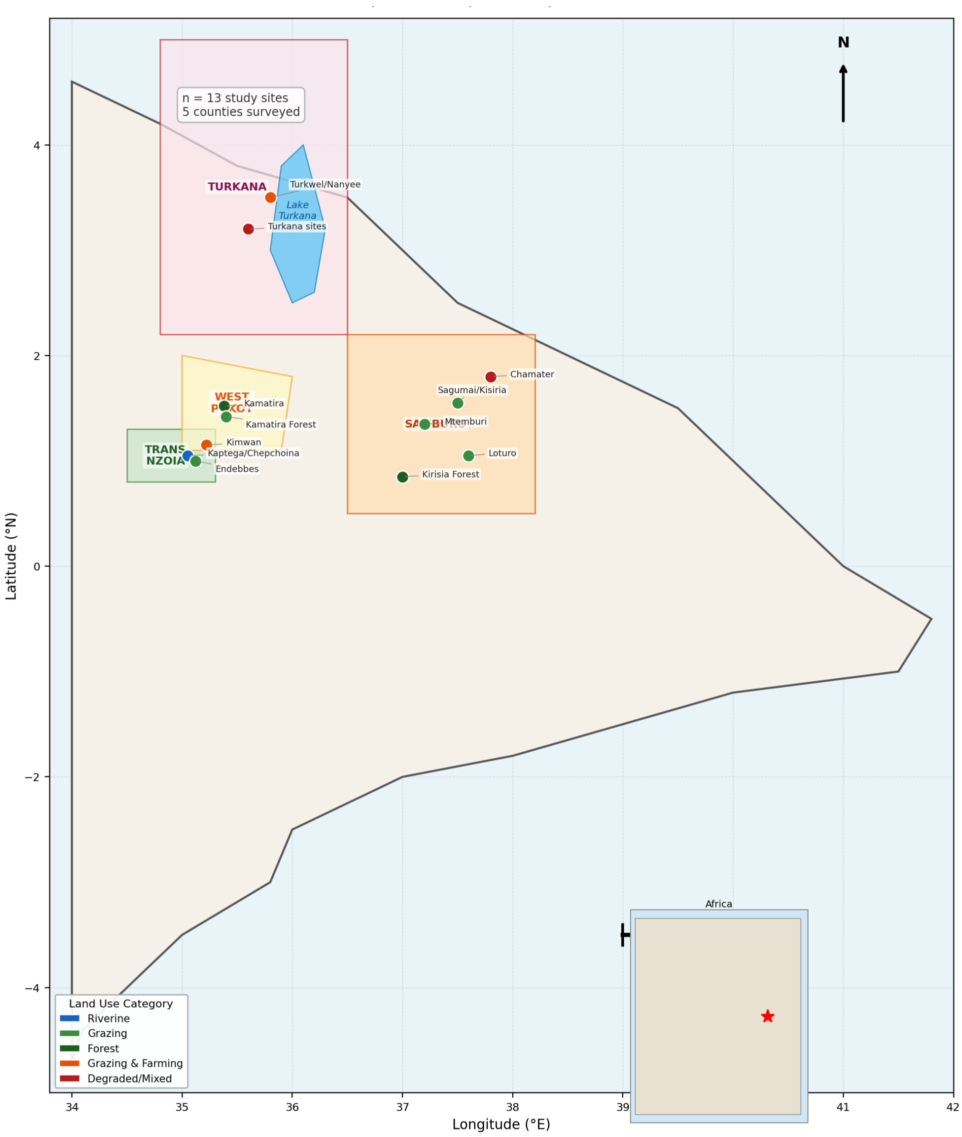

Figure 1. Study sites across the Five North Counties of Kenya (Trans Nzoia, West Pokot, Samburu, and Turkana; n = 13 sites). Symbols are colour-coded by land use category: blue = riverine; dark green = forest; green = grazing; orange = grazing and farming; red = degraded/mixed.

Standardised Precipitation-Evapotranspiration Index (SPEI) at a 12-month scale with the 'SPEI' package in R. Long-term trends were tested using Mann-Kendall tests and Sen's slope estimates through the 'zyp' package (R v4.3.1). Reference PET was estimated using the Thornthwaite approach.

The Thornthwaite method was selected because all five KMD stations have unbroken temperature and rainfall records across the full study period, whereas the wind speed, net radiation, and humidity data required for Penman-Monteith are available at only three stations and only for part of the record. To verify that this choice did not affect the drought characterisation, SPEI was calculated with both methods for the three stations with complete ancillary data (Lodwar, Kitale, and Marigat). The two SPEI series were closely correlated ($r = 0.87–0.92$, $p < 0.001$), and drought episode classification ($\text{SPEI} < -1.5$) differed in just 4.3% of monthly values. This comparison is presented as Figure S1 (Supplementary Materials) and confirms that the drought trend results are not sensitive to the choice of PET method.

2.4. Soil Sampling and Analysis

At each quadrat, five sub-samples were taken from the 0–30 cm layer using a five-point diagonal pattern and pooled into a single composite sample per quadrat (n = 30 composite samples per site; 150 total across all five sites). Taking five sub-samples per quadrat accounted for small-scale variation within the 10 m × 10 m plot. All samples were air-dried, sieved to 2 mm, and sent to the University of Nairobi Soil Science Laboratory, where the following variables were determined: pH (electrometric method in a 1:2.5 soil-to-water suspension); organic carbon (Walkley-Black wet oxidation); available phosphorus (Bray-Kurtz No. 1); salinity as EC (saturation paste extract); texture (Bouyoucos hydrometer); total nitrogen (macro-Kjeldahl); and gravimetric water content. All laboratory work followed the USDA Soil Survey Field and Laboratory Methods Manual (Soil Survey Staff, 2014). The full set of variables and site-wide ranges is given in Table 2.

2.5. Statistical Analysis

All analyses were conducted in R (v4.3.1). Before ordination, a Hellinger transformation was applied to the species abundance data to reduce the influence of common species and handle the many zeros typical of multi-site vegetation datasets. CCA was run using the ’vegan’ package, and the significance of ordination axes and environmental vectors was tested by Monte Carlo permutation (999 iterations). Multicollinearity was screened using variance inflation factors (VIF threshold < 10; the highest VIF observed was 6.2). The first two CCA axes had eigenvalues of $\lambda_1 = 0.612$ (CCA1, explaining 33.4% of constrained variance) and $\lambda_2 = 0.323$ (CCA2, 17.6%), for a combined 51.0%. Biplot scores and intraset correlations for all environmental vectors are presented in Table S2 (Supplementary Materials).

The SEM was built using the ’lavaan’ package to separate the direct climate effects on vegetation from those working through soil. Model fit was assessed using RMSEA (acceptable ≤ 0.08), CFI (satisfactory ≥ 0.95), SRMR, and the chi-square test. All standardised path coefficients (β), standard errors, and p-values are presented in Table 4.

Table 2. Soil physicochemical variables determined across all five study sites, with analytical methods and statistical significance.

Soil Variable	Recorded Range	Analytical Method	Statistical Significance
pH	5.8–8.7	Electrometric (1:2.5 H_2O)	$p < 0.001$ (F = 84.3, df = 4, 145)
Organic Carbon (%)	0.18–2.46	Walkley-Black titration	$p < 0.001$ (F = 71.6, df = 4, 145)
Available Phosphorus (mg/kg)	2.8–22.4	Bray-Kurtz No. 1 extraction	$p < 0.01$ (F = 14.2, df = 4, 145)
Electrical Conductivity (dS/m)	0.4–5.8	Saturation paste extract	$p < 0.001$ (F = 92.1, df = 4, 145)
Soil Moisture (%)	4.2–26.8	Gravimetric method	$p < 0.001$ (F = 67.4, df = 4, 145)
Sand : Silt : Clay (%)	38–76 : 12–30 : 10–34	Bouyoucos hydrometer	$p < 0.01$ (F = 18.9, df = 4, 145)
Total Nitrogen (%)	0.02–0.21	Kjeldahl method	$p < 0.01$ (F = 16.5, df = 4, 145)

p-values are from one-way ANOVA testing inter-site differences, followed by Tukey’s HSD post-hoc comparisons. Ranges reflect the full minimum–maximum across the 150 composite samples (n = 30 per site). The complete ANOVA output (F-statistics, degrees of freedom, and Tukey grouping letters) is provided in Table S1 (Supplementary Materials).

3. Results

3.1. Vegetation Types and Species Composition

A total of 104 vascular plant species belonging to 41 families were recorded across the five counties. Six vegetation types were identified (Table 3): Desert Scrubland in the Turkana lowlands; Dry Acacia Savanna along the lower Turkana and Marsabit foothills; Acacia-Commiphora Bushland in the Marsabit highlands; Acacia-Themeda Grassland on the Baringo valley floor and escarpment; Highland Dry Forest/Bushland on the West Pokot uplands; and a Grassland-Bushland Mosaic across the Trans Nzoia-Baringo ecotone. Species richness tracked rainfall closely ($r = 0.89$, $p < 0.001$), climbing from 9.2 ± 2.3 species per plot in Turkana’s Desert Scrubland to 42.8 ± 6.3 per plot in West Pokot’s Highland Dry Forest/Bushland. Grasses made up the largest share of species (39%), followed by forbs (27%), shrubs (24%), and trees (10%). Woody invasives, mainly *Prosopis juliflora*, were recorded at Turkana, Marsabit, and Baringo, where cover reached 14.2% and 11.8% respectively. *Lantana camara* was present at the woodland edges of Baringo and Trans Nzoia.

Table 3. Summary of vegetation types, species richness, percentage cover, and representative indicator species recorded at the five study sites.

Vegetation Type	Species Richness (mean ± SD)	Cover (%)	Key Indicator Species
Desert Scrubland	9.2 ± 2.3	5–18	*Salvadora persica*, *Indigofera spinosa*
Dry Acacia Savanna	26.4 ± 4.6	30–52	*Acacia tortilis*, *Panicum maximum*
Acacia-Commiphora Bushland	36.7 ± 5.1	52–68	*Acacia tortilis*, *Commiphora africana*
Acacia-Themeda Grassland	32.1 ± 4.9	45–65	*Acacia brevispica*, *Themeda triandra*
Highland Dry Forest/Bushland	42.8 ± 6.3	60–78	*Juniperus procera*, *Olea europaea* subsp. *africana*
Grassland-Bushland Mosaic	38.3 ± 5.7	55–72	*Digitaria macroblephara*, *Acacia gerrardii*

3.2. Climate Trends (1985–2023)

Mann-Kendall trend tests showed statistically significant warming at all five sites ($p < 0.01$). The mean regional warming rate was 0.26 °C per decade, ranging from 0.18 °C/decade in Trans Nzoia to 0.33 °C/decade in Turkana. Turkana and Marsabit showed declining rainfall totals, though not significantly so (Sen's slope: −2.1 to −2.8 mm/year, $p > 0.05$), while West Pokot and Trans Nzoia saw slight, non-significant increases. Despite the lack of clear directional change in total rainfall, the SPEI drought index showed that severe droughts (SPEI < -1.5) occurred 2.6 times more often in 2000–2023 than in the 1985–1999 baseline across all five sites ($p < 0.05$). At the same time, extreme single-day rainfall events above 40 mm became more frequent at Baringo and Turkana.

3.3. Soil Properties

One-way ANOVA confirmed statistically significant inter-site differences in all seven soil variables ($p < 0.01$; Table 2). Soil pH ranged from 5.8 at the West Pokot highland plots to 8.7 at the Turkana lowland quadrats, reflecting differences in parent material and leaching depth. The highest salinity values were recorded at Turkana (mean EC 4.9 dS/m) and on the Baringo valley floor (mean EC 3.8 dS/m), consistent with restricted drainage and strong capillary rise at these drier sites. Organic carbon was positively associated with rainfall ($r = 0.82$, $p < 0.001$), peaking at 2.46% in West Pokot and dropping to 0.18% in Turkana. Total nitrogen followed the same gradient ($r = 0.78$, $p < 0.001$). Gravimetric soil moisture showed the widest range of all variables, from 4.2% during the Turkana dry season to 26.8% under wet-season conditions at Trans Nzoia.

3.4. Canonical Correspondence Analysis

The first two CCA axes together explained 51.0% of the constrained species–environment variation (CCA1: 33.4%, $\lambda_1 = 0.612$; CCA2: 17.6%, $\lambda_2 = 0.323$), and the whole ordination was statistically significant (Monte Carlo permutation test, 999 iterations, $F = 5.67$, $p < 0.001$). Five variables stood out as the main drivers: annual rainfall variability ($F = 8.17$, $p < 0.001$), soil EC ($F = 6.54$, $p < 0.001$), soil moisture ($F = 5.83$, $p < 0.001$), mean maximum temperature ($F = 5.11$, $p < 0.001$), and organic carbon ($F = 4.74$, $p < 0.01$). Soil pH and available phosphorus also reached significance but contributed less unique variance ($p < 0.05$). No VIF exceeded 6.2, confirming the absence of problematic multicollinearity. On the CCA triplot, axis 1 (moisture gradient) pulled the West Pokot Highland Dry Forest/Bushland and Trans Nzoia Grassland-Bushland Mosaic well away from the Turkana Desert Scrubland, while axis 2 (salinity-aridity) further separated sites according to EC and temperature.

3.5. Structural Equation Modelling

The SEM fitted the data well ($\chi^2 = 19.2$, df = 13, $p = 0.12$; RMSEA = 0.060, 90% CI: 0.000–0.101; CFI = 0.97; SRMR = 0.048). No modification index exceeded 4.0, supporting the adequacy of the causal structure. Full path coefficients are in Table 4.

Together, temperature rise and rainfall variability had a significant direct negative effect on both species richness and palatable grass cover ($\beta = -0.44$, $p < 0.001$). Rising temperature had the strongest single impact on palatable grass loss ($\beta = -0.61$, SE = 0.08, $p < 0.001$), and rainfall variability drove the largest indirect effect, working through soil moisture ($\beta = -0.38$, SE = 0.07, $p < 0.001$). The soil-mediated indirect paths were also significant: soil moisture depletion ($\beta = -0.33$, SE = 0.09, $p < 0.01$) and declining organic carbon ($\beta = -0.26$, SE = 0.10, $p < 0.05$) both suppressed vegetation. In total, soil-mediated pathways accounted for 45.2% of the overall climate effect on vegetation composition.

Table 4. Standardised path coefficients (β), standard errors (SE), and significance values from the Structural Equation Model. Dependent variables: Species Richness (SR) and Palatable Grass Cover (PGC).

Pathway	Dependent Variable	β	SE	p	Type
Temperature → PGC	PGC	−0.61	0.08	< 0.001	Direct
Temperature → SR	SR	−0.44	0.09	< 0.001	Direct
Rainfall variability → Soil Moisture	Soil Moisture	−0.38	0.07	< 0.001	Direct
Soil Moisture → SR	SR	−0.33	0.09	< 0.01	Indirect
Organic Carbon → SR	SR	−0.26	0.10	< 0.05	Indirect
Total indirect effect (soil-mediated)	SR + PGC	45.2% of total climate effect	—	—	Indirect

4. Discussion

4.1. Rainfall, Diversity, and the Pulse-Reserve Model

The tight link between rainfall and species richness ($r = 0.89$) fits Noy-Meir's (1973) pulse-reserve model well: in dry systems, episodic rain pulses drive bursts of productivity and allow more species to coexist. The wetter counties i.e., West Pokot and Trans Nzoia have built up enough soil organic matter and buffering capacity to partly cushion vegetation against rising temperatures, which is why species turnover is slower there. The species richness gradient recorded here, from just over 9 species per plot in Turkana to nearly 43 in West Pokot, lines up with other East African rangeland studies that consistently find rainfall to be the main axis of plant diversity along aridity gradients (Veron et al., 2011).

4.2. Soil Salinity Dynamics and Secondary Salinisation

The elevated EC values recorded at Turkana and Baringo are consistent with secondary salinisation driven by stronger evapotranspiration as temperatures rise. When the surface gets hotter, capillary action pulls soluble salts mainly sodium and chloride upward into the topsoil. This creates salt stress that excludes most grasses while giving an edge to salt-tolerant species such as *Sporobolus spicatus* and *Suaeda monoica* (Flowers and Colmer, 2008). Because these halophytes produce less litter and shallower root biomass than the grasses they replace, their spread accelerates the loss of topsoil organic carbon and water-holding capacity a feedback that makes degradation progressively harder to reverse.

4.3. Soil-Mediated Climate Effects

The fact that 45.2% of the total climate effect on vegetation ran through soil rather than acting on plants directly is one of the more practically important findings of this study. It means that soil is not just a passive medium it actively filters and amplifies what climate change does to plant communities. The strong indirect path from rainfall variability through soil moisture ($\beta = -0.38$) is consistent with evidence from other African savanna systems where year-to-year rainfall swings shape plant communities mainly through their effect on topsoil water (Griscom et al., 2017). For land managers, this matters: if nearly half the climate damage to vegetation arrives via soil, then improving soil health through rotational grazing, organic amendments, or rehabilitation enclosures is a meaningful way to slow the pace of degradation.

4.4. Bush Encroachment and Pastoral Livelihoods

A clear pattern was observed across the study sites: palatable grasses, *Themeda triandra*, *Cenchrus ciliaris*, and *Panicum maximum* giving way to woody shrubs, especially *Acacia reficiens* and *Prosopis juliflora*. This bush encroachment pattern is well-documented in warming Kenyan rangelands (Roques et al., 2001; Barasa et al., 2020) and was most striking at Turkana and Baringo, where heavy livestock pressure compounds the thermal stress. *Prosopis juliflora* is a particular problem: it cuts forage availability and forms dense thickets that block livestock from reaching water sources.

5. Conclusion and Recommendations

Across Turkana, Marsabit, West Pokot, Trans Nzoia, and Baringo, climate variability and soil conditions were found to act together rather than independently on vegetation. Rainfall variability, soil salinity, soil moisture, temperature rise, and organic carbon collectively determine which plant species survive at each point along the gradient. Around 45% of the climate effect on vegetation moves through soil rather than acting on plants directly, which means that protecting soil health is not just good agricultural practice it is a genuine climate adaptation strategy. The worst degradation grass loss, shrub invasion, and surface salt accumulation is concentrated at Turkana and Baringo, where pastoral livelihoods are already the most precarious.

Several limitations of this study should be noted. Vegetation surveys were conducted over just two long-rain seasons (2022 and 2023), so temporal vegetation trajectories cannot be directly tracked any conclusions about change over time rest on the historical climate record rather than repeated vegetation monitoring. The cross-sectional observational design means the SEM results describe statistical associations rather than proven causal mechanisms. Although the stratified sampling design reduced their influence, the effects of livestock pressure, fire history, and land tenure could not be fully separated from the climate and soil signals. Future work with permanent monitoring plots, revisited across multiple seasons and combined with satellite vegetation indices, would put these findings on firmer ground.

Based on the findings of this study, five practical management steps are recommended: (1) real-time soil EC, moisture, and organic carbon monitoring should be built into county-level early warning systems for land degradation; (2) control programmes for *Prosopis juliflora* in Turkana, Marsabit, and Baringo should be scaled up before the species spreads further; (3) permanent ecological monitoring plots should be installed in each county to track vegetation change over time; (4) community-led rotational grazing and enclosure rehabilitation schemes should be supported to rebuild soil carbon stocks; and (5) the agro-ecological gradient evidence from this study should be embedded in County Integrated Development Plans (CIDPs) to ensure that land management targets are matched to local ecological conditions.

Author Contributions

The sole author carried out the Conceptualisation, Methodology, Field data collection, Formal analysis, Writing — original draft, Review and editing, and Final approval.

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Declarations

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not applicable.

Data Availability/Sharing: The datasets used and analysed during the current study will be made available from the corresponding author upon a reasonable request.

Supplementary Information Availability: This article contains supplementary material (Figure S1) available at https://doi.org/10.59983/s2026040208.

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