

Spatial Distribution and Temporal Expansion of *Prosopis Juliflora*, pasture availability and livestock productivity in Ngaremara Ward, Isiolo County

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Abstract

Prosopis juliflora is among the most aggressive invasive alien woody species threatening the ecological integrity of arid and semi-arid rangeland ecosystems. Although originally introduced to combat desertification and provide fuelwood and fodder, its rapid expansion has transformed pastoral landscapes by reducing grazing resources and threatening livestock-dependent livelihoods. This study assessed the spatial distribution and temporal expansion of *P. juliflora* and evaluated their implications for pasture availability and livestock productivity in Ngaremara Ward, Isiolo County, Kenya. A stratified household survey of 413 pastoral livestock keepers, complemented by seven key-informant interviews, four focus-group discussions and rangeland observations, was conducted to assess household-level impacts and livestock-production outcomes. Google Earth Engine was used to process multi-temporal Landsat imagery to characterize long-term land-use and land-cover dynamics, while higher-resolution Sentinel-2 imagery was used to validate and refine recent invasion patterns. Supervised Random Forest classification was integrated with Normalized Difference Vegetation Index analysis to estimate pasture availability across invasion gradients. The land-cover classification achieved an overall accuracy of 88.6% and a Kappa coefficient of 0.84. Household-level analysis showed that perceived impacts differed significantly among households, with age, production system and feed shortage showing threshold-specific associations with impact severity. Older household heads and agro-pastoral households were particularly vulnerable at the highest severity level, while adaptation effectiveness varied by production system and household-head gender. Long-term analysis revealed continuous expansion of *P. juliflora* between 2013 and 2025, particularly after 2019. Coverage increased by approximately 249% during the dry season and 213% during the wet season, while pastoral rangelands declined by approximately 1.2% and 10.2%, respectively. Normalized Difference Vegetation Index (NDVI) analysis indicated declining vegetation productivity within invaded areas, while evergreen *P. juliflora* sometimes produced high greenness values without indicating recovery of palatable pasture. These findings provide robust evidence to inform invasive species management, rangeland restoration, and sustainable pastoral resource planning across Kenya's arid and semi-arid lands.

Keywords: *Prosopis juliflora*, Google Earth Engine, Random Forest classifier, rangeland degradation, pastoral livelihoods.

1.0 Introduction

The environmental conditions of northern Kenya, characterized by ephemeral rivers and recurrent droughts, provide favorable conditions for the expansion of *P. juliflora*. In Isiolo County, the invasion has emerged as a significant ecological and socioeconomic concern, as dense thickets replace native forage species and restrict livestock access to grazing areas and water resources (Mbaabu et al., 2019). Within the county, Ngaremara Ward has experienced substantial invasion, particularly along drainage networks and communal grazing areas (Akala et al., 2026). Nevertheless, the limited availability of quantitative spatiotemporal data, despite field reports of extensive encroachment, continues to constrain effective management and evidence-based policy development.

Remote sensing and geographic information systems offer valuable approaches for monitoring the distribution and dynamics of invasive species. Multitemporal satellite imagery enables researchers to quantify changes in vegetation cover, identify invasion hotspots, and assess land-use and land-cover transitions. When combined with local ecological knowledge, these approaches can enhance understanding of invasion processes and inform evidence-based management interventions (Mbaabu et al., 2019). In particular, analysis of seasonal and long-term vegetation dynamics can provide insights into changes in vegetation condition and the availability of pasture resources within invaded rangelands.

Recent research in Isiolo has documented the rapid expansion of *P. juliflora* across pastoral landscapes. High-resolution imagery has indicated substantial increases in *P. juliflora* cover alongside declines in shrubland and cropland areas (Akala et al., 2026). These findings highlight the need to integrate spatial patterns and temporal trends with changes in land use and land cover, as well as seasonal and long-term vegetation dynamics, when assessing the implications of *P. juliflora* expansion for rangeland resources and pastoral livelihoods. Since livestock production is strongly dependent on the availability and accessibility

of forage, examining the relationship between invasion and livestock productivity indicators is also important for understanding the broader implications of the invasion.

“Long-term NDVI spectral greenness alone creates a misleading proxy for ecosystem health, as high seasonal greenness peaks often reflect dense, unpalatable evergreen Prosopis thickets rather than genuine forage recovery”

Despite these advances, detailed ward-level assessments of the spatial and temporal dynamics of *P. juliflora*, associated land-use and land-cover changes, vegetation dynamics, and implications for livestock productivity remain limited. High-resolution mapping and analysis are therefore necessary to identify priority areas for restoration, monitor invasion trajectories, assess changes in pasture availability, and examine the potential effects of invasion on pastoral production. Accordingly, this study evaluates the spatial distribution and temporal expansion of *P. juliflora* in Ngaremara Ward between 2013 and 2025. Specifically, the study aims to: (1) assess the spatial distribution and temporal expansion of *P. juliflora* in Ngaremara Ward between 2013 and 2025; (2) determine changes in land use and land cover associated with the expansion of *P. juliflora*; (3) assess seasonal and long-term vegetation dynamics and their implications for pasture availability; and (4) examine the relationship between *P. juliflora* invasion and livestock productivity indicators among pastoral households. The study generates empirical evidence to support sustainable rangeland management and pastoral livelihood planning in the study area. The approach adopted in this study captures data from various sources (survey, KIIs, FGDs and various imagery) resulting assessment of the

broader implication of invasion and livestock productivity indicators.

2.0 Materials and Methods

Study Area

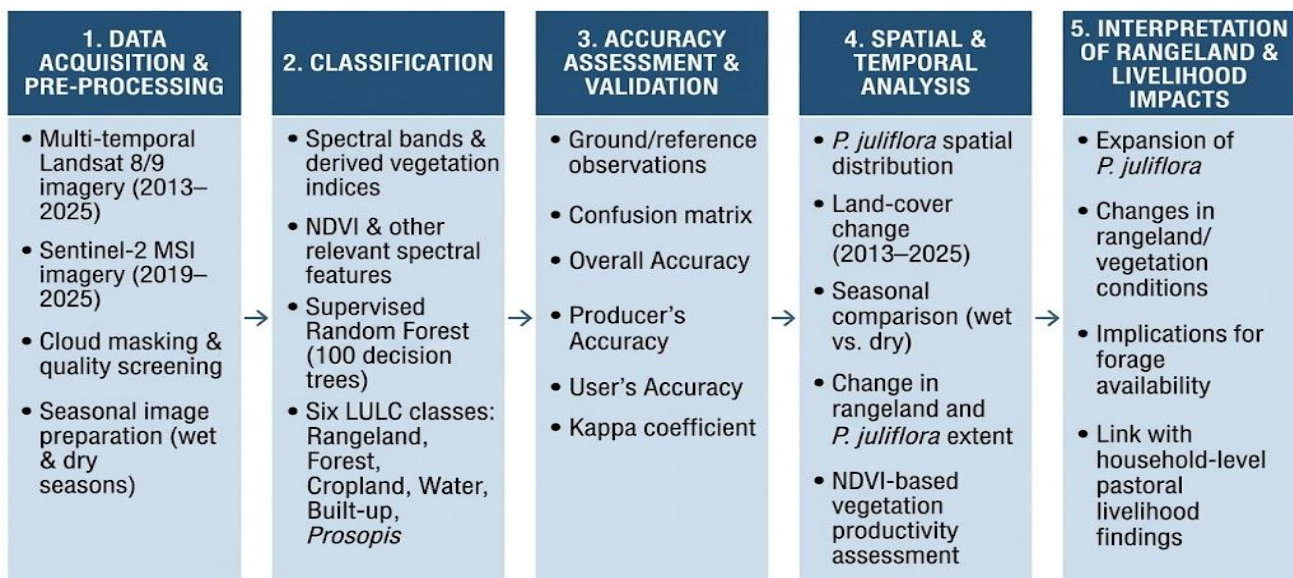
This study was conducted in Ngaremarara Ward, one of the ten administrative units in Isiolo County, Kenya. Located in the former Eastern Province, Isiolo County forms a geographic transition zone between northern and southern Kenya and extends from approximately 36°50'E to 39°50'E longitude and 0°05'S to 2°00'N latitude. Ngaremarara Ward lies at approximately 0°25'N and 37°35'E and is characterized by an arid climate, with mean annual rainfall ranging from 250 to 500 mm and average temperatures of 24°C–35°C. Its vegetation consists primarily of sparse grasslands and shrublands, together with increasingly extensive stands of invasive *Prosopis juliflora*. Pastoralism is the principal livelihood, with Turkana, Somali, and Borana communities rearing cattle, goats, sheep, and camels (Affognon, et al. 2017).

Research Design

The analytical workflow consisted of six interconnected stages: acquiring and quality-controlling satellite, rainfall, and field datasets; preprocessing imagery and screening for clouds and shadows; calculating and seasonally aggregating NDVI; analyzing temporal trends using non-parametric statistical methods; conducting supervised classification and post-classification change detection; and identifying spatial hotspots through analysis validated against field observations. This integrated sequence ensured that the assessment of *P. juliflora* invasion was supported by multiple complementary sources of evidence rather than relying exclusively on a single vegetation index. Figure 1 shows the geospatial analytical framework used to assess the spatial and temporal dynamics of *Prosopis juliflora* and its implications for pastoral rangeland conditions and livelihoods in Ngaremarara Ward, Isiolo County.

Figure 1

Geospatial analytical framework used to assess the spatial and temporal dynamics of Prosopis juliflora



Field Data Collection and Sampling

Field data comprised GPS-referenced observations documenting the presence or absence of *Prosopis juliflora*. These observations served as reference data for

supervised classification and validation of the remotely sensed invasion map. Sampling covered both invaded and non-invaded sites, thereby representing the principal environmental and land-cover conditions within the study area. To minimize spatial bias, field

points were distributed throughout the study area and adequately separated to reduce spatial dependence between the training and validation samples. Before model development, the dataset was divided into independent training and validation subsets. The training subset was used to develop the Random Forest classifier, whereas the validation subset was withheld until the prediction stage was complete.

The observations were complemented by data on the perceived household-level impacts on livestock production outcomes. The data was collected through a stratified household survey of 413 pastoral livestock keepers, seven key-informant interviews, four focus-group discussions each with 15 participants.

Satellite Image Pre-processing

Satellite imagery was processed in Google Earth Engine. The preprocessing workflow comprised atmospheric correction, cloud screening using a 10% maximum scene-level cloudiness threshold, and clipping to the study-area boundary. These procedures were standardized across all images to ensure consistent quality control before NDVI computation. For Sentinel-2, Level-2A surface-reflectance products were used, with preprocessing involving quality masking, selection of the required spectral bands, spatial clipping, and temporal compositing.

Pixels affected by clouds and cloud shadows were excluded using the available quality-assurance and scene-classification information. Although images with scene-level cloudiness exceeding 10% were excluded, pixel-level masking was subsequently applied to remove residual cloud- and shadow-contaminated pixels from the NDVI calculations. The filtered images were then clipped to the established study-area boundary.

Landsat 8/9 Level-2 surface-reflectance imagery was processed using the corresponding quality-assurance layers to mask clouds, cloud shadows, and other unsuitable pixels. The same study-area boundary was applied to these datasets.

Normalized Difference Vegetation Computation

The Normalized Difference Vegetation Index (NDVI) was calculated using the red and near-infrared surface-reflectance bands according to the following equation:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

For Sentinel-2 imagery, the appropriate 10-m NIR and red spectral bands were used. For Landsat 8/9 imagery, the corresponding NIR and red surface-reflectance bands were selected. Because NDVI is affected by rainfall variability and seasonal vegetation dynamics, it was not interpreted independently as conclusive evidence of *Prosopis juliflora* invasion.

NDVI was computed at the pixel level for each valid satellite observation. The resulting images were assigned acquisition dates and seasonal classifications and retained as a temporal dataset. Quality-control procedures were then applied to identify anomalous values, missing observations, and spatial artefacts before temporal aggregation.

Seasonal Temporal Aggregation and NDVI Trend Analysis

To capture the ecological contrast between persistent woody vegetation and seasonal herbaceous vegetation, annual NDVI observations were aggregated into two analytical seasons: the dry-season window of January–February and the wet-season window of April–May. For each year, the median or mean NDVI of all valid observations within each seasonal window was calculated for each analytical unit. Median compositing was considered preferable when the number of valid observations was limited or residual atmospheric noise was present, as it minimizes the influence of extreme values. Furthermore, this approach helps isolate the spectral signature of persistent species like *Prosopis juliflora* from ephemeral ground cover, which may shed leaves or senesce entirely during the dry season (Shiferaw et al., 2019). By contrasting these seasonal metrics, the analysis effectively exploits the unique phenological behavior of

invasive species that maintain photosynthetic activity even under moisture-stressed conditions (Wakie et al., 2014).

The seasonal contrast was used to identify areas in which vegetation greenness remained relatively stable during the dry season. The underlying hypothesis was that *Prosopis*, as an evergreen species or one capable of retaining green foliage during periods when seasonal herbaceous vegetation declines, may exhibit comparatively elevated dry-season NDVI values. Nevertheless, similar spectral patterns may also be associated with other evergreen woody vegetation, irrigated land, riparian vegetation, or alternative land-cover types. Accordingly, dry-season vegetation persistence was interpreted as an indicator or proxy of potential *Prosopis* presence rather than as definitive evidence of invasion.

Spatial Aggregation to 1-ha Analytical Units

Sentinel-2 NDVI data acquired at a 10-m spatial resolution were aggregated to a 1-ha grid to minimize pixel-level spatial variability and harmonize the remote-sensing analysis with the approximate spatial scale of the field plots. A regular 1-ha grid was established across the study area, and the mean NDVI for each grid cell was calculated from all contributing 10-m Sentinel-2 pixels using spatial-reduction functions in Google Earth Engine. Aggregation was performed after image-quality masking and NDVI computation. Accordingly, each grid cell represented a spatially averaged vegetation signal rather than an individual 10-m observation. The same analytical grid was retained across all years to ensure that temporal differences reflected changes within consistent spatial units. Where Landsat data were used, the correspondence between the 30-m pixels and the 1-ha grid was explicitly documented, given differences in the number and spatial arrangement of contributing pixels. This multi-sensor integration strategy aligns with recent methodological advancements that prioritize reconciling distinct spatial resolutions to improve the accuracy of vegetation change detection (Leroux et al., 2017).

Supervised Classification of *Prosopis* Invasion

A supervised Random Forest classifier was employed to differentiate between *Prosopis*-invaded and non-invaded rangelands. The model was trained using the designated training data subset and subsequently applied to the complete analytical grid to produce a spatially continuous map of invasion status. Particular consideration was given to areas with less than 30% *Prosopis* cover, where low-density invasion may be difficult to identify through conventional visual interpretation. These areas were therefore retained as a distinct analytical category rather than being automatically classified as non-invaded. Model performance was assessed using independent validation observations. In addition to overall accuracy metrics, the confusion matrix was analyzed to evaluate precision and recall specifically for low-density encroachment classes, ensuring the model effectively distinguished subtle spectral signatures from background savanna vegetation (Wiethase et al., 2024).

Land-Use/Land-Cover Change Detection

Land-use/land-cover maps were generated for the relevant years and compared using a post-classification change-detection approach. The analysis primarily sought to quantify the conversion of non-invaded rangeland into *Prosopis*-invaded areas. Before change detection, all classification maps were standardized to a common spatial grid and map projection. A transition matrix was then constructed to quantify the area that changed from non-invaded to *Prosopis*-invaded rangeland, as well as the areas that remained unchanged. The net change in invaded area was determined by subtracting the invaded area at the beginning of the assessment period from that recorded at the end. The annual rate of change was calculated by dividing the net change in invaded area by the length of the observation interval in years. To validate the temporal consistency of these classifications, the resulting transition patterns were cross-tabulated with historical imagery to ensure observed shifts accurately represent woody encroachment rather than sensor artifacts (Jombo & Elbasit, 2025; Sengani et al., 2023).

This verification step utilized both visual interpretation of very high-resolution satellite imagery and local expert historical knowledge to confirm that the detected land-cover transitions corresponded to actual *Prosopis* spread (Mbaabu et al., 2021).

Hotspot Analysis, Rainfall Analysis and Control for Climate Variability

Spatial hotspot analysis was performed using the Getis–Ord G_i^* statistic to identify spatial clusters characterized by unusually high or low values of NDVI trends and *Prosopis* invasion indicators. The analysis was conducted using the 1-ha analytical grid to maintain consistency with the spatial units employed in the NDVI and classification analyses.

CHIRPS rainfall data were used to characterize rainfall variability throughout the study period (D’Adamo et al., 2021). The classification of January–February as the dry-season window and April–May as the wet-season window was based on the established bimodal rainfall regime of Isiolo County, characterized by the March–May long rains and October–December short rains, with rainfall generally peaking in April. January–February occur between the short rains and the onset of the long rains and are therefore generally characterized by low and unreliable rainfall, whereas April–May fall within the main long-rains period and represent relatively wetter conditions. The selected months are thus consistent with the local rainfall calendar and provide contrasting seasonal conditions for assessing vegetation dynamics. Given the substantial interannual variability in rainfall onset, amount, and distribution in Isiolo, these periods are considered representative seasonal windows rather than fixed climatic boundaries. In all cases images corresponding to the period were used in the study.

Validation and Accuracy Assessment

Validation was performed by comparing the final remote-sensing classification with independent GPS-based observations that had not been used to train the classifier. A confusion matrix was constructed by comparing the predicted classes with the corresponding reference classes. Overall accuracy was

calculated as the proportion of correctly classified validation observations relative to the total number of observations. Model validation used an independent validation dataset generated through a 70:30 partition of the reference samples. Thus, 70% of the samples were used to train the classifier, while the remaining 30% were reserved exclusively for validation. The same ratios were used for *Prosopis* presence and absence. Furthermore, the Kappa statistic and F1-score were derived to assess the reliability of the classification, specifically accounting for the class imbalance inherent in the low-density encroachment strata (Smith et al., 2023). Particular emphasis was placed on the *Prosopis* class because misclassification directly affects estimates of invaded area. Validation was further complemented by a spatial comparison of field-based GPS observations and NDVI-derived invasion indicators. Correlation or association analyses were used to assess whether areas identified by the remote-sensing proxy corresponded to locations where *Prosopis* was observed in the field.

Data Analysis and Statistical Procedures

All spatial preprocessing, image compositing, NDVI calculation, spatial aggregation, and classification were conducted in Google Earth Engine. Statistical analyses were performed using an appropriate statistical computing environment. To support reproducibility, the workflow was documented using consistent dataset names, temporal filters, spatial boundaries, classification categories, training and validation partitions, and model parameters. Furthermore, the Random Forest model architecture relied upon 500 decision trees to ensure stability in the classification outcomes, with variable importance scores computed to rank the influence of environmental predictors (Hagani et al., 2023).

Descriptive statistics were used to summarize NDVI distributions, rainfall totals, invaded area, and annual rates of change. Temporal trends were evaluated using the Mann–Kendall test and Theil–Sen slope estimator, while spatial clustering was assessed using the Getis–Ord G_i^* statistic. Relationships between field

observations and remote-sensing indicators were examined using appropriate correlation or association measures. Statistical significance was evaluated at the predefined level of $\alpha = 0.05$. To minimize the influence of isolated anomalous pixels, the results were interpreted at the 1-ha analytical scale and assessed in relation to spatially contiguous patterns. The resulting maps were examined alongside field observations and rainfall data. This triangulation supported the differentiation of probable *Prosopis* invasion from temporary vegetation responses, isolated classification artefacts, and other persistent sources of vegetation greenness.

Integration with Livestock-Production Evidence

The geospatial findings were interpreted alongside household-level indicators of livestock production collected through a concurrent cross-sectional survey of pastoral households in the same ward, including reported changes in forage availability, herd size, milk and meat production, reproductive performance,

feed shortage and grazing distance. This integration allowed the study to relate spatially explicit ecological change to household-reported production outcomes rather than treating the two forms of evidence in isolation.

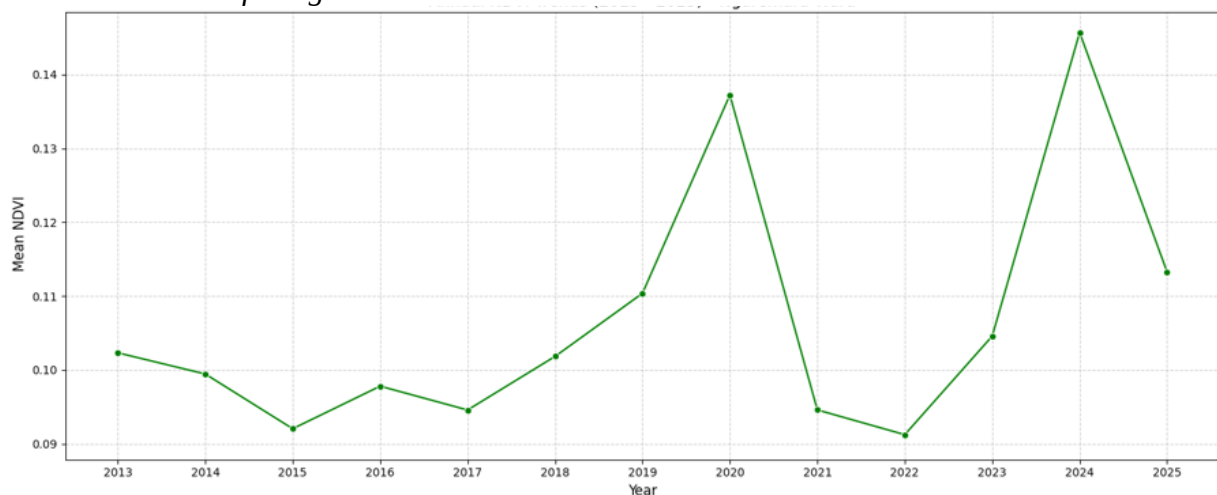
3.0 Results and discussions

Annual NDVI Trends

As shown in Figure 2, the annual Normalized Difference Vegetation Index analysis revealed marked interannual variability in vegetation greenness across Ngaremara Ward between 2013 and 2025. The pronounced decline in NDVI across Ngaremara Ward during 2014–2015 coincided with severe drought conditions that reduced soil moisture, constrained plant growth, and diminished the chlorophyll concentration detected by satellite sensors (Campoy et al., 2020). Comparable drought-related reductions in NDVI have been documented in arid environments, where rainfall variability strongly regulates primary productivity (Vrieling et al., 2011, 2013; Mark, 2015).

Figure 2

Annual NDVI Trends for Ngaremara Ward



The prolonged, multi-season drought experienced during 2021 and 2022 resulted in severe pasture depletion, acute water scarcity, and substantial livestock losses. In contrast, the elevated NDVI values recorded during 2019–2020 and 2023–2024 corresponded with above-average rainfall, which replenished soil moisture, stimulated herbaceous regeneration, and promoted woody vegetation growth (Huete

et al., 2002; Schwinning & Sala, 2004). Unlike native grasses, the invasive shrub *Prosopis juliflora* maintains a persistent green canopy throughout the year, producing high NDVI values while suppressing native herbaceous vegetation through competition for water, nutrients, and light. Consequently, high NDVI values in the study ward cannot be assumed to indicate enhanced pasture quality. Vegetation

indices derived solely from satellite imagery are unable to reliably distinguish palatable forage from dense *Prosopis* thickets. The integration of long-term Landsat imagery, high-resolution Sentinel-2 data, and land-cover classification was therefore necessary to determine whether observed greening represented genuine pasture recovery or the expansion of *Prosopis* invasion.

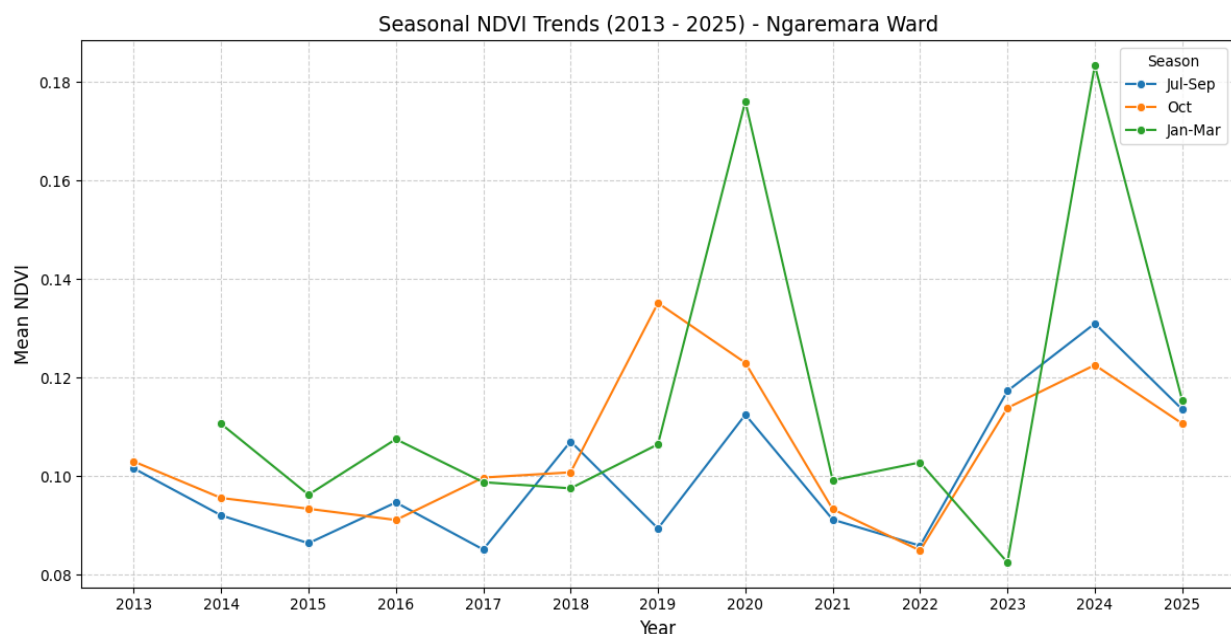
Seasonal NDVI Dynamics in Ngaremara Ward

Figure 3 presents the seasonal vegetation dynamics in Ngaremara Ward which closely

mirrored local rainfall cycles, exhibiting low baseline NDVI during dry periods, rapid greening following rainfall onset, and peak biomass during wet seasons. Low dry-season NDVI across the ward stems from depleted soil moisture, high evapotranspiration, and herbaceous senescence. Conversely, post-rainfall greening highlights the strict reliance of Ngaremara's pastoral ecosystem on seasonal precipitation, which fuels seed germination, leaf expansion, and biomass production.

Figure 3

Seasonal NDVI Trends for Ngaremara Ward



This seasonal cycle conforms to the pulse-reserve model, where vegetation productivity occurs in rapid bursts following rain events (Schwinning & Sala, 2004; Vrieling et al., 2013). However, seasonal biomass recovery within Ngaremara Ward varied substantially across years. Droughts in 2014–2015, 2017, and 2021–2022 suppressed seasonal NDVI peaks, indicating poor pasture regeneration even after rain events and aligning with documented

drought impacts on forage and livestock survival (Ahmed et al. 2023). In contrast, wet periods in 2019–2020 and 2023–2024 produced high seasonal NDVI peaks and temporarily improved forage availability.

The trends are further supported by the results of combined seasonal NDVI Mann-Kendall and Sen's Slope Results (2013–2025) presented in Table 1.

Table 1

Combined seasonal NDVI Mann-Kendall and Sen's Slope Results for the period 2013–2025

Season	Kendall's Score (S)	Kendall's Tau (τ)	Sen's Slope (year ⁻¹)
Jul–Sep	+26.0	+0.333	+0.0020
Oct	+24.0	+0.308	+0.0021
Jan–Mar	+14.0	+0.212	+0.0025

The non-parametric Mann-Kendall trend analysis reveals a persistent, monotonic upward trajectory in mean vegetation greenness across all three evaluated seasonal periods in Ngaremara Ward between 2013 and 2025. Positive Kendall scores ($S > 0$) and Tau correlation values ranging from +0.212 to +0.333 demonstrate a consistent baseline greening signal. Quantifying this magnitude, Sen's slope estimator indicates positive annual growth rates across all seasons, peaking during the dry post-rain period of Jan–Mar ($\beta = +0.0025 \text{ year}^{-1}$) compared to Oct ($\beta = +0.0021 \text{ year}^{-1}$) and Jul–Sep ($\beta = +0.0020 \text{ year}^{-1}$). However, none of these trend trajectories achieve statistical significance at the standard 95% confidence threshold ($p > 0.05$). This lack of statistical significance despite positive slope parameters is largely attributable to pronounced inter-annual climate variability and high-amplitude rainfall oscillations exemplified by steep NDVI peaks during wet anomalies (e.g., 2020 and 2024) juxtaposed against severe dips during dry spells (e.g., 2017, 2021, and 2022). Econometrically and ecologically, this perennial greening signature during dry periods notwithstanding cyclical drought events aligns with the aggressive, deep-rooted expansion profile of invasive woody vegetation such as *Prosopis juliflora*, which maintains active canopy photosynthetic capacity when herbaceous native rangeland vegetation senesces.

The seasonal dynamics established in this study have direct implications for pastoral livelihoods and livestock management. It is noteworthy that dry-season forage shortages reduce livestock-carrying capacity and compel pastoralists to travel greater distances in search of pasture and water, while also adversely affecting livestock body condition, milk production, and reproductive performance. Although wet seasons temporarily enhance herbaceous pasture production, they also provide favorable soil-moisture conditions for establishment of *Prosopis juliflora* seedlings (Shiferaw, Bewket, & Alamirew, 2019; Shiferaw, Bewket, Alamirew, et al., 2019; Shiferaw, Schaffner, et al., 2019). This dual effect highlights the complex interaction between seasonal climatic variability and biological invasion; whereby short-term rainfall periods may simultaneously support temporary pasture recovery and accelerate the long-term degradation of grazing lands.

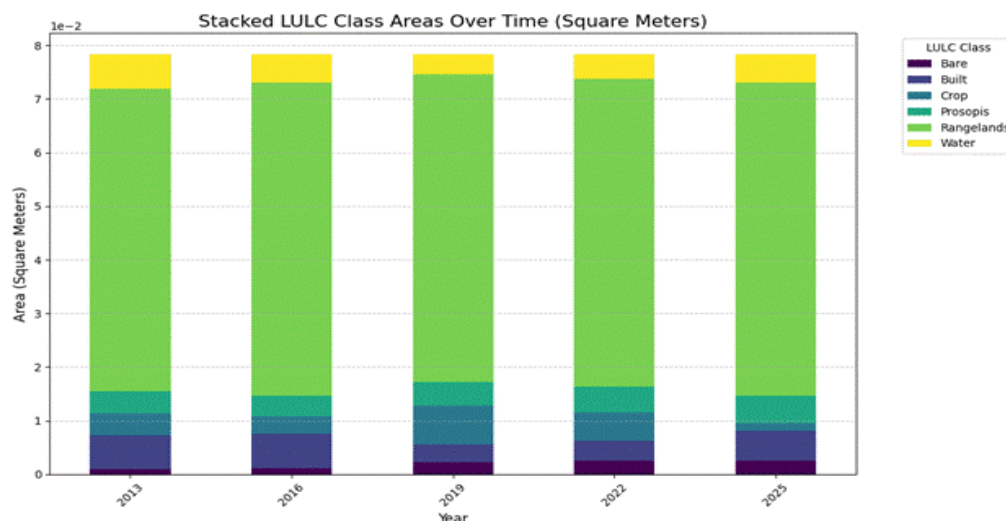
Land Use and Land Cover (LULC) Dynamics in Ngaremara Ward

Spatial and Temporal Landscape Transformation

The LULC mapping is shown in Figure 4 and reveals more persistent landscape transformations associated with climate variability, biological invasion, and changing land-use patterns in contrast to temporary, rainfall-induced fluctuations in NDVI.

Figure 4

Stacked LULC class areas over the period between 2013 and 2025



The conversion of contiguous pasture into dense *Prosopis* thickets among other LULC changes disrupts essential ecological processes (Laurance, 2002) with the encroachment of *Prosopis juliflora* onto the communal grazing

lands been observed to facilitate the displacement of native flora, ultimately diminishing the overall livestock-carrying capacity of the region (Opiyo et al., 2015; Paliwal et al., 2024). Figures 5, and 6 clearly present the changes across the years.

Figure 5
LULC classification for the years 2013 and 2016

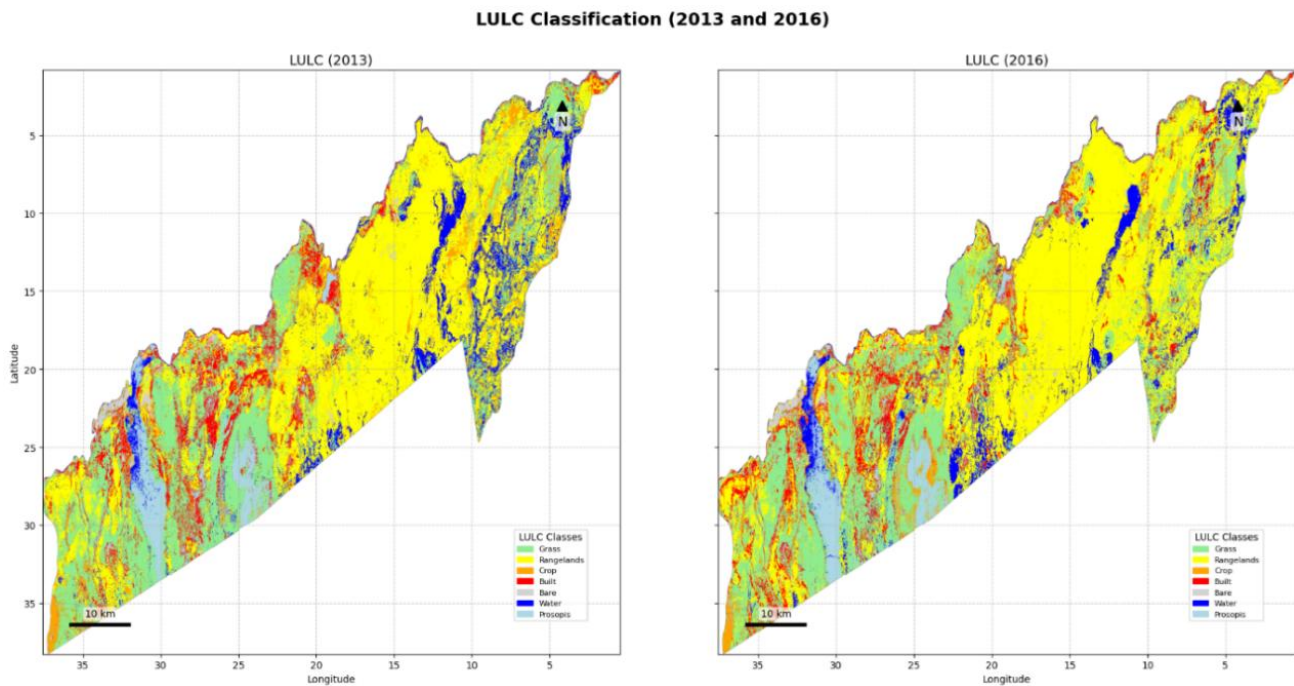
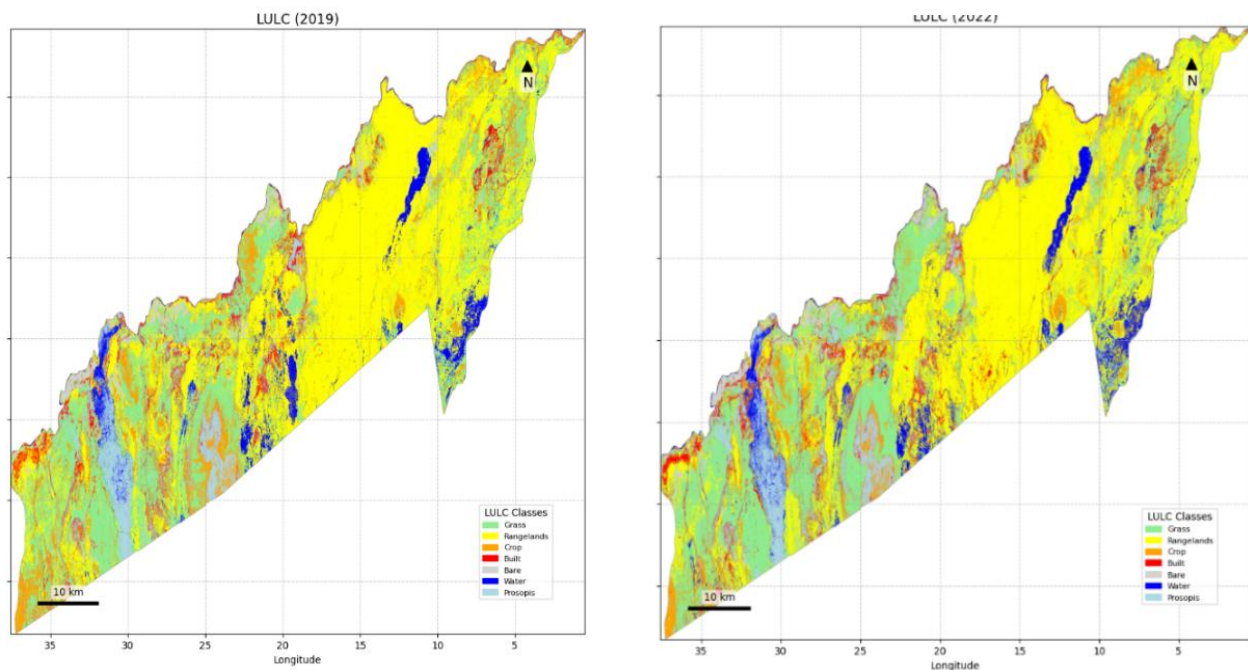


Figure 6
LULC classification for the years 2019 and 2022



Quantitative Changes in Land Cover Classes Between 2019 To 2025

Quantitative classification statistics presented in Table 2 demonstrate a progressive transformation of land-cover classes within the study ward between the years 2019 and 2025. During the dry season, rangeland area declined from 68,696.73 ha in 2019 to 67,838.51 ha in 2025. This reduction poses a significant threat to Isiolo County's pastoral economy, which depends heavily on open grazing lands. The

Table 2

Land-cover statistics for the period 2019 - 2025

Classification	2019	2022	2025
Dry Season			
Rangeland	68,696.73	68,339.94	67,838.51
Forest	20,828.88	16,200.24	16,200.24
Crops	2,902.54	3,307.55	964.30
Built-up	684.65	790.73	964.30
Prosopis	2,777.18	5,342.22	9,691.22
Wet Season			
Rangeland	65,958.12	62,988.08	59,246.59
Forest	22,844.27	20,578.16	24,300.36
Crops	3,066.47	2,140.75	1,099.30
Built-up	819.66	1,041.44	1,330.73
Prosopis	3,172.55	4,773.29	9,941.93

Forested areas provide important localized ecosystem services, including microclimate regulation, soil stabilization, and watershed protection (Assessment, 2005; Programme, 2021). The contraction recorded in cropland may be attributed to recurrent drought, unreliable rainfall, direct invasion of cultivated plots by *Prosopis juliflora*, and the abandonment of agricultural land (Shiferaw et al., 2007). These processes reflect broader patterns of agricultural decline in climate-stressed semi-arid environments (Shiferaw et al., 2007). Built-up areas increased steadily from 684.65 ha to 964.30 ha, primarily as a result of population growth and settlement expansion. The expansion in built-up areas fragments open rangelands and restrict livestock mobility, which is an important pastoral adaptation strategy.

continued loss of rangeland, including during wet seasons when herbaceous biomass would typically be expected to reach its maximum, indicates a persistent decline in forage availability irrespective of rainfall conditions. This finding is consistent with documented trends in dryland grazing systems, where recurrent drought, grazing pressure, and woody encroachment collectively reduce the abundance of palatable grasses (Reed et al., 2015).

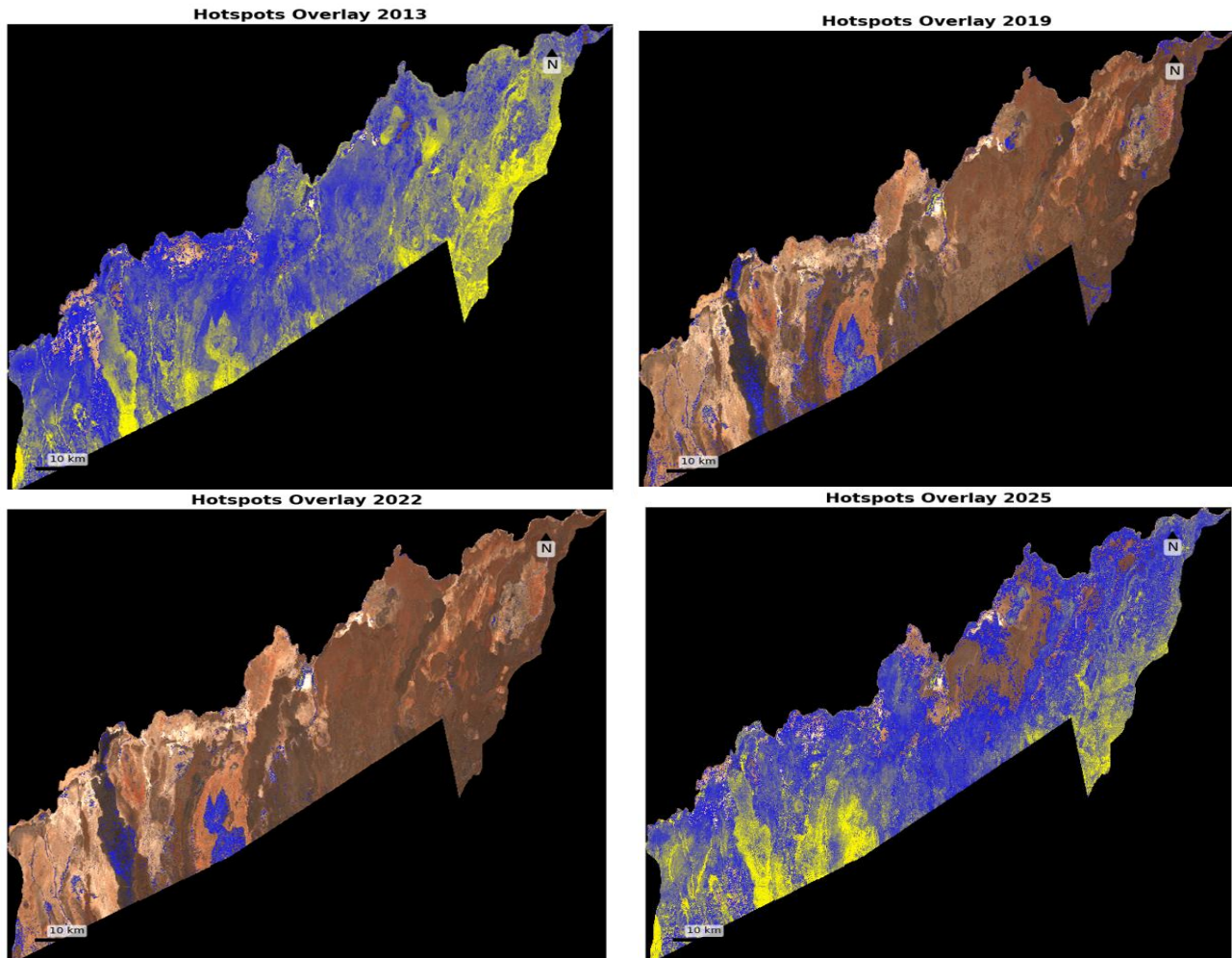
Overall, the integration of NDVI analysis with multi-temporal LULC mapping provides a robust framework for assessing landscape change in Ngaremara Ward. Because NDVI alone cannot reliably distinguish healthy native pasture from invasive evergreen woody canopies, the integration of vegetation indices with land-cover classification is essential for evaluating actual ecosystem condition. The rapid and sustained expansion of *Prosopis juliflora* emerges as a major driver of long-term landscape transformation in Ngaremara Ward, underscoring the need to prioritize targeted invasive-species management and rangeland restoration within local land-use planning.

Prosopis invasion hotspots

Results for *Prosopis* hotspots across the years are presented in Figure 7.

Figure 7

Hotspot overlay maps for the study period



The multi-temporal hotspot overlay maps (2013, 2019, 2022, and 2025) illustrate significant spatiotemporal dynamics in *Prosopis juliflora* invasion intensity, shifting from extensive, localized concentrations to broader landscape-level homogenization. In 2013, primary invasion clusters (yellow hotspots) were predominantly anchored along alluvial floodplains, drainage channels, and low-lying rangeland zones in the southern and eastern sectors, where shallow water tables and moisture availability facilitated initial establishment (Shackleton et al., 2014). By 2019 and 2022, severe multi-year drought conditions induced widespread canopy dieback and reduced spectral greenness (reflected in the diminished yellow hotspot footprint), causing the invasion front to temporarily contract into persistent core refugia. However, the 2025 hotspot overlay highlights a rapid, aggressive

recolonization and spatial diffusion, driven by *P. juliflora*'s deep phreatophytic root systems, high seed bank viability, and rapid opportunistic response to subsequent rainfall anomalies (Kahi et al., 2020; Haregeweyn et al., 2023). This pronounced spatial expansion from riparian corridors into surrounding communal rangelands underscores a classic invasive trajectory where localized disturbance corridors function as stepping stones for wider ecological encroachment, progressively outcompeting native forage species and severely altering local pastoral livestock habitats.

Implications for forage availability and livestock productivity

The land-cover statistics in Table 2 provide the ecological basis for inferring lost pasture and browse production and, by extension, reduced livestock-carrying capacity in Ngaremaru Ward.

The estimated loss of approximately 1.3% of rangeland, rising to 6.5% when rangeland and forest — the two habitats jointly supporting pasture and browse are considered together, represents a materially significant erosion of the resource base underpinning pastoral production, particularly given that the loss occurred within a six-year interval and coincided with an accelerating rate of *Prosopis* expansion after 2019.

These spatial and vegetation-productivity findings are consistent with, and help to explain, the household-level evidence reported by pastoral livestock keepers in the same ward. During prolonged dry seasons, declining pasture availability reduces grazing capacity and compels households to extend and intensify livestock movement in search of forage and water, with corresponding adverse effects on livestock body condition, milk production, reproductive performance and overall productivity (Turner & Schlecht, 2019; Tugjamba et al., 2023). Households in Ngaremara Ward reported exactly this pattern: the majority perceived forage availability to be lower in invaded than in uninvaded areas, most reported moving livestock over longer distances and with greater frequency to access grazing, and a majority reported declining herd size, milk production, meat production and reproductive performance since the onset of invasion. The convergence between the spatially explicit ecological evidence presented here and these household-reported production outcomes strengthens the interpretation that *Prosopis* invasion is not merely a localised vegetation change but a landscape-scale process with direct and measurable consequences for pastoral livelihoods.

The findings also carry an important methodological implication for how ecological recovery is assessed in invaded drylands. Wetter periods can simultaneously increase short-term vegetation greenness and create favourable conditions for the establishment and expansion of *P. juliflora*, particularly in riparian environments where increased soil moisture supports seedling recruitment and survival

(Mwangi & Swallow, 2005). The same rainfall events that support apparent short-term pasture recovery may therefore, over a longer horizon, facilitate further woody encroachment a dual effect that underscores why seasonal or annual NDVI increases should never be interpreted independently of concurrent land-cover change. Programmes and monitoring systems that rely on NDVI alone risk systematically overestimating the resilience of the rangeland resource base in areas undergoing active *Prosopis* invasion.

4.0 Conclusion

Prosopis juliflora experienced a dramatic, expansion in Ngaremara Ward between 2019 and 2025, increasing from roughly 2,777 ha to nearly 10,000 ha across both wet and dry seasons. Long-term NDVI spectral greenness alone creates a misleading proxy for ecosystem health, as high seasonal greenness peaks often reflect dense, unpalatable evergreen *Prosopis* thickets rather than genuine forage recovery.

5.0 Recommendations

Establish integrated rangeland restoration initiatives to combat the spread of the *Prosopis juliflora*.

Adopt geospatial and high-resolution monitoring protocols such as the ones used in this to detect low-density invasion hotspots early and track the efficacy of ongoing management interventions.

The combined application of remote sensing, Geographic Information Systems, machine learning, and NDVI analysis provides an effective approach for monitoring invasive species dynamics and assessing their ecological consequences.

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