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Spatio-temporal distribution and impacts of *Prosopis juliflora*: an application of remote sensing and experiential ecological knowledge in a semi-arid rangeland of Kenya

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Prosopis juliflora species was introduced in the Kenyan drylands as part of an afforestation program to rehabilitate rangelands and supply fuelwood in the 1980s. However, the species has since spread beyond areas of intervention, altering ecosystem integrity and threatening the livelihoods of pastoralists. This study analysed the spatial and temporal dynamics of *P. juliflora* in Cherab Ward, Isiolo County, to provide empirical evidence for the management and utilisation of this species. High-resolution satellite imagery was used to assess land-use and land-cover changes between 2017 and 2024, complemented by participatory socio-ecological approaches to elicit pastoralists' local knowledge of the species' invasion patterns and impacts. The results show that *P. juliflora* cover increased by approximately 706.1 km^2 between 2017 and 2024. Equally, shrubland and crop land declined by approximately 414.9 km^2 and 122.8 km^2, respectively. Bare land decreased by 397.4 km^2, whereas built-up land increased slightly by 26.2 km^2. These trends were corroborated by maps generated through participatory approaches with communities, which showed that *P. juliflora* invaded riverine and roadside areas, making it difficult for livestock to access pasture and water in the affected area. These results imply both ecological and socioeconomic consequences, with expected negative impacts on livestock production in the study area. The observed rate of spread of *P. juliflora* (103%) from 2017 to 2024 indicates that, if the invasion continues unabated, grazing resources in the area will diminish, leading to the loss of ecosystem services and, consequently, impacting pastoral livelihoods. These findings highlight the need for context-specific, codeveloped management approaches that integrate spatial evidence with local knowledge to ensure the sustainable control and exploitation of the species, thereby maximising ecological and economic benefits.

KEYWORDS

invasive species, *P. juliflora*, participatory mapping, pastoral resilience, rangeland management

Introduction

Rangeland ecosystems, mainly composed of shrubs and grasses, particularly in dry regions, cover approximately 40% of the Earth's surface (Siraj and Abdella, 2018). Sub-Saharan Africa has the largest expanse of rangelands, covering approximately 14.5 million square kilometres. These ecosystems offer important environmental and economic benefits, including recreational opportunities, carbon storage, biodiversity, animal forage production, and food production (Maestas et al., 2022; Siraj and Abdella, 2018). Despite their importance, these ecosystems are increasingly threatened by land use change (Bilyaminu et al., 2021), bush encroachment, climate change (Chen et al., 2019), biodiversity loss (Jesse et al., 2021; Linders et al., 2019; Mbaabu et al., 2019; Poland et al., 2021), soil degradation (Yin et al., 2020) and declining in surface and groundwater resources (Dzikiti et al., 2017). The cumulative effects of these pressures raise concerns regarding the long-term ecological integrity and productivity of the arid and semi-arid (He et al., 2023).

Woody plant invasion has emerged as a major ecological challenge among the drivers of rangeland degradation. Fast-growing, drought-tolerant species, such as *Prosopis* species, have been introduced across the dry regions of Africa, Asia, and Australia for land rehabilitation, fuelwood provision, and soil stabilisation (Choge et al., 2021). However, in many regions, these species have become highly invasive, spread rapidly, and disrupt ecosystems (Shackleton et al., 2014). *Prosopis* suppresses native vegetation by altering soil properties, including increasing soil salinity, organic matter, and nitrogen levels, which favours its persistence and reduces herbaceous cover (Kishoin et al., 2024). The resulting decline in pasture quality increases the risk of erosion and elevates vulnerability to flooding, posing a threat to the communities' livelihoods dependent on grazing lands (Athamanakath et al., 2025; Shackleton et al., 2014).

In Kenya, *Prosopis* species were first introduced in the 1970s in Bamburi, Mombasa County and later in the 1980s in Bura, Tana River County, and Baringo County (South, 2014). Three *Prosopis* species were introduced in Baringo: *P. pallida*, *P. juliflora,* and *P. chilensis*. However, only *P. juliflora* grew rapidly and became invasive (Choge et al., 2021; van Wilgen et al., 2024). Since its introduction, *P. juliflora* has extensively expanded across dryland landscapes, displacing native vegetation (Linders et al., 2019). Its encroachment into grazing areas and farmland contributes to shifts in land-use and land-cover (LULC) patterns (Mbaabu et al., 2019; Soper et al., 2016). Globally, approximately 210 species are recognised as invasive, with 49 in Kenya; *P. juliflora* is considered the world's worst invasive species due to its rapid expansion (Witt et al., 2018). According to a recent assessment, *Prosopis* thickets cover approximately 2% of Kenya's land cover, underscoring their ecological significance (Choge, 2019).

Efforts to manage *Prosopis* include physical removal, chemical control, biological control, and integrated management approaches (DeSisto et al., 2020; Mungoche et al., 2025). However, the effectiveness of these interventions has been limited by high labour demands, rapid sprouting of the plant, inadequate monitoring, and inconsistent policy frameworks (Mungoche et al., 2025). Management is further complicated by divergent views on species benefits, such as charcoal production versus eradication campaigns, owing to the observed ecological degradation. Additionally, there are debates surrounding biological control and concerns over non-target effects (Mungoche et al., 2025). These inconsistencies highlight the need for context-specific, evidence-based management strategies that are cognizant of local livelihoods.

Despite the recent academic attention on *Prosopis* in East Africa, existing studies in Kenya have predominantly emphasised socio-economic impacts with limited focus on ecological dynamics, spatial distribution patterns, and temporal trends of invasion (Mungoche et al., 2025; Venter et al., 2018). Moreover, while pastoral communities possess detailed, place-specific knowledge of landscape change, their observations are rarely systematically integrated into spatial and temporal analyses of land-cover change. This limits the understanding of the invasion of *Prosopis*, its ecological impacts, and community perceptions of the affected areas. This imbalance is incompatible with sustainability, a paradigm that requires a fair balance between the environmental, social, and economic dimensions.

To address these gaps, this study examined the dynamics of *P. juliflora* invasion in Isiolo County, Kenya, to inform effective sustainable management interventions. By integrating LULC change with community-based local knowledge, this study maps the spatial extent of *Prosopis* invasion to enhance sustainable utilisation and rangeland governance.

Materials and methods

Study area description

This study was conducted in Cherab Ward in Isiolo County, Northern Kenya (Figure 1), which County borders Marsabit,

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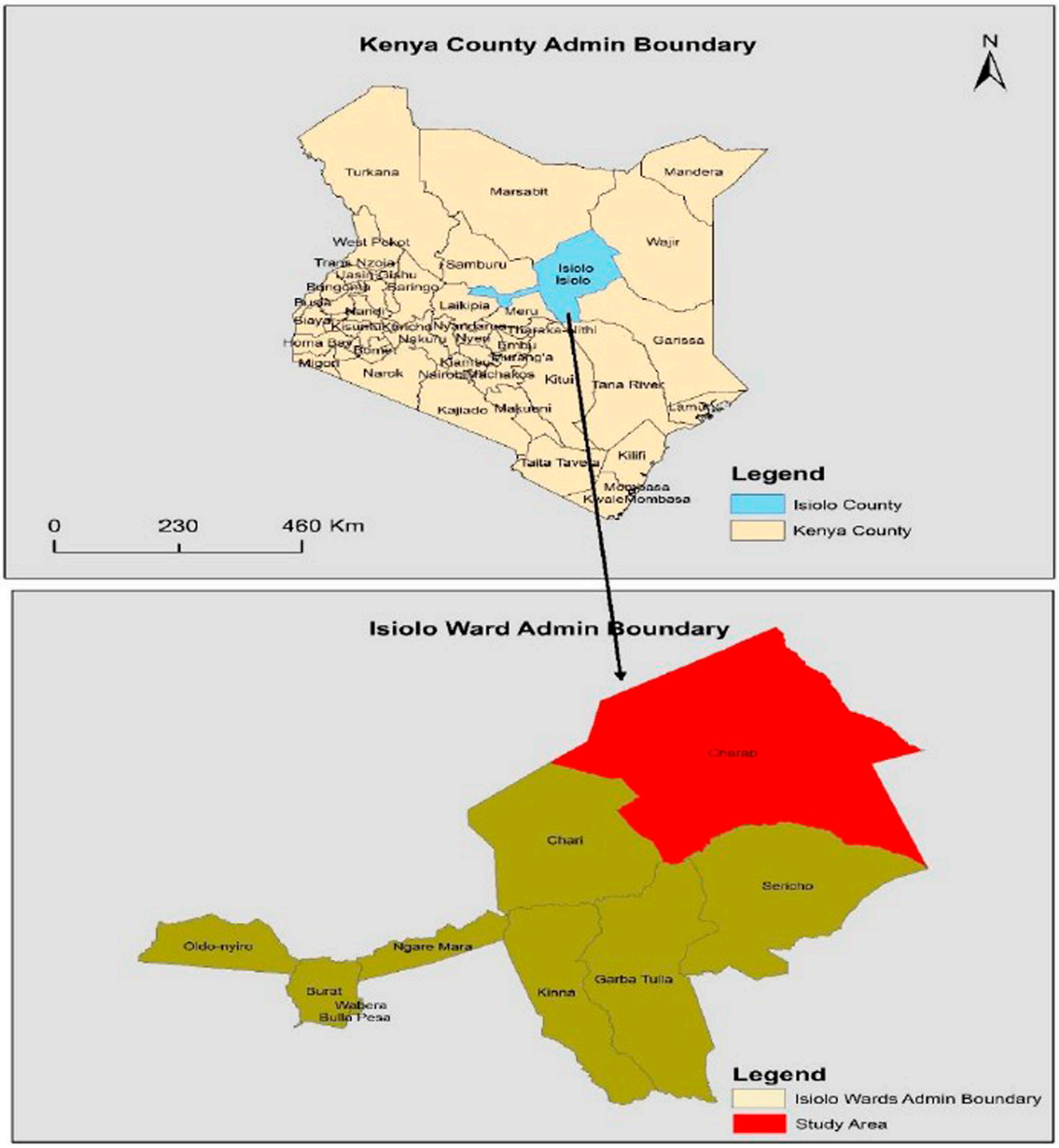

FIGURE 1
Map of study area.

Samburu, Laikipia, Wajir, the Tana River, Kitui, Meru, and Tharaka Nithi Counties. The county covers 25,606 km^{2,} with most of the area being lowland. The county experiences a predominantly hot and dry climate year-round, with most areas having mean annual temperatures above 25 ˚C. In the western highlands, temperatures can drop to approximately 21 ˚C due to the higher elevation. Rainfall is generally low, with southeastern regions receiving less than 250 mm annually, whereas central areas receive between 250 mm and 500 mm. Rainfall distribution varies with topographic features; higher-elevation areas receive more rainfall than lowlands. The current population of Isiolo is estimated to be 315,937, with Borana, Sakuye, Turkana, Samburu, Meru, and Somali as the dominant ethnic communities (Isiolo County Government, 2020).

Extensive livestock production, a key characteristic of pastoralism, is a land-use activity that supports approximately 80% of the communities in Isiolo. However, livelihoods in the area face challenges owing to climate uncertainty, increasing pressure on land, and frequent droughts, among others, leading to environmental degradation (Mbaabu et al., 2019). These challenges are exacerbated by the invasion of *P. juliflora*, which further undermines livelihoods by diminishing pasture and water

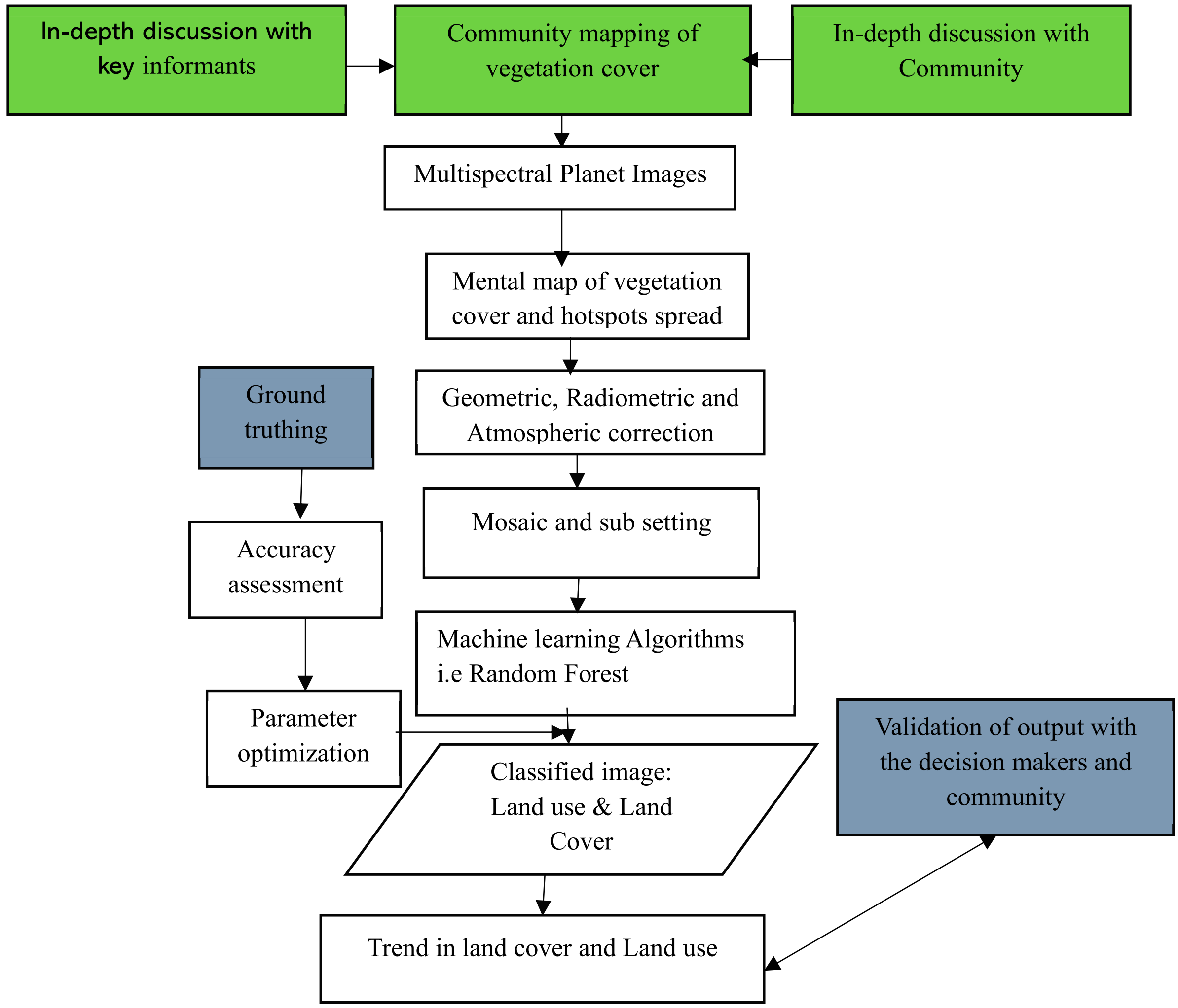

FIGURE 2
Research methodology flowchart.

resources. *P. juliflora* was introduced to Isiolo in the 1980s to reclaim bare land and provide firewood, shade, and fodder for livestock. This was part of the ACTION AID program, an initiative for afforestation and erosion control in the drylands. The desire of the community to plant trees, provide shade, and live fences led to the adoption of this species (Nduro, 2024). However, it is evident that the species is spreading and dominant along the Ewaso Nyiro river (Mungoche et al., 2025; Nduro, 2024).

Data collection and analysis

This study utilised remotely sensed data with local community knowledge to analyse LULC dynamics. Satellite images were analysed to delineate spatial and temporal changes in LULC, identifying trends from 2017 to 2024, with a focus on the spatial and temporal distribution of *P. juliflora* relative to other vegetation types. PlanetScope imagery was available from 2016. However, 2017 was selected as the base year because near-daily satellite coverage was achieved, completely covering the areas of interest (AOI). In addition, the 2016 images contained missing scenes (Planet Labs PBC, 2025). The communities participated in land-cover mapping and in documenting historical LULC trends from 1985 to 2024. Seven classes were identified for classification based on socio-ecological importance following community engagement: *Prosopis*, shrubland, grassland, built-up areas, cropland, indigenous trees, and bare land. The step-by-step procedure adopted in this study is illustrated in Figure 2.

Prior to data collection and analysis, a stakeholder meeting was held with 8 community members and 12 representatives of

FIGURE 3
Participatory land use and land cover mapping with community representatives.

government and non-governmental organisations to prioritise research ideas and jointly develop the proposed research agenda. During the stakeholder consultation, AOI for the analysis of *Prosopis* spread and its effects on other vegetation were defined. Stakeholders emphasised that the *Prosopis* invasion was concentrated along the river in the study area. Therefore, the delineation of the AOI focused on the riparian zone adjacent to the affected areas where invasion impacts were most evident. The AOI was demarcated on Google Earth Pro and shared with stakeholders for validation.

Participatory mapping of land-cover and land-use

Participatory GIS workshops involved 8–16 purposively selected participants from communities affected by *Prosopis* invasion in Cherab ward, as well as stakeholders with experience working with these communities on different aspects of plant management. The participants comprised representatives from non-governmental and community-based organisations, local administrators, herders, women, youth, and elders from the villages of Mnandanur, Merti, and Korbesa. They contributed to the elicitation of local knowledge on LULC changes. The exercise aimed to map and delineate village boundaries, map and verify land use and land cover (LULC) categories, develop a visioning LULC for 10 years (2034), and document the communities' valuable insights into the current and various land use and land cover types based on their understanding of the environment.

A 1:20,000-scale base map satellite image of the study area was printed for the LULC mapping exercise in the villages of Merti, Mnandadur, and Korbesa in Cherab Ward. The exercise was guided by a trained local facilitator who explained the aim of the mapping activity and provided participants with tools, including a flip chart, a Dictaphone, a camera, a printed map, marker pens, and other local materials. The entire session was conducted in the local dialect (Borana) with the assistance of a translator to ensure not only the participation of all but also the clarity and elicitation of appropriate responses. After the introduction, the participants were asked to mention and mark on the flip chart the common features/landmarks with which they were familiar, such as rivers, roads, plateaus, schools, and market centers (Figure 3).

The participants were asked to delineate and draw the boundaries of their perceived current LULC for their respective areas by 2024 on a printed map. They were asked to select preferred symbols to represent various land-cover types. The symbols were recorded in the legend at the base of the map for ease of identification. The facilitator then presented LULC categories derived from satellite image analysis, which the participants reviewed and validated using local knowledge to establish consensus on their landscape. After validation, participants mapped the historical LULC conditions for 1985 and 2005 on separate printed maps and were asked to indicate their impressions of LULC, highlighting changes observed over time (Figure 4). Prompt questions were asked to discuss the reasons for these changes. After mapping historical changes, the participants were asked to envision the future trajectories of their village's landscape and to sketch anticipated LULC changes over the next 10 years (2034). Additional information regarding the reasons for the observed changes and related discussions was recorded on a flip chart and audio recorded for later transcription.

Participatory analysis of trends in land use and land cover with the community

The community members who participated in the mapping exercise conducted a participatory analysis of LULC trends in their villages from 1985 to 2024. Proportional pilling was used to assess land use and land change during the study period. A matrix was drawn on the ground, with land use and land cover on

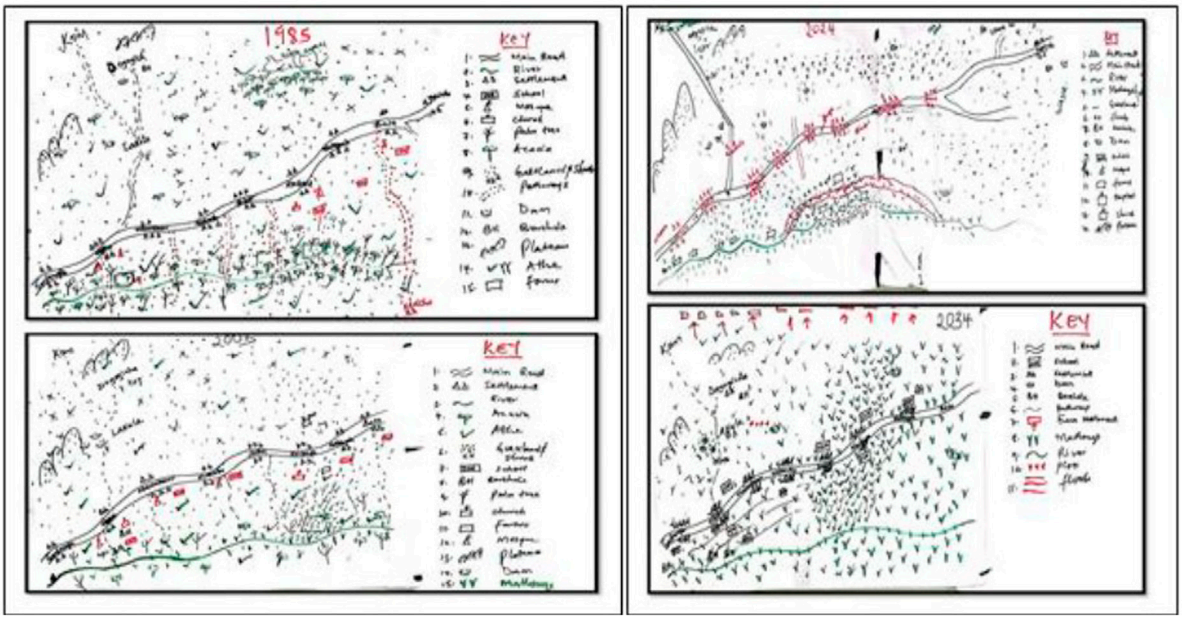

FIGURE 4
Community mental map of land cover Merti, Mnadanur and Korbesa villages (Source: Participatory mapping with the communities).

the x-axis and years (1985, 1995, 2005, 2015, and 2024) on the y-axis. The participants were given 100 stones to distribute among the categories representing the extent of land cover each year. The second activity involved matrix scoring to assess changes in identified key LULC categories. A similar matrix was drawn on the ground, and participants were asked to use symbols representing various LULC. The exercise aimed to score LULC changes and validate the data by using proportional pilling. The participants were provided with 30 stones (five per land-cover category) for the years 1985–2024, allocated across the categories represented in the matrix (Figure 5). The final exercise was to determine the abundance of various vegetation types (grass, shrubs, indigenous trees, *Prosopis*) over the years, using matrix scoring. A matrix was drawn on the ground, with vegetation life forms on the x-axis and years on the y-axis. Participants were provided with 20 stones to score the abundance of each vegetation type for each year by piling stones in accordance with their perceived abundance.

Remote sensing and image classification

Multi-temporal high-resolution imagery (PlanetScope, 3 m resolution, spectral bands: red, green, blue, near-infrared) from 2017 to 2024, with 2017 as the base year for the AOI, was acquired for LULC analysis. The imagery was selected between June and September to minimise cloud cover and seasonal vegetation effects. Geometric and radiometric corrections, image subsetting, and pre-processing were conducted using the acquired imagery. Pre-processing steps enhanced the accuracy and reliability of the analysis by ensuring good alignment, consistency, and focus on the areas of interest (Jebiwott et al., 2021).

The LULC analysis utilised Random Forest (RF) algorithms (Breiman, 2001), with training samples generated in Google Earth Engine (GEE), while classification was conducted in ArcMap 10.8 using the PlanetScope multispectral image as a predictor variable. The RF classifier was run with default parameter settings and a sufficiently large number of decision trees to ensure optimal classification performance. The RF method is preferred for its precision and ability to yield superior results with small sample sizes, making it an ideal choice for analysis. The RF classifier uses decision trees, which require careful management of the number of input samples to ensure an accurate classification. Each tree was trained on a random subset of predictor variables at each node, reducing overfitting and improving classification reliability (Breiman, 2001; Jebiwott et al., 2021).

To validate the training sample, ground-truth data were collected to evaluate the model's performance in terms of accuracy, precision, and recall. A transect walk was conducted with two knowledgeable community representatives, and 56 GPS coordinates were obtained for land-cover features. The different LULC classes were digitised in the KoboToolbox platform. The dense cover of *Prosopis* limited the feasible coverage of the ground surveys. However, the land cover classes were spatially

FIGURE 5
Participatory proportional pilling and matrix scoring of trends in land use and land cover.

extensive and relatively homogenous, reducing the need for dense sampling on accessible areas.

Data processing analysis

The audio recording of the discussion was manually transcribed verbatim. Qualitative data were analysed using thematic analysis. Coding was conducted manually, and Microsoft Excel was used for data management. Google Earth Pro was used to digitise the participatory sketch map, delineating the locations and different LULCs identified by the communities. These Keyhole Markup Language (KML) files were exported to ArcGIS for projection and conversion to shapefiles for data visualisation. Post-processing of remotely sensed data involved refining change-detection results to remove noise and artefacts using spatial filtering and morphological operations. ArcGIS (version 10.8) was used to analyse supervised-classified images, enabling the analysis of LULC changes. Cross-tabulation matrices were generated to quantify LULC changes and compare land-cover classifications across two periods, revealing transitions among categories (Supplementary File 1). Using these matrices, the area changes were calculated in square kilometres (km^2), percentages, and rates of change to illustrate the LULC dynamics of the study area over time. The changes were further subjected to both linear and polynomial regression models (quadratic) using R software to estimate the area of each land cover class in 2034 to inform future land management strategies. The linear regression model assumes a constant rate of change in land use over time (Statistics Solutions & Intellectus360, 2025). In contrast, the Polynomial Regression Model (quadratic) accounts for non-linear changes and can capture accelerations or decelerations in the rate of change (Chellai, 2024). Model performance was evaluated using the coefficient of determination (R^2) to quantitatively assess the strength of the relationship between time and land-cover change.

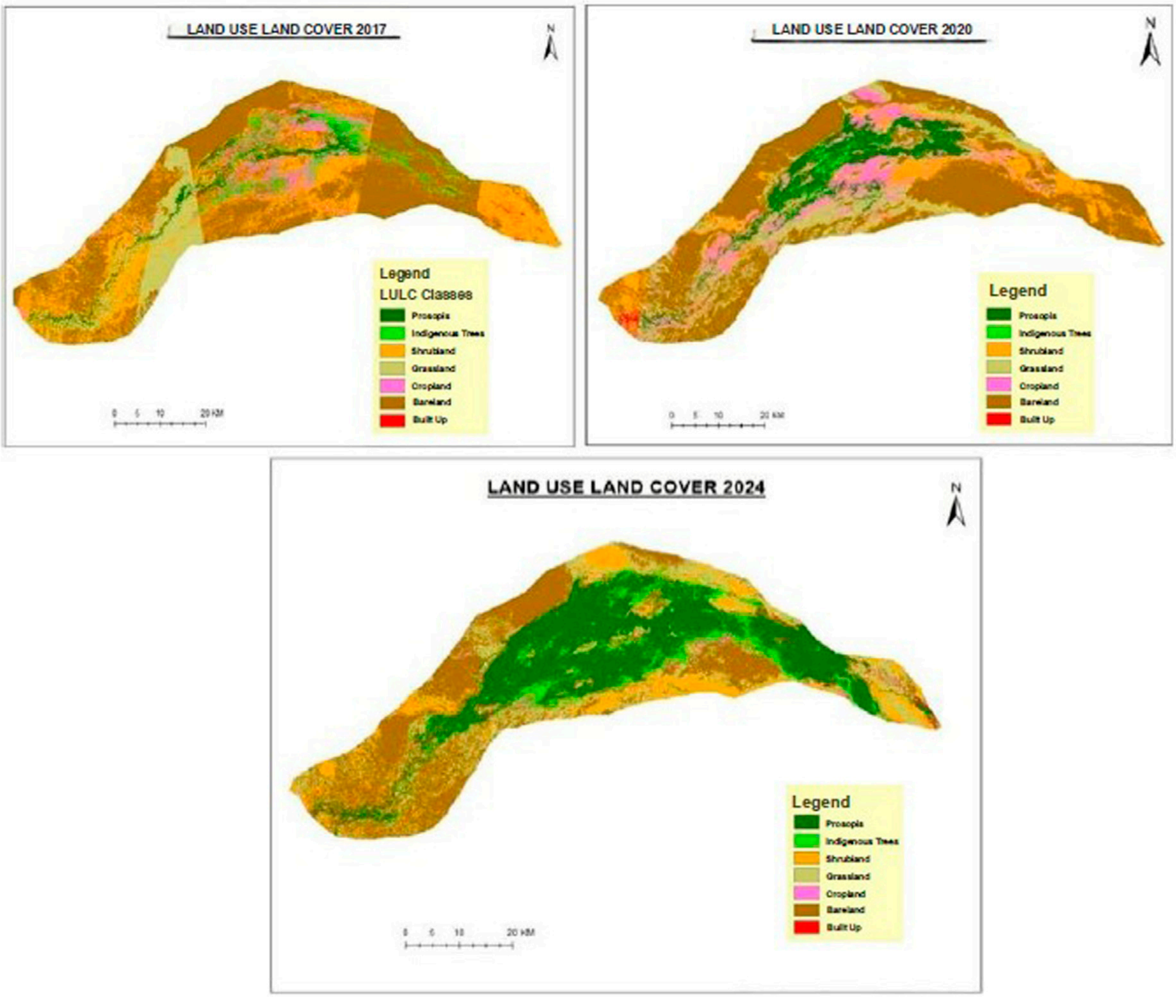

FIGURE 6
Land use and land cover change of the selected area.

Interpretation was undertaken cautiously due to the limited number of data from temporal observations.

The community and stakeholders validated the findings. This was achieved through a structured workshop with sectoral stakeholders and community representatives, involving 15–30 participants. A four-workshop series was conducted, comprising one workshop with stakeholders and three workshops with the community in three villages. The aim of the workshop was to verify the study output and interpretation.

Results

Land use and land cover change trends

The use of dry-season Normalised Difference Vegetation Index (NDVI) and texture metrics enhanced the separability of *P. juliflora* thickets from native vegetation. Between 2017 and 2024, the study area experienced significant changes in land cover. The cover of both *P. juliflora* and indigenous trees has increased between 2017 and 2024 (Supplementary File 1). Shrublands and bare land declined, whereas grasslands and croplands showed mixed trends. Cover of *P. juliflora* increased by 198.64 km^2 between 2017 and 2020 and by 507.45 km^2 from 2020 to 2024, a cumulative increase of 706.09 km^2. Shrubland declined by 340.31 km^2 between 2017 and 2020 and by 74.61 km^2 between 2020 and 2024 (a total decrease of 414.92 km^2 between 2017 and 2024). Grassland increased by 218.14 km^2 from 2017 to 2020 but decreased by 51.56 km^2 from 2020 to 2024 (a cumulative increase of 166.58 km^2). Cropland increased by 77.57 km^2 between 2017 and 2020, but decreased by 200.33 km^2 from 2020 to 2024 (a cumulative decrease of 122.76 km^2), and built-up areas increased by 26.23 km^2 (Figure 6).

TABLE 1 Land cover and rate of change from 2017 to 2024.

Land cover type	Area in 2017 (km^2)		Area in 2020 (km^2)		Area in 2024 (km^2)		Change (2017–2020)	Change (2020–2024)	Annual rate of change (2017–2024)
	Km^2	%	Km^2	%	Km^2	%	%	%	%
P. juliflora	97.82	4.08	296.46	11.59	803.91	32.69	67.69	42.79	103.11
Indigenous trees	101.02	4.21	130.43	5.10	149.22	6.07	9.70	3.60	6.82
Shrubland	652.11	27.21	311.80	12.19	237.19	9.65	−17.40	−5.98	−9.09
Grassland	290.29	12.11	508.43	19.87	456.87	18.58	25.05	−2.54	8.20
Cropland	147.13	6.14	224.70	8.78	24.37	0.99	17.57	−22.29	−11.92
Bare land	1,090.76	45.51	1,073.41	41.95	693.38	28.20	−0.53	−8.85	−5.20
Built-up areas	17.67	0.74	13.62	0.53	43.90	1.79	−7.65	55.60	21.21

Satellite imagery analysis revealed that *P. juliflora* invasion increased from approximately 97.8 km^2 in 2017 to 803.9 km^2 in 2024, a net gain of 706.1 km^2, indicating that *P. juliflora* is the fastest-increasing vegetation-cover category in the landscape (Table 1). The analysis reveals that most areas formerly covered by shrublands and croplands have transitioned to *P. juliflora* cover, which now forms continuous stands along riverbanks and extends outward from village edges. The spatial maps indicate that the *P. juliflora* invasion corridors are along waterways and old vehicle tracks. Much of this expansion occurred at the expense of grassland cover, transforming formerly open rangelands into dense *P. juliflora* thickets. This suggests that if *P. juliflora* spread is unchecked, it could soon displace other vegetation-cover categories, as it currently dominate*s* the Cherab landscape.

Bare land decreased steadily (−397.4 km^2), indicating vegetation encroachment, whereas built-up areas expanded by 26.2 km^2 (3.8 km^2 yr^{-1}), reflecting urban development. Grassland initially increased (218.1 km^2; 72% rise by 2020) but declined thereafter (−51.6 km^2), resulting in a net gain of 166.6 km^2. Shrubland and cropland declined by 414.9 km^2 and 122.8 km^2, respectively, while indigenous tree cover grew modestly by 48.2 km^2.

Historical land use and land cover changes, *Prosopis* invasion and impacts as perceived by communities

Participants linked *P. juliflora* invasion to community-level scorings of historical land cover for 1985–2024, indicating a notable increase in woody vegetation. Participants reported minimal *P. juliflora* cover in the study area in 1985, moderate presence by 2005, and extensive invasion by 2024. Proportional piling indicated *that P. juliflora* was the dominant land-cover category by 2024 (>50%), corroborating satellite trends (Figure 7).

The community reported that *P. juliflora* has invaded areas previously used for cultivation and grazing. The discussions revealed that whereas *P. juliflora* cover has increased, native tree and grass species have declined in cover and abundance over the years. *"Just a few years back, all you could see along the river was palm trees that we used to weave baskets, but now that is gone, and all that we have left is Prosopis everywhere,"* FDG 3, Korbesa. The participants also noted hydrological changes associated with *P. juliflora* invasion, such as frequent flooding along the Ewaso Nyiro River, which is believed to result from the extensive root networks of *P. juliflora* that retain soil moisture and increase river levels. "*Prosopis* has changed the river flow. Its roots hold soil, raising the riverbed and narrowing the river channel. Nowadays, we experience floods more often, forcing us to relocate" FDG 1 Merti.

The participants noted that in Korbesa village, the community-led clearing of *Prosopis* in 2024 along roadsides and river edges created new arable land for maize and bean cultivation. However, *P. juliflora* continued to spread along roads, near homesteads, and water pans, thereby drying water pans and restricting access to water. "We cleared *Prosopis* and planted maize, but it is growing very fast, even blocking the roads," FGD 3 Korbesa. Overall, the community mapping exercise indicated that residents observed a decline in indigenous tree cover and an increase in *P. juliflora* across space and time.

Community perceptions of vegetation abundance trends

The community assessment of land cover revealed a decline in indigenous trees and an increase in *P. juliflora* cover. In the villages of Merti, Mnandadur, and Korbesa, community members recalled that the riverbanks once supported abundant native trees, such as palms, valued for cultural use and traditional construction. "Along the riverbank, there used to be plenty of grass, and we could easily cross to the village on the other side," FGD 2 Korbesa. However, the aggressive spread of *P. juliflora* has displaced these species, limiting the community's

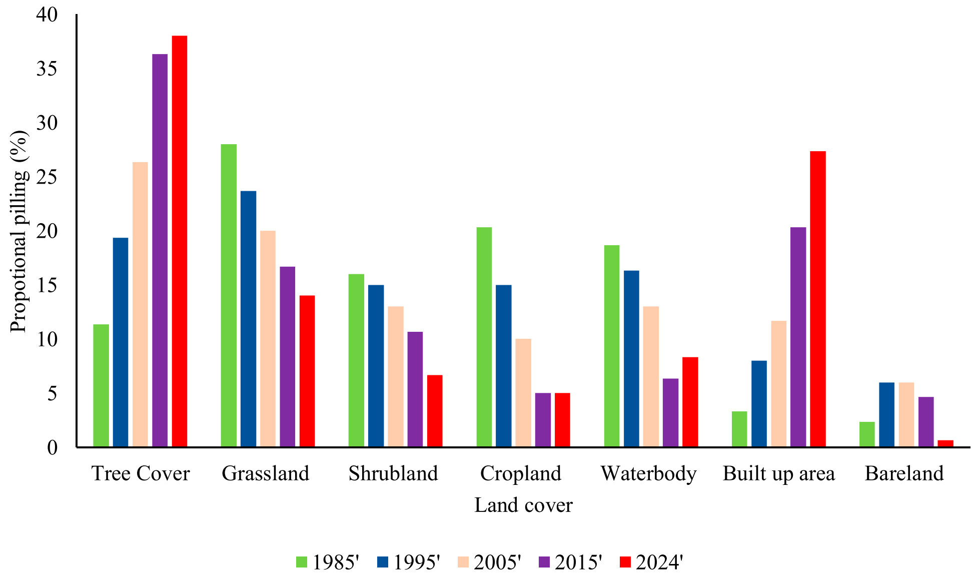

FIGURE 7
Temporal variation in land cover as perceived by the community.

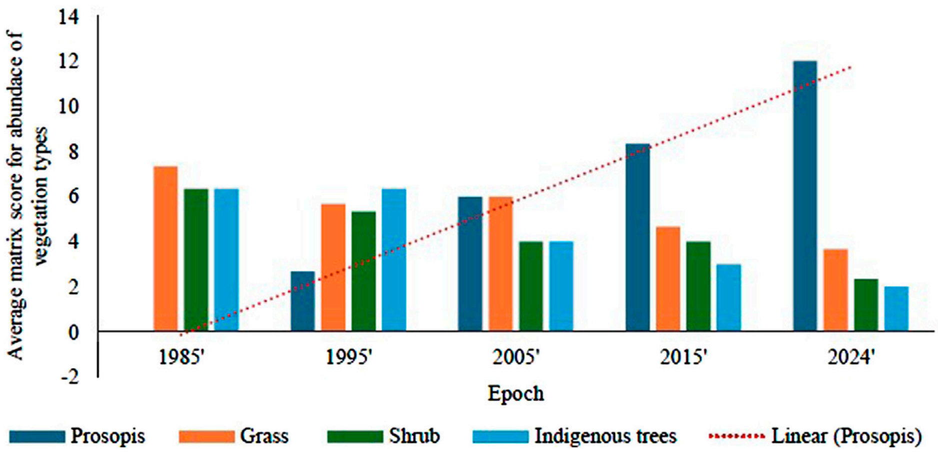

FIGURE 8
Community perception of vegetation abundance.

access to these areas. The older people recounted the introduction of *P. juliflora,* noting that a few rows of the species were planted and later spread to other parts of the village. They recalled that palm trees whose leaves were used in wedding rituals had disappeared, along with some native shrub species. "In the past, we used cut branches of palm trees for our traditional weddings and ceremonies. Now we use the Acacia tree and paint as substitutes," FGD 2 Mnadanur. The herding range of villages in Cherab was reported to have changed, and some livestock losses were attributed to dense stands of *P. juliflora*, in which animals became entangled in thorns, often left behind, making them highly vulnerable to predation.

The 1985–2024 scoring of vegetation abundance showed that shrub species abundance declined by approximately 60%–70%, whereas *P. juliflora* abundance increased by 60% (Figure 8). The participants reported that the landscape had changed significantly; areas that were open grassland along the river, used for dry-season grazing, have been replaced by dense *P. juliflora* thickets that restrict access. This disrupts movement, reduces grazing area, and alters the community's interaction with

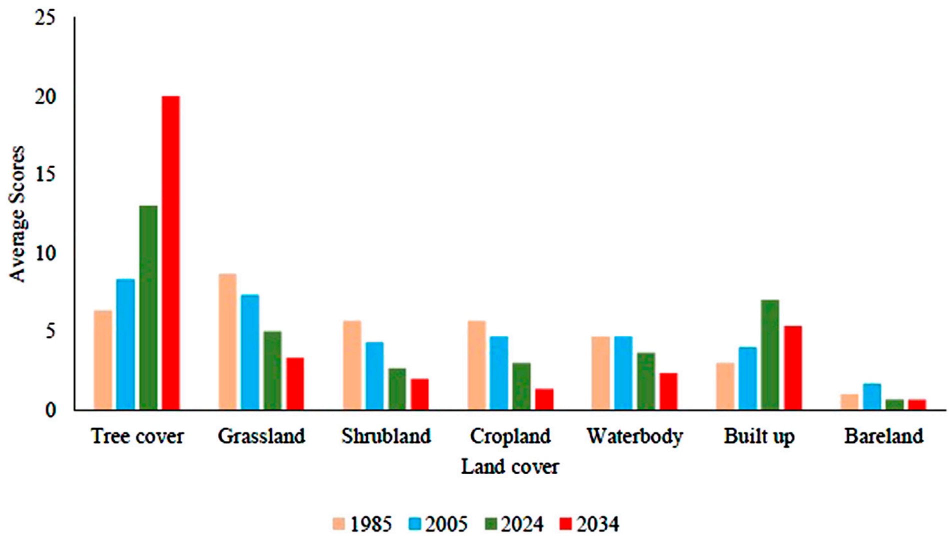

FIGURE 9
Community future visioning of land cover.

the environment. Shows the perceived abundance of vegetation from 1985 to 2024.

Future vision of the land cover by communities

Figure 9 presents the community's future land cover projections for the study area. The community expressed concerns about potential displacement from the rapid encroachment of *P. juliflora*. They projected that by 2034, the species would dominate the area, disrupt livelihoods, and force relocation, particularly for households near the river that are likely to be affected first. In anticipation of this, the land north of Merti Town has already been identified as a potential site for resettlement. Residents have also reported that water was abundant in Merti in the past, noting that reliable water sources have declined since the 2000s. They attributed this decline to the invasion of *P. juliflora*, which they believe has contributed to groundwater depletion, raising concerns about the long-term sustainability of the piped water supply.

Rate of land cover change

Between 2017 and 2024, the land cover changed notably, primarily driven by the rapid spread of *P. juliflora*, which invaded an average of 100.87 km^2 per year (Table 1). The cover of indigenous trees increased gradually, whereas that of shrublands declined significantly, with an average annual loss of 59.27 km^2. Grassland cover fluctuated, with early gains followed by a later decline, but averaged a steady net increase. Croplands initially expanded, but later declined, resulting in an average annual decrease of 17.54 km^2. Bare land consistently decreased, indicating vegetation recovery, whereas built-up areas grew gradually, reflecting urban development pressure (Figure 10). These shifts highlight dynamic landscape transformations with ecological and socioeconomic implications.

Land use and land cover model 10-year projection

Both the linear and polynomial model projections showed significant growth in *P.juliflora* and indigenous trees, with the polynomial model predicting much larger (3285.52 km^2) areas under *Prosopis* in 2034 (Table 2). The linear model projected the disappearance of shrublands, croplands, and bare land (Figure 11). The polynomial model, however, provides flexible projections, particularly for shrublands, which are predicted to show some recovery, and built-up areas, which are expected to show substantial growth by 2034 (Figure 12). While polynomial and linear models indicate potential increases or decreases in land use, they may overestimate trends when the underlying changes are non-linear.

The linear regression analysis showed marked differences in temporal trends across LULC classes. *Prosopis* (R^2 = 0.85), bareland (R^2 = 0.85), shrubland (R^2 = 0.82), and built-up areas (R^2 = 0.71) exhibited a strong linear relationship over time. This indicates that a large proportion of observed temporal variation in these classes was consistently captured in the linear trend. In contrast, indigenous trees (R^2 = 0.09) showed a weak linear relationship, whereas grassland (R2 = 0.45) showed a moderate linear relationship, suggesting that linear trends account for only limited variation across these classes.

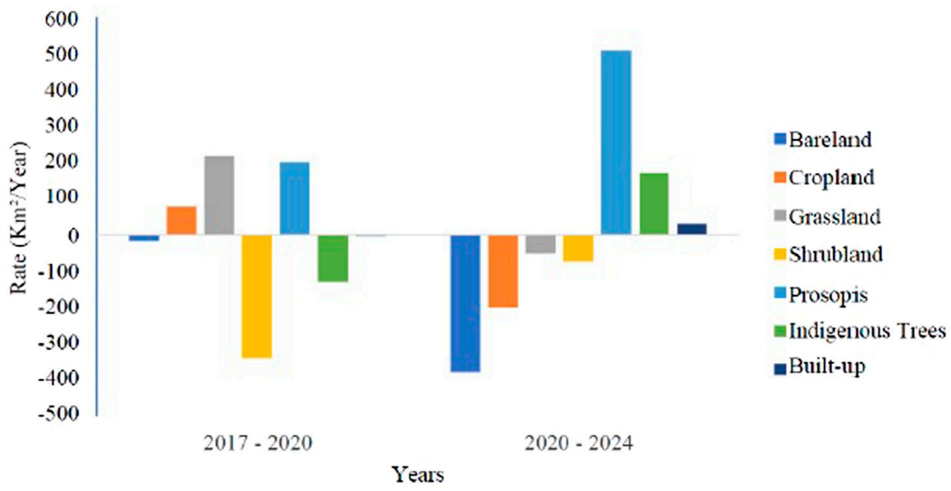

FIGURE 10
Rate of land use and land cover change.

TABLE 2 Land use and land cover projections for 2034.

Type of land cover	Linear model projections (2034)- km^2	Polynomial model projections (2034)-km^2	Linear R^2	Polynomial R^2
Prosopis	1,797.16	3,285.52	0.97	1
Indigenous trees	231.95	2,335.75	0.09	1
Shrubland	0.00 (complete loss)	1946.35	0.82	1
Grassland	716.66	0.00 (complete loss)	0.45	1
Cropland	0.00 (complete loss)	0.00 (complete loss)	0.45	1
Bareland	148.43	0.00 (complete loss)	0.84	1
Built-up areas	79.10	298.00	0.71	1

The polynomial models showed a perfect fit (R^2 = 1.00) across all classes. This suggests that, with only three parameters, the results inevitably overfit and have zero degrees of freedom. The apparent superiority of the polynomial model is artefactual and limits statistical inferences about a genuine nonlinear model.

Discussion

Land-use and land-cover change and the social impacts

This study presents the current patterns and future projections of *P. juliflora* invasion in arid and semiarid rangeland ecosystems. The observed patterns of *P. juliflora* encroachment into watercourses and roads before its spread into adjacent rangelands have been documented elsewhere. Previous studies have reported the same patterns in the drylands of Ethiopia and Kenya, where woody invaders have been reported to initially occupy riparian grazing areas before spreading to other areas (Mbaabu et al., 2019; Ng et al., 2017; Wakie et al., 2016). The Ewaso Nyiro River, which drains through Cherab Ward, and its canal irrigation systems likely serve as seed corridors, likely through livestock and irrigation water (Nduro, 2024). The dispersal of *Prosopis* has also been reported to be directed through tracks made by moving vehicles (Njuguna et al., 2021; Nzombeand, 2018). The dominance of *P. juliflora* along watercourses and the eventual invasion of rangelands corroborate the findings from studies in Ethiopia and Kenya that *P. juliflora* threatens rangelands by reducing the availability of grazing areas for livestock (Kishoin et al., 2024; Ng et al., 2017).

The increase in cropland from 2017 to 2020 and its subsequent decrease from 2020 to 2024 were consistent with the narrations of villagers and may have been due to the

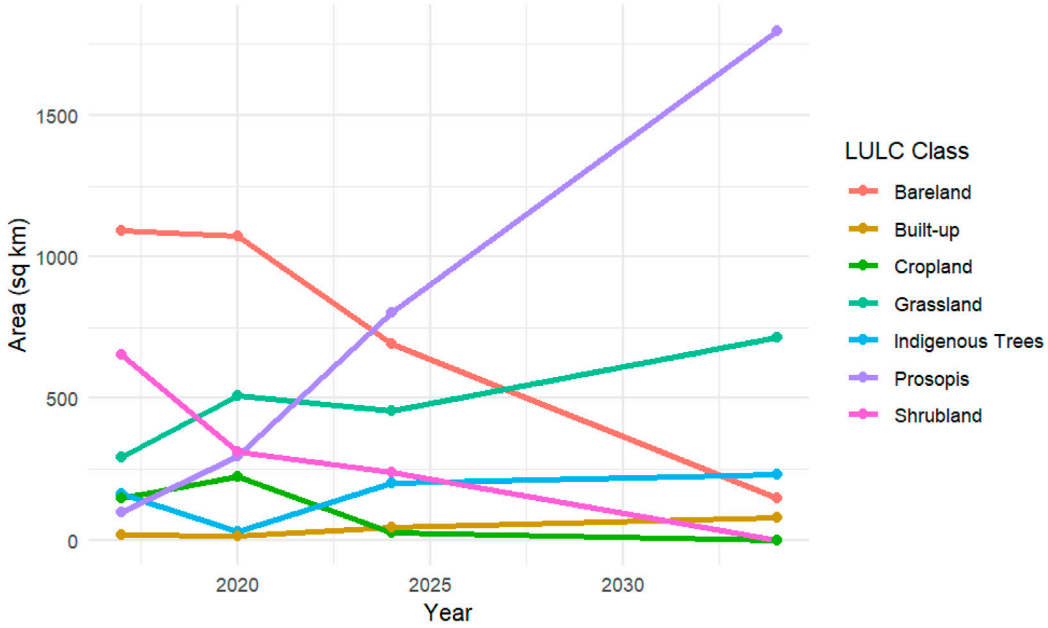

FIGURE 11
LULC projections (2017–2034)-Linear model.

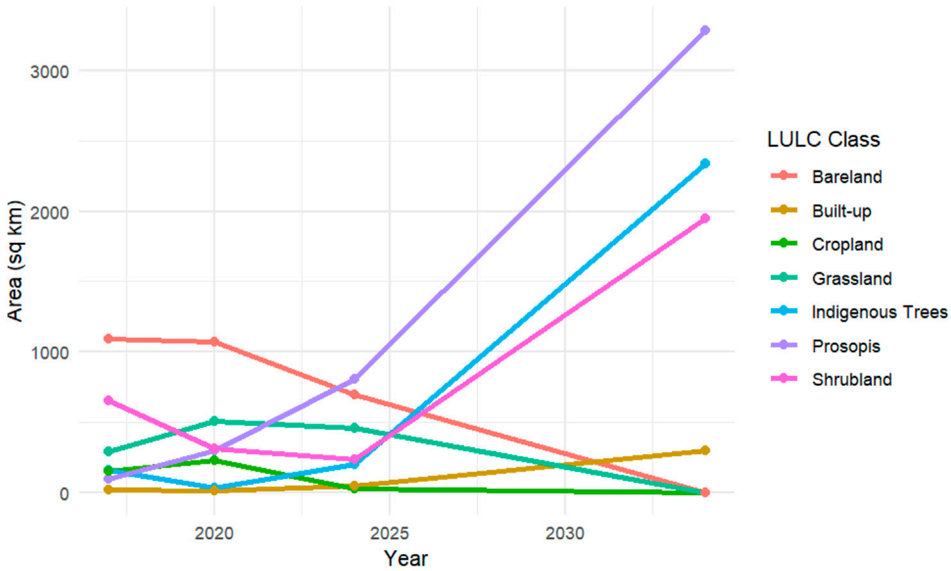

FIGURE 12
LULC projections (2017–2034)-Polynomial model.

aggressive regeneration of *P.juliflora* following its clearance, a typical characteristic of weedy plants. Another probable resurgence of *P. juliflora* in areas cleared for farming and charcoal production might have induced coppice growth. As observed by Mwangi and Swallow (2005), some modes of *P. juliflora* utilisation, such as charcoal production and fencing, have not been widely used to control the species' invasion, as they may exacerbate it.

The social and economic implications of *P. juliflora* invasion are significant in the pastoral landscape. Encroachment into rangeland reduces the availability of grazing resources, which is closely linked to livestock production and household livelihoods in pastoral systems (Fox et al., 2025). The findings on the expansion of *Prosopis* suggest heightened vulnerability of pastoral households to food and income stress, given their dependence on livestock production. The financial burden of restoring invaded croplands and pastures is considerable, with studies indicating that such efforts are expensive and often beyond the means of the affected communities (Eschen et al., 2021). Furthermore, access to water is increasingly constrained in invaded areas because *P. juliflora* often dominates water points, forming dense thickets that hinder access for both humans and livestock. Community observations associate increased proliferation of *P. juliflora* with reduced water availability, consistent with a study by Mbaabu et al. (2019).

Rate of spread of *Prosopis* and predicted future scenarios

The displacement of indigenous plant species by *P. juliflora* can be attributed to its competitive ability. Bezaredie et al. (2023) reported that *P. juliflora* outcompetes the native flora through rapid growth and allelopathic suppression. The annual rate of spread of *P. juliflora* underscores its aggressive invasion and potential to outstrip the adaptive capacity of pastoralist systems to respond effectively (Kishoin et al., 2024). Previous studies have reported that *P.juliflora* stands replace diverse native tree species, leading to reduced biodiversity and simplified vegetation structure (Abenu et al., 2023; Mutua et al., 2019; Rachmat et al., 2021). Reports from communities in the current study on the decline in palm trees and grasses concur with this observation. It is expected that *P. juliflora* invasion alters ecosystem functions, with dense canopies and a deep root system that affect soil and other plant species, as well as the water cycle. As noted by the community, soil is retained beneath *P. juliflora* thickets, causing siltation in the riverbed, raising water levels during heavy rainfall, and exacerbating floods. *P. juliflora* has high evapotranspiration, which leads to increased water consumption and reduced groundwater recharge (Salma and Debbie, 2018). The increase in the thickness of *P. juliflora* is associated with future water scarcity, suggesting that the species' water consumption outpaces natural recharge (Tundia et al., 2025). Water stress associated with *P. juliflora* invasion may exacerbate the impacts of climate change by intensifying drought severity and increasing the susceptibility of arid and semi-arid regions to extreme climatic events (Tadros et al., 2020).

P. juliflora invasion is associated with significant socio-economic costs to pastoralist livelihoods. The expansion of thick *P. juliflora* stands reduces access to pastures and the availability of palatable forage, thereby directly affecting herd health and productivity. This ecological alteration of grazing land necessitates herder migration to distant pastures, thereby reducing livestock productivity. Critically, the community anticipates that if *P. juliflora* continues unchecked, grazing land will further decline and settlements will have to be relocated by around 2034. The projections from the two models highlight significant shifts in land use with the expansion of *P. juliflora* and indigenous trees and declines in shrubland, cropland, and bareland. This projection underscores that the invasion of *P. juliflora* is not only an ecological challenge but also has far-reaching socio-economic implications. These non-linear responses suggest that these land-cover classes are more sensitive to disturbance and seasonal variability than to consistent directional change. Importantly, these spatio-temporal variations align with local community observations of fluctuating pasture availability and land productivity, underscoring the need to integrate local knowledge with spatial analysis (Tokbergenova et al., 2025). The findings highlight that, although *P. juliflora* invasion follows a relatively consistent expansion trajectory, other land-cover types respond in a more complex manner. Therefore, these call for spatially targeted and context-specific rangeland management strategies.

On the adaptive side, the findings of the current study showed community ingenuity, in which locals organised clearing campaigns, repurposed cleared land for bean and maize production, and used the cleared wood for charcoal production. While this represents an important adaptive strategy that enables households to regain access to their productive land, its sustainability remains uncertain. Similarly, the utilisation of cleared biomass provides income to the community but does not fully offset the ecological and economic costs associated with the continued spread of the plant (Shackleton et al., 2019). These local efforts contribute to household resilience but partially mitigate the invasion dynamics. Therefore, the dual pressures of controlling *P. juliflora* and identifying alternative income options highlight the need for multi-level coordinated management strategies that complement community initiatives (Hodbod et al., 2019).

Overall, *P. juliflora* encroachment threatens traditional pastoral production systems by diminishing grazing and water resources, with the possibility of causing resource-based conflicts when pastoral communities are forced to compete over scarce resources, while also prompting new forms of land use as communities adapt to invasion (GIZ, 2014; Kamiri et al., 2024). These trends suggest the need for proactive conservation of native biodiversity, grazing resources, and water access, along with inclusive and community-driven approaches to sustainable land management to mitigate adverse impacts.

Invasive species and ecosystem change monitoring for evidence-based sustainable land management

Monitoring and analysing changes in landscapes over time and across regions is important for promoting the long-term sustainability of ecosystems, particularly amid global environmental changes. These alterations reflect the impact of human actions, both at the local level, such as the shift in species composition, and at global scales, through broader trends (Alphan, 2017). Wildfires, increasingly intensive agriculture, population growth, habitat fragmentation, climate variability, pollution, new technologies, globalisation, and the spread of invasive species are key drivers. These forces affect ecosystems, biodiversity, local economies, and social wellbeing (Bürgi et al., 2005). Systematic monitoring, therefore, promotes innovative and effective management strategies (Alphan, 2017).

The degradation of grasslands and its detrimental effects on ecosystems and human wellbeing are well-documented (Han et al., 2020). This decline has been accompanied by the increasing popularity of invasive species. Such plants grow rapidly, disrupt vital ecosystem services, and adversely affect the environment and livelihoods of the local populations. Climate change is likely to intensify these challenges. However, designing effective policies and interventions to control such invasions is difficult, as data on their extent and impact are often unavailable, particularly at the local level. For example, in Kenya and Ethiopia, the 'utilisation' strategy for *Prosopis* control was implemented without robust scientific evidence of its effectiveness (Gebrehiwot and Steger, 2024; Kamiri et al., 2024).

This study addresses the gap in *P. juliflora* research by providing spatially explicit, temporally grounded evidence of its invasion dynamics and associated ecological and livelihood impacts. Integrating LULC change analysis with local knowledge, the findings indicate that *P. juliflora* is highly invasive, consistent with observations across Kenya, Africa, and beyond (Athamanakath et al., 2025; Gebrehiwot and Steger, 2024; Mungoche et al., 2025). The invasion reduces essential ecosystem services, such as access to grazing areas, food production, and water availability and access, undermining pastoral livelihoods (Kishoin et al., 2024). Although *P. juliflora* has the potential for charcoal production, timber production, and landscape greening, evidence shows that ecological costs and livelihood losses at both local and national levels may outweigh its benefits (Bekele et al., 2024). Encroachment into agricultural and grazing land further raises management costs and constrains to rural livelihoods, highlighting the need for spatially targeted, locally informed interventions (Moslehi Jouybari et al., 2022; Zeray et al., 2017). These findings highlight the significance of integrating spatio-temporal analysis with local community knowledge to inform the prioritisation of control and utilisation efforts, and the development of sustainable, context-specific rangeland management strategies. This calls for the co-production of new knowledge on the species' spread, its impacts, and opportunities for its sustainable control and exploitation for ecological and economic benefits.

Climate change mitigation strategies in semi-arid regions have increasingly emphasised afforestation (Yosef et al., 2018). However, the findings of this study demonstrate that the introduction of invasive species such as *P. juliflora* can be counterproductive. Although often promoted for carbon sequestration, *P. juliflora* is well adapted to arid and variable climatic conditions, enabling it to continue spreading under rising temperatures and water stress. While spreading, it simultaneously reduces biodiversity and disrupts essential ecosystem services, particularly the provision of forage for livestock. These outcomes are consistent with evidence from other semi-arid environments (van Wilgen et al., 2024). In contrast, the rehabilitation of native grasslands appears to be a superior choice because it enhances climate mitigation, biodiversity, and rural livelihoods by reversing land degradation (Filbert et al., 2025).

Against the backdrop of rapidly accelerating climate change, species' habitats are being altered at unprecedented rates (Eckert et al., 2020). The spread of *Prosopis* reported in this study aligns with the broader evidence that anthropogenic environmental change can accelerate the expansion of woody invasive species in certain areas, but decelerate it in others (Wakie et al., 2016). These dynamics intensify existing ecological challenges, particularly the displacement of native species and simplification of rangeland ecosystems. Given the high financial and logical cost associated with controlling *Prosopis* invasion, especially in resource-limited settings, the findings highlight the need for evidence-based, cost-effective management strategies that are viable under present and projected climatic conditions (Fox et al., 2025). This is particularly significant for vulnerable ecosystems that support communities facing numerous socioeconomic and environmental stressors.

Integrated management is urgently required to curtail the spread of *Prosopis*. Multi-stakeholder collaborations linking communities, NGOs, researchers, and government agencies should co-develop control measures, including biocontrol trials, pod harvesting for livestock feed, and mechanical clearing. Capacity-building programs can equip communities with the skills for native species restoration and *P. juliflora* utilisation (Mekuyie et al., 2018). The limited temporal depth of LULC data constrained the statistical robustness of on-trend analyses and the accuracy of projections. Additionally, although the regressions reproduced observed LULC changes, their perfect goodness-of-fit reflects over-parameterisation rather than ecological predictability. The model's projections nonetheless provide complementary insights by distinguishing classes characterised by consistent trends from those governed by complex, non-linear dynamics. Therefore, future research should incorporate long time series, higher temporal resolution, and integrate socioeconomic and climatic drivers to improve the reliability of projections and further elucidate the processes that shape LULC change.

Conclusion

This study documents a rapid expansion of *P. juliflora* across rangelands in Isiolo County, increasing from 97.8 km^2 in 2017 to 803.9 km^2 in 2024. This accelerated invasion trajectory has significant implications for rangeland ecosystems and the pastoral livelihoods. This expansion has displaced native vegetation and reduced grazing land, contributing to reduced forage availability, limited water access, increased risk of displacement, and declining biodiversity. These changes pose growing challenges for livestock production systems that underpin local livelihoods in the study area.

By integrating remote sensing with participatory mapping, this study provides a locally grounded baseline for monitoring the spatial dynamics of *P. juliflora*. Community observations corroborated spatial trends and provided context-specific insights into the impacts of invasions and local responses, demonstrating the value of participatory approaches in invasive research. This co-creative mapping approach represents a theoretical advancement in land management, sustainable development, and conservation planning in rangeland environments.

The findings of this study suggest that addressing *P. juliflora* invasion necessitates coordinated management approaches that consider both ecological processes and local livelihood realities. While community-led initiatives contribute to mitigation efforts, they are insufficient in isolation. These point to the need for integrated, multi-level strategies that support sustainable rangeland while safeguarding grazing resources, water access, and native biodiversity.

Author's note

Future research should expand participatory assessments to more communities and develop detailed, site-specific maps to better target interventions and track land use changes over time.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

Conceptualization: OW, DI, and HA; Original draft preparation and writing, HA; Writing – review and editing: all authors; Validation of content, OW & HA. All authors reviewed the results and approved the final version of the manuscript.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2026.15673/full#supplementary-material

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