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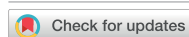
Disentangling the drivers of vegetation change in a mobility-constrained pastoral landscape in Laikipia Kenya

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Disentangling the drivers of vegetation change in a mobility-constrained pastoral landscape in Laikipia Kenya

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E-mail: ryanr.unks@uab.cat**Keywords:** rangeland ecology, dryland ecology, pastoralism, degradation, rangeland biodiversitySupplementary material for this article is available [online](#)

Abstract

Dryland ecosystems around the world support high biodiversity and extensive pastoralism, but the drivers of landscape change are often poorly understood. Reductionistic understandings have tended to overemphasize livestock impacts and support restrictive interventions, which can ironically undermine synergistic relationships between pastoralism and biodiversity. Within a collectively-titled pastoralist landscape in Laikipia, Kenya, we built on long-term research to examine spatial relationships between locally-varying livestock use intensity and patterns of vegetation change over a 26 year period. We integrated remote sensing, field vegetation measurements, and pastoralist expert accounts of vegetation change to map vegetation transitions and their spatial distribution. We triangulated between multiple lines of inference, including classifications of vegetation community types and transitions, maps of varying livestock use zones and topography, qualitative analysis of expert explanations of vegetation change, and NDVI time series, to infer the contributions of grazing intensity and other drivers to the observed vegetation transitions. First, the most salient landscape change was the loss of two *Euphorbia* spp. in ~22% of the study area; with elephants largely driving the loss of one species, and climate being a probable driver of loss of the other. Second, approximately 40% of the area experienced some degree of shrub encroachment. Spatial comparisons with livestock use zones indicated that shrub encroachment was more likely driven by fire suppression and/or climate. Third, there was ~26% decrease of area supporting moderate or dense herbaceous vegetation cover. These decreases were primarily associated with increasing temperature, woody encroachment, and higher livestock pressure in areas that both formerly supported *Euphorbia* spp. canopies and also experienced year-round livestock use imposed through a conservation intervention. We recommend integrative triangulation between multiple epistemologies to understand how landscape changes in dryland ecosystems are driven by complex, interacting drivers such as spatio-temporal climate variability, megaherbivores, fire suppression, sedentarization, and changing livelihoods.

1. Introduction

Global drylands support high plant and wildlife biodiversity as well as extensive pastoralism (Western *et al* 2009, Sayre *et al* 2013, Sala *et al* 2017, Maestre *et al* 2021). In drylands, with high spatial and temporal variability of key resources, landscape connectivity is essential for both extensive pastoralism and migratory wildlife populations (Behnke *et al* 1993, Fratkin 2001, Hobbs *et al* 2008, Homewood 2008). The ecological impacts of fragmentation and sedentarization, changing climate regimes, fire suppression, and other complex drivers of landscape change in rangelands worldwide are salient (Galvin *et al* 2008, Groom and Western 2013, Sayre *et al* 2013, Bond 2019, Briske *et al* 2020, Maestre 2021). Complex dynamics of nutrients, water, herbivory, soils, and fire are known to play strong roles in structuring dryland vegetation (Sankaran *et al* 2005, 2008, D'Odorico and Porporato 2006, Bond 2019, Maestre *et al* 2021). Consequently, the intensity, timing, duration, and spatial distribution of rainfall, nutrient deposition, and disturbance are critical factors to consider in assessing vegetation dynamics (Ellis and Swift 1988, Adler *et al* 2001, Vetter 2005, Good and Caylor 2011, von Wehrden *et al* 2012, Rasmussen *et al* 2018).

Despite a shift in paradigm in dryland rangeland ecology that emphasizes these complexities (Ellis and Swift 1988, Westoby *et al* 1989, Briske *et al* 2003, Van Langevelde *et al* 2003), pastoral management practices and stocking rates often remain assumed to be primary drivers of rangeland vegetation change (Briske *et al* 2020). Studies that have misattributed dryland degradation primarily to local livelihoods have often justified policies that both restrict livelihood practices and reinforce existing power dynamics in natural resource management (Fairhead and Leach 1996, Dahlberg and Blaikie 1999). In Laikipia, Kenya, pastoralists' lands have undergone broad changes in vegetation composition and density (Njenga 2001, Nareda 2004, Unks 2017). These trends are frequently generalized and cited as indicators of 'overgrazing', breakdown of common property regimes, or human overpopulation, and are invoked to cast pastoralism as undermining wildlife conservation planning and to justify calls for alternate rangeland management (Lent *et al* 2002, Nareda 2004, Sumba *et al* 2007, Fennessy 2009, Alexovich *et al* 2012, Strum *et al* 2015, Kimiti *et al* 2017, Kibet *et al* 2021, Scheetz *et al* 2022). However, we are unaware of any strong empirical evidence which rigorously supports these generalizations about the impacts of extensive pastoralism on vegetation in the region, which are often at odds with pastoralists' highly nuanced understandings of different types of landscape changes and the interactions among multiple factors that drive them (Roba and Oba 2009, Unks 2017, Unks *et al* 2019a). A large body of ecological research in Laikipia

has examined the interactions between wild herbivores and vegetation (e.g. Young *et al* 1997, Augustine and McNaughton 2004, Young and Augustine 2007, Sankaran *et al* 2013), as well as cattle and vegetation (Mizutani 1999, Young *et al* 2005, Odadi *et al* 2007, Riginos and Young 2007, Veblen and Young 2010). While informative, these studies have primarily occurred on privately held conservation ranches, where rainfall is higher and less variable, and livestock herding practices and socio-cultural and economic relations differ markedly from nearby pastoral areas; their extrapolation across contexts is inappropriate (Unks *et al* 2019a, Unks 2023).

We conducted a detailed analysis of vegetation changes over a period of 26 years within the landscape of one collectively-titled ranch in Laikipia, Kenya. The complex socio-cultural, economic, political, and land use history, and highly heterogeneous vegetation in the study site, create a high potential for misinterpreting interrelated changes in livelihoods and land use, particularly using data-limited and inherently subjective remotely-sensed analyses (Robbins 2003, Turner 2003, Velásquez Runk *et al* 2010). To empirically evaluate commonly stated assumptions about landscape change in the study site, we devised an integrative, spatially explicit, mixed-methods analytical procedure. We incorporated pastoralist expert understandings, while recognizing Indigenous ways of knowing as sovereign and vital for inclusive decision-making (Latulippe and Klenk 2020, Trisos *et al* 2021, Aini *et al* 2023). Pastoralist experts' knowledge informed our analysis, but also served as a counterbalance to powerful actors' generalizations, assumptions, and narratives that can bias problem framings of ecological analyses (Nadasdy 2005, Goldman 2007, Klenk *et al* 2017, Martel *et al* 2021, Cumming *et al* 2023). This methodology contrasts with approaches that instrumentally use information from Indigenous ways of knowing as confirming or supplementary to ecological science (Berkes *et al* 2000, Agrawal 2002, Sillitoe and Marzano 2009).

We elicited Indigenous pastoralist experts' oral histories of site-specific vegetation changes, qualitatively analyzed these interviews, and combined results with vegetation surveys to guide satellite image classification of vegetation types present in 1987 and 2013. This enabled us to characterize the types and spatial patterns of recent and past vegetation composition across the landscape, which was highly heterogeneous at fine scales (10^1 – 10^2 m). Livestock use intensity varies spatially within this landscape due to land use zones that were imposed as part of wildlife conservancy formation, enabling us to distinguish between livestock effects and other possible drivers. By analyzing localized vegetation changes, and their correlations with landforms and pastoralist land use at each location, we were able to quantitatively assess the likelihood that livestock pressure contributed to

different types of vegetation change. Drawing from experts' discussions of drivers of vegetation changes, additional analyses of time series climate and NDVI data, and our previous analyses of livelihood, land use change, and plant ecology (King and Stanton 2008, King *et al* 2012, King and Franz 2016, Unks *et al* 2019a, 2019b), we were able to further assess these drivers and to identify other factors that are essential to consider in analyses of vegetation change.

2. Methods

2.1. Study site description

The study took place on Koija Group Ranch in Laikipia County, Kenya (figure 1). The majority of the people who reside at Koija today primarily practice pastoralism as a livelihood (see Unks *et al* 2019a for detailed history of study site). Decreasing livestock mobility is driven by recent loss of land access due to exclusion from settler ranches, conflict over nearby administrative boundaries, and the recent establishment of wildlife conservancies on community land (Herren 1991, Lengoiboni *et al* 2010, Letai and Lind 2013, Unks *et al* 2019a; note S1). The ecological implications of exclusion of mobile pastoralism along new landscape partitions are numerous and amount to a drastically altered landscape process; including that of concentrated pressure due to seasonal changes in cattle mobility, as well as the concentrated, differential impacts of the foraging habits of sheep and goats (Unks 2023). The study area is located at an elevation of 1700 m. It is characterized as semi-arid with a mean annual precipitation of ~500 mm per year, and an annual coefficient of variation of approximately 23%–24% (figure S1). Rainfall is bimodal, primarily occurring in April–May and November (figure S1). Laikipia rainfall events have become significantly less frequent and more intense over the last 80 years (Franz *et al* 2010). The vegetation at the landscape scale is a diverse mosaic of savanna, grassland, dense shrubland, and succulents. Fire has been infrequent for decades, but was integral to the ecosystem historically (Augustine 2003). The soils are a mosaic of luvisols and vertisols. Impala, gazelles, dik–dik, hares, and elephants are common wild herbivores. Elephant populations increased through the study period, from the 1980s to the 2010s (Litoroh *et al* 2010, Ogutu *et al* 2016), and are known for their impacts on the densities of trees and vegetation composition (Western and Maitumo 2004, Kimuyu *et al* 2014). Termites and aardvarks also redistribute nutrients and influence the heterogeneity of the landscape (Pringle *et al* 2010, Tarnita *et al* 2017).

2.2. Expert vegetation change analysis

To consider Indigenous pastoralist experts' knowledge of ecological process alongside remote sensing analysis and conservation actor understandings,

we used a combination of focus-group discussions, key-informant interviews, and semi-structured interviews (see note S2). We first conducted eight focus group discussions with elders, two within each of four areas where homesteads (nkangitie) are clustered at Koija, and five in-depth key-informant interviews on landform taxonomies and terminology. Fourteen expert interlocutors were then approached after being recommended highly by community members for their extensive knowledge of plants and historical changes in ecological factors. We conducted semi-structured interviews with experts at ten different locations that were selected to represent the distinct landform/vegetation assemblages that experts agreed existed across the Koija landscape. At each location, experts were asked a series of standardized questions using terminology and concepts identified in key-informant interviews, focus-group discussions, and informal discussions of salient landscape features. They explained landforms and vegetation present, indicators that they used to distinguish certain ecological zones or vegetation assemblages (e.g. soil properties, plant species composition, physiognomy of vegetation structure, etc), salient changes in these variables over the past 30 years, how vegetation assemblages have changed in relative abundance and spatial distribution, the underlying factors that shaped their current distribution, and the different transitions between states. The main landform, vegetation assemblages, soil concepts, landscape positions, transitions, drivers, and interrelation/interdependence of these factors were systematically analyzed to inform vegetation classifications and tests of potential drivers of transitions.

2.3. Hybrid supervised/unsupervised classification of vegetation

We developed hybrid classification methods for a study period of 1987–2013, working within constraints of limitations in cloud free images, sensor errors, comparable climate histories, image resolution, and reliable ground truth data. Using Erdas Imagine 16.0, we first classified a Landsat 8 Level 2 Image (23 May 2013, Path 168/Row 60), taken following a time of two years of consistent rainfall (figure S2). We collected four plant community composition datasets using plot-based sampling (figure 1; note S3), and used these to build training sets to optimize classification of a pan-sharpened copy of the Landsat image, using Quickbird and Pleiades images to iteratively assess the classification (see note S4 for detailed methodology). We then resampled this classification to 30 m and iteratively tested unsupervised algorithms to determine which most closely matched (figure 2, blue paths). Because signatures of distinct vegetation on luvisol and vertisol soils were not consistently distinguishable by unsupervised algorithm,

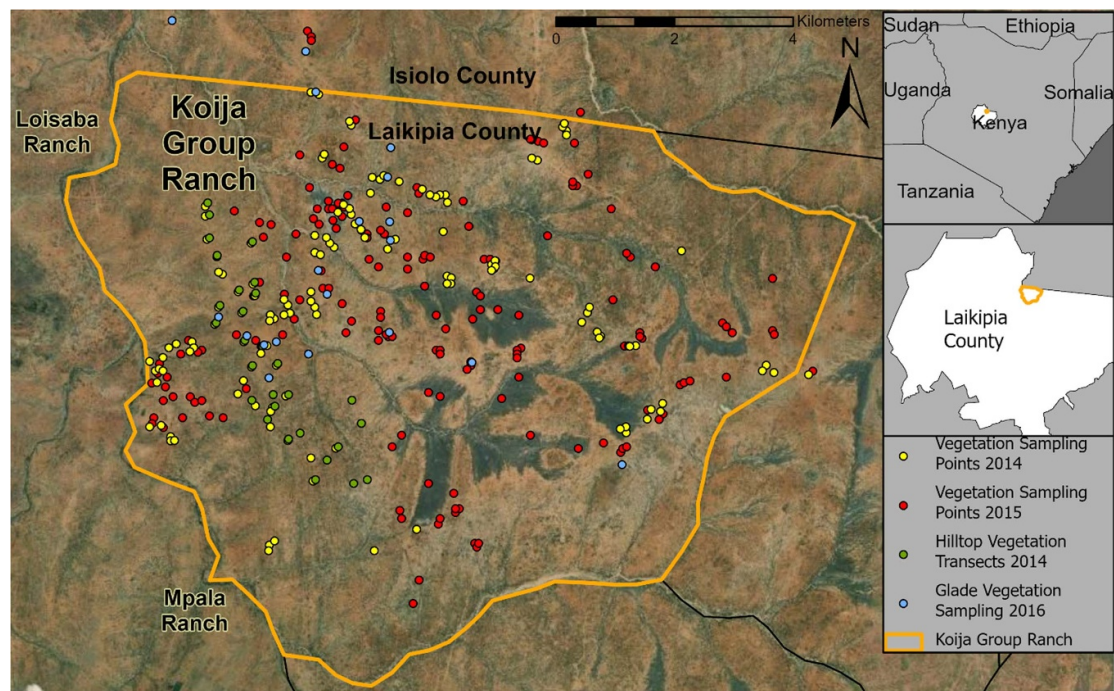


Figure 1. Map of the study site and locations of vegetation sampling at Koija Group Ranch, in Laikipia County, Kenya. Vegetation sampling points in 2014 and 2015 were spatially randomized, stratified by preliminary vegetation classification. Hilltop transects and glade sampling points were purposively distributed in those landscape features.

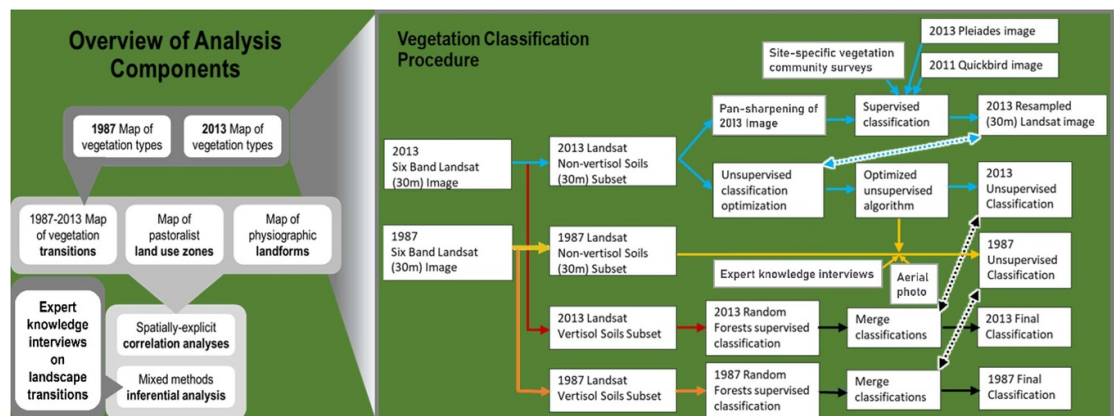


Figure 2. Summary of study's analysis components (left) and detailed workflow diagram for hybrid vegetation classification procedure (right). Sub-processes: 2013 luvisol classification (blue paths); 2013 vertisol classification (red path); 1987 classifications (yellow and orange paths); luvisols/vertisols merged (black paths). Dashed arrows indicate iterative processes.

we created a binary luvisol/vertisol mask, and independently classified vertisol areas using a Random Forest classifier in R software (figure 2, red path; Breiman 2001).

We next classified a Landsat 5 Level 2 image from 3 July 1987 that corresponded to a period of similarly consistent antecedent rainfall (figure S2), but with no available ground truth data (note S5). We applied the 2013 optimal unsupervised algorithm to luvisol soils (figure 2, yellow paths), and performed a supervised Random Forest classification for vertisol soils (figure 2, orange path). We drew from expert oral histories of vegetation changes to determine which

plant communities the 1987 unsupervised classification corresponded to, and to guide creation of signatures for Random Forest classification of vegetation. Both procedures were iteratively refined using historical images available in Google Earth Pro, and an aerial photo from 1977.

The final classifications for luvisols and vertisols were merged (figure 2, black paths), then verified for overall accuracy using stratified random sampling of 50 points per class for both 1987 and 2013 classifications. The full classifications had an 89.25% total accuracy for 1987 (figure S3), and an 88.08% accuracy for 2013 (figure S4).

2.4. Preparation of vegetation classes for analysis

Detailed vegetation classifications (derived as described above in 2.3) included 44 and 40 distinct categories in 1987 and 2013, respectively, with varying tree, shrub, grass, and forb composition and NDVI values (figures S3 and S4). For each category, we also estimated the characteristic amount of woody and herbaceous cover using Landsat NDVI readings, Pleiades near-infrared spectra false color displays (2013) and aerial photos (1987). Based on these estimates, we merged categories according to similarity of assemblage type, as well as their relative percentages of herbaceous and woody cover (figures S3 and S4). Woody and herbaceous cover were categorized: 0%–5% as none/bare, 5%–25% as sparse, 25%–50% as moderate, and >50% as dense (figure S5). In this way, initial detailed vegetation classifications that had similar cover patterns were merged into simplified woody/herbaceous classes for all subsequent analyses.

2.5. Landform and land use mapping

Using SAGA-GIS software and Shuttle Radar Topography Mission-derived Digital Elevation Model data, Topographic Position Index landforms (Guisan *et al* 1999) for the study area were mapped. The resulting landform map was reclassified into simplified classes that corresponded to hillslopes, hilltops, river valleys, and plains (figure 3). Building on previous detailed research on herding ranges and GPS records of land use zones (Unks 2017, Unks *et al* 2019a), as well as maps and satellite imagery, we traced polygons on-screen to approximate land use zones, ca 2000–2013). In 1987 residences and herding ranges were widely distributed, but from ~2000 onwards, a new land use zonation system was imposed as part of a wildlife conservation trust, creating partitions with distinct spatial patterns of intensity, frequency, timing, and duration of livestock use within the study area (Unks *et al* 2019b). Because of decreasing mobility and changes in herd composition (fewer cattle and more smallstock) changes in total herd numbers at Koiya do not adequately represent the increasingly localized livestock pressure at Koiya (Herren 1991, Unks 2023). This land zonation, approximately mapped in figure 3, enabled us to make inferences about the influence of these partitions and changes in livestock pressure. Low-livestock use refers to wildlife conservancy areas that were rarely visited while herding. Dry season grazing refers to areas that were only used annually when restriction was lifted after forage resources were exhausted within year-round grazing areas. Thus, the three mapping products used in our subsequent analyses—vegetation, landform, and land use maps—were all generated independently, using different data sources.

2.6. Vegetation transition, land use, and landform analysis

We performed a vegetation transition analysis, which indicated the change between community composition, as well as woody and herbaceous classes at each pixel over time, enabling us to quantify the types and frequencies of transitions across the landscape. Informed by expert interviews, we tested the association of both woody and herbaceous vegetation density change with historical (1987) vegetation type, land use, and landform, using mixed effects spatial logistic regression models with the spaMM package (Rousset and Ferdy 2014). Spatial logistic models included landform, rainfall, land use, and distance from settlements as predictive variables in candidate models. Sampling strategy and detailed methodology are described in note S6.

To account for spatial autocorrelation and spatio-temporal influence of climate on herbaceous vegetation over time, we then fit a mixed effects spatial linear regression model using time series climate and NDVI data (Rousset and Ferdy 2014). We used Landsat Level 2, Collection 2 images from 1984–2011, CHIRPS v2.0 rainfall data (Funk *et al* 2015), and CHIRTS temperature data (Verdin *et al* 2020). We isolated pixels dominated by herbaceous vegetation in 1987 and where woody encroachment did not occur, and fit a distributed lag model (Gasparrini 2011) that best accounted for lagged effects of rainfall and temperature over the two years preceding each annual maximum NDVI reading (see note S7 for detailed methodology). We then input these optimized lagged climate data into the spatial linear regression model as fixed effects, with the same predictive landform and land use variables used in spatial logistic regressions above, plus an added time block variable (to test for differences in trends between 1987–2000 and 2001–2013), and then selected the best fitting model.

3. Results

Our approach integrated remote sensing, field vegetation assessments, and expert oral histories (note S8) to construct spatially explicit vegetation maps (figures 4 and 5) and to analyze transitions (figure 6). Analysis of these maps and expert interviews pointed to three main trends: (a) the disappearance of canopy classes dominated by arborescent tree-like *Euphorbia* spp., (b) transitions of increasing woody cover, and (c) decreases in herbaceous cover.

3.1. *Euphorbia* species canopy loss

All experts we interviewed emphasized two changes, both related to arborescent *Euphorbia* species: (a) widespread extirpation of a former canopy species *Euphorbia tirucalli* L. (figure S6, note S8), and

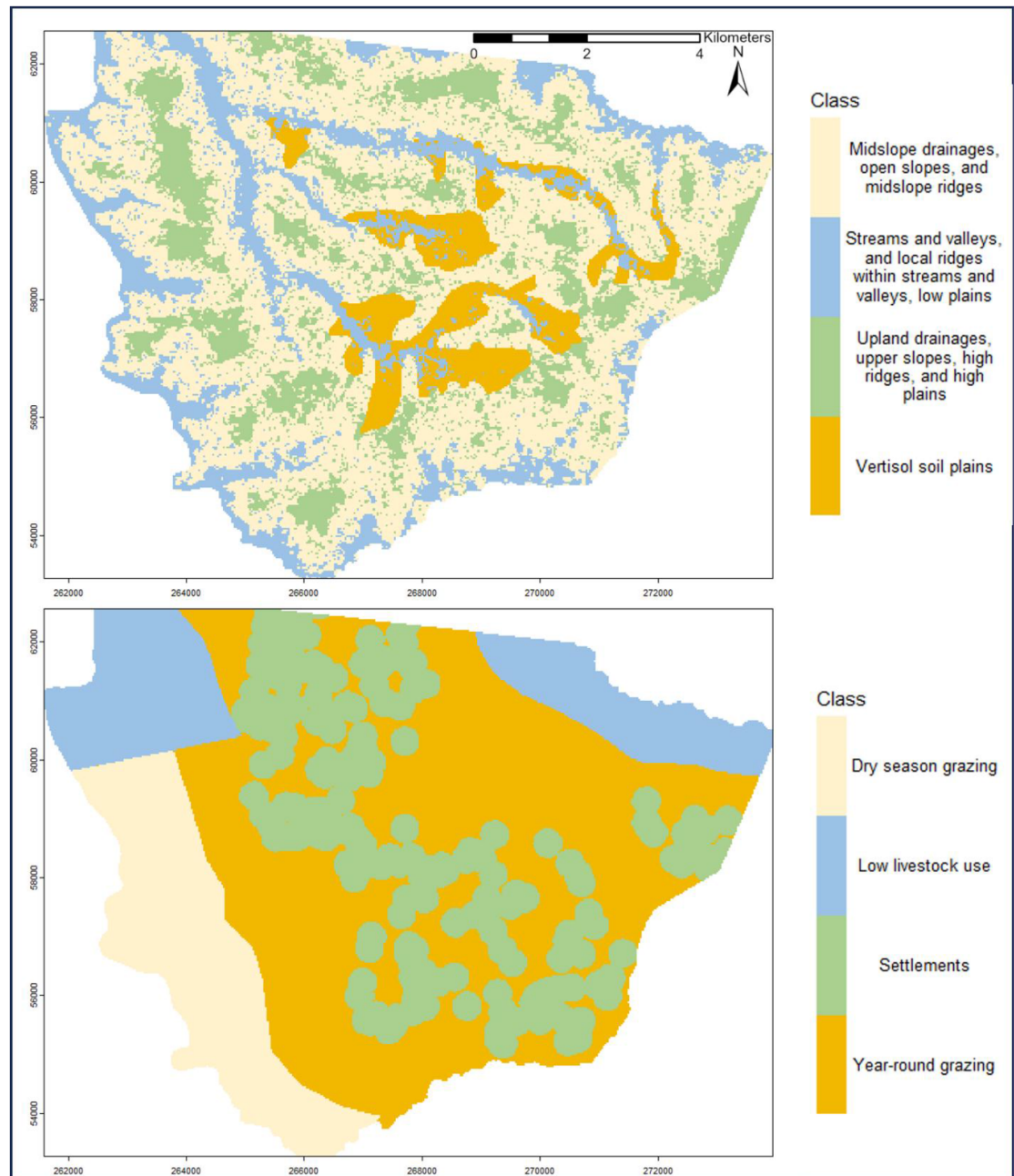
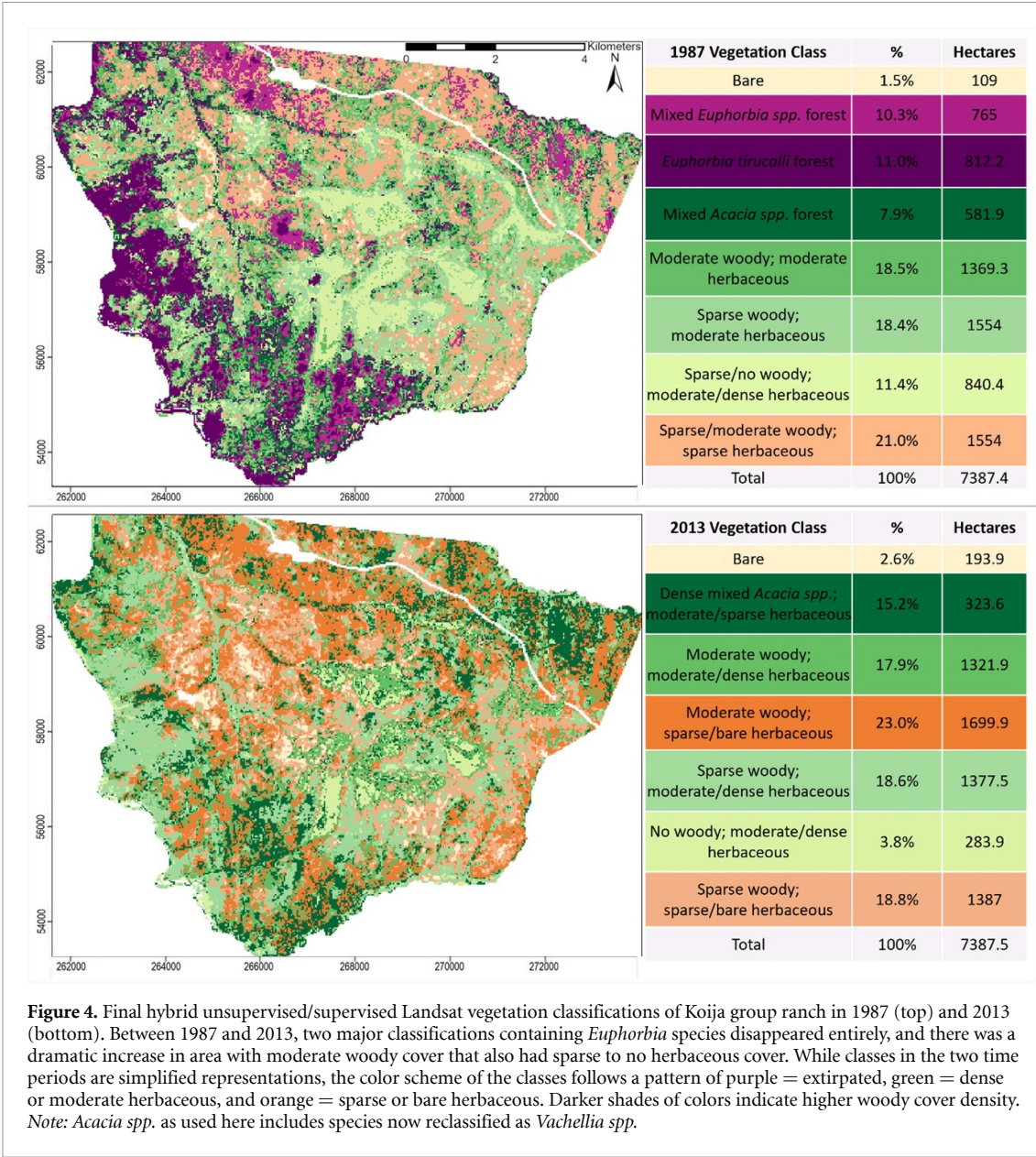


Figure 3. Simplified SAGA-GIS Topographic Position Index landform and heads-up digitized post-2000 land use classification estimations of Koija Group Ranch. Settlement areas were delineated by creating a 250 m buffer around mapped homestead locations.

(b) decreased occurrence of canopies dominated by arborescent *Euphorbia bussei* (N.E.Br.) S. Carter, a large, single-stemmed tree-like succulent (figure S7).

Experts described a historic presence and disappearance of dense *E. tirucalli* canopy forest, especially near the Ewaso Ng'iro river on the western boundary of Koija (figure 4, top). Remote sensing and vegetation change analysis estimated that in 1987, these forests covered 11.1% of the study area. By 2013, 55.5% of its former area had transitioned to moderate to dense herbaceous with low woody cover, 40.8% became dominated by dense or moderate woody cover, and the remainder had sparse or no herbaceous and woody cover (figure 5).

Experts did not share a strong consensus explaining the dramatic decrease of *E. tirucalli*, and none individually claimed certainty; 8 of 14 mentioned drought, 6 of 14 mentioned elephants, 5 of 14 mentioned settlers perhaps intentionally destroying it, and 2 of 14 suggested livestock. Experts indicated that use of fire had long since ceased, and none indicated that fire could have contributed to its loss. Because *E. tirucalli* canopies were completely absent in 2013, we could not analyze transition correlations with land use or landform. Landsat data indicated a gradual decline from 1992 to 1995, (figure S8), corresponding with strong droughts in 1992 and 1994 (figure S2), rather than a punctuated shift as would be expected



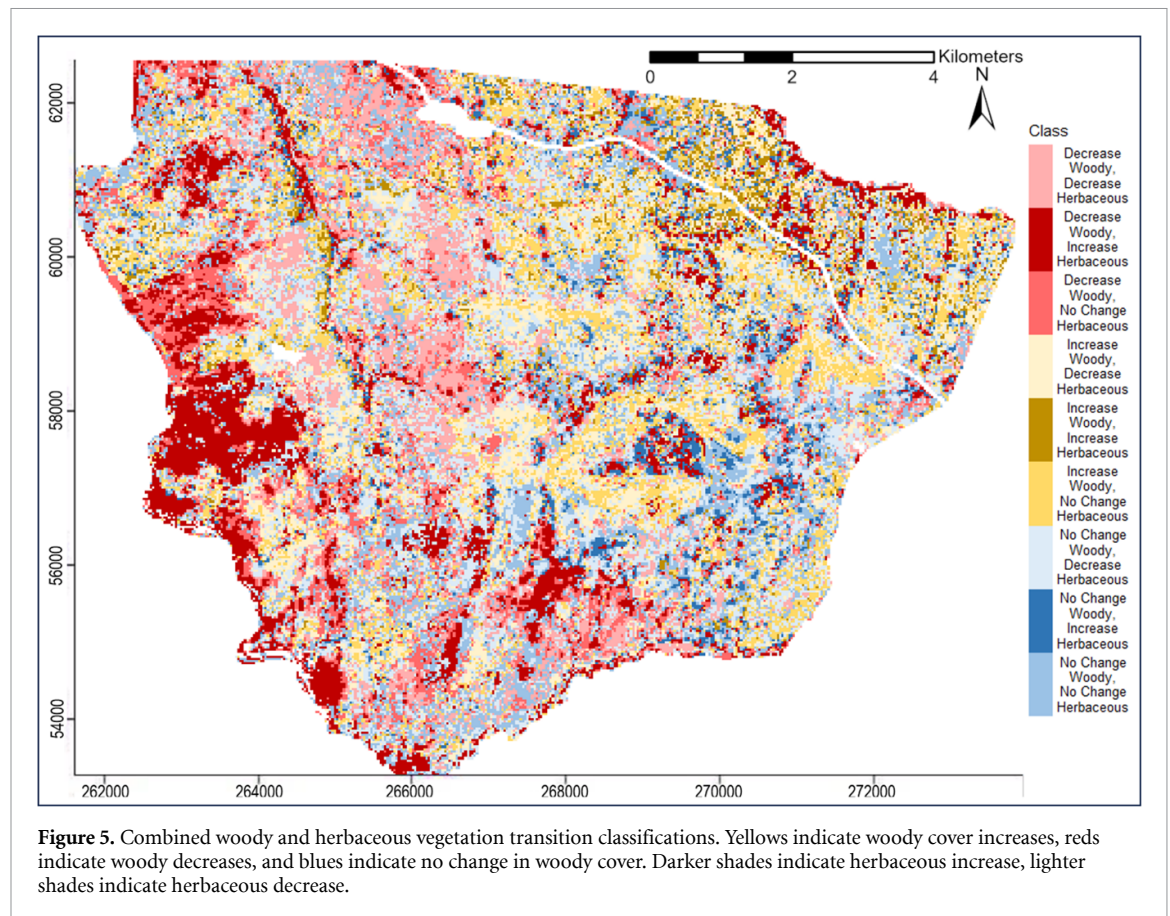
from fire. Landsat Normalized Burn Ratio data, likewise did not indicate fire during this period (figure S9). While we were unable to test the influence of climate due to lack of data, *E. tirucalli*'s sustained presence nearby in areas of higher rainfall implies climate was the most likely driver of its local extirpation at Koiya, rather than elephant damage, livestock herbivory, or fire.

In 1987, areas with tree-sized *E. bussei*, (classified as 'Mixed *Euphorbia* spp. forest'—these areas also likely included *E. tirucalli* and *E. candelabrum*), covered about 10.3% of the study site (figure 4, top, Unks 2017). Several lines of reasoning point to elephants as the predominant factor causing declines of *E. bussei*. There was near-consensus among experts of this causation (12/14). While shrub-sized plants are not uncommon, older arborescent *E. bussei* are now almost exclusively found within fenced areas that

exclude elephants but are used by livestock (figure S10). This was confirmed by three authors' long-term observations of elephants regularly toppling arborescent *E. bussei* at Koiya (see also Unks 2017, Volpato and King 2023). These forests were more likely to be replaced by other woody vegetation in areas of low livestock use, and within settlements, sites of former *Euphorbia* spp. canopies were also associated with decreased herbaceous presence (figure 5), which we discuss below in section 3.3.

3.2. Changes in other woody species cover

Experts universally agreed that there had been widespread increases in dominant tree species, especially *Senegalia mellifera* (Vahl) Seigler & Ebinger and *Vachellia reficiens* Wawra & Peyr. (figure S11). No experts explained their increase as due to livestock



herbivory, though they commonly mentioned livestock's role in seed dispersal. Remotely-sensed analysis showed that dense, non-*Euphorbia* spp. woody cover increased from 7.9% of the area in 1987 to 15.2% in 2013 ('Mixed *Acacia* spp. forest', figure 4, bottom). Moderate woody cover classes made up 18.5% of the total area in 1987, and in 2013 made up 40.9% of the landscape, showing a 22.4% increase in area with moderate woody cover. Overall, excluding areas classified as extirpated canopy in 1987 within Koija, 40.3% of the area indicated some amount of tree or shrub cover increase (most of this likely *S. mellifera* or *V. reficiens*) between 1987 and 2013.

After accounting for spatial-autocorrelation, spatial logistic regression showed that woody increase was highly dependent on landform, with vertisol soils being most likely to experience woody increase and no differences detected due to household distance (figure 7, top, and bottom, a & b), and no influence of land use (figure 7, bottom, a–c).

3.3. Herbaceous vegetation change

There was general agreement among experts that there had been widespread decreases in perennial grasses, with the main cause being changing rainfall (note S8). Overall, in 1987, 77.5% of the landscape supported moderate or dense herbaceous vegetation, but that decreased to 51.2% in 2013—a decline

of ~26%. 29.7% of the 1987 landscape had moderate/dense herbaceous cover and sparse/no woody cover (figure 4, bottom), which decreased to 22.5% in 2013 (figure 4, top). Thus, only ~7 of the 26 percentage points of overall loss occurred in areas with sparse/no woody cover. However, classes that sustained dense or moderate herbaceous vegetation and sparse or no woody cover, at both time stages in 1987 and 2013, were just 8.0% (figure 6) and were concentrated in areas with vertisol soils and in valleys. Overall, land with bare or sparse/bare herbaceous cover increased from 22.5% of the area in 1987 (figure 4, top) to 44.4% in 2013 (figure 4, bottom). Experts often concluded that these localized decreases in herbaceous cover were driven primarily by woody encroachers. They also sometimes added that small stock had localized impacts on grass, especially within settlement areas, where grasses were often grazed before they could sufficiently regenerate following rainfall (note S8).

As herbaceous vegetation overall was closely associated with woody transitions, we tested for herbaceous change while controlling for woody change category. While woody decrease overall predicted herbaceous increase, with former *E. tirucalli* areas in dry season grazing areas being replaced by herbaceous cover, settlement areas that experienced woody loss were more likely to show herbaceous decreases

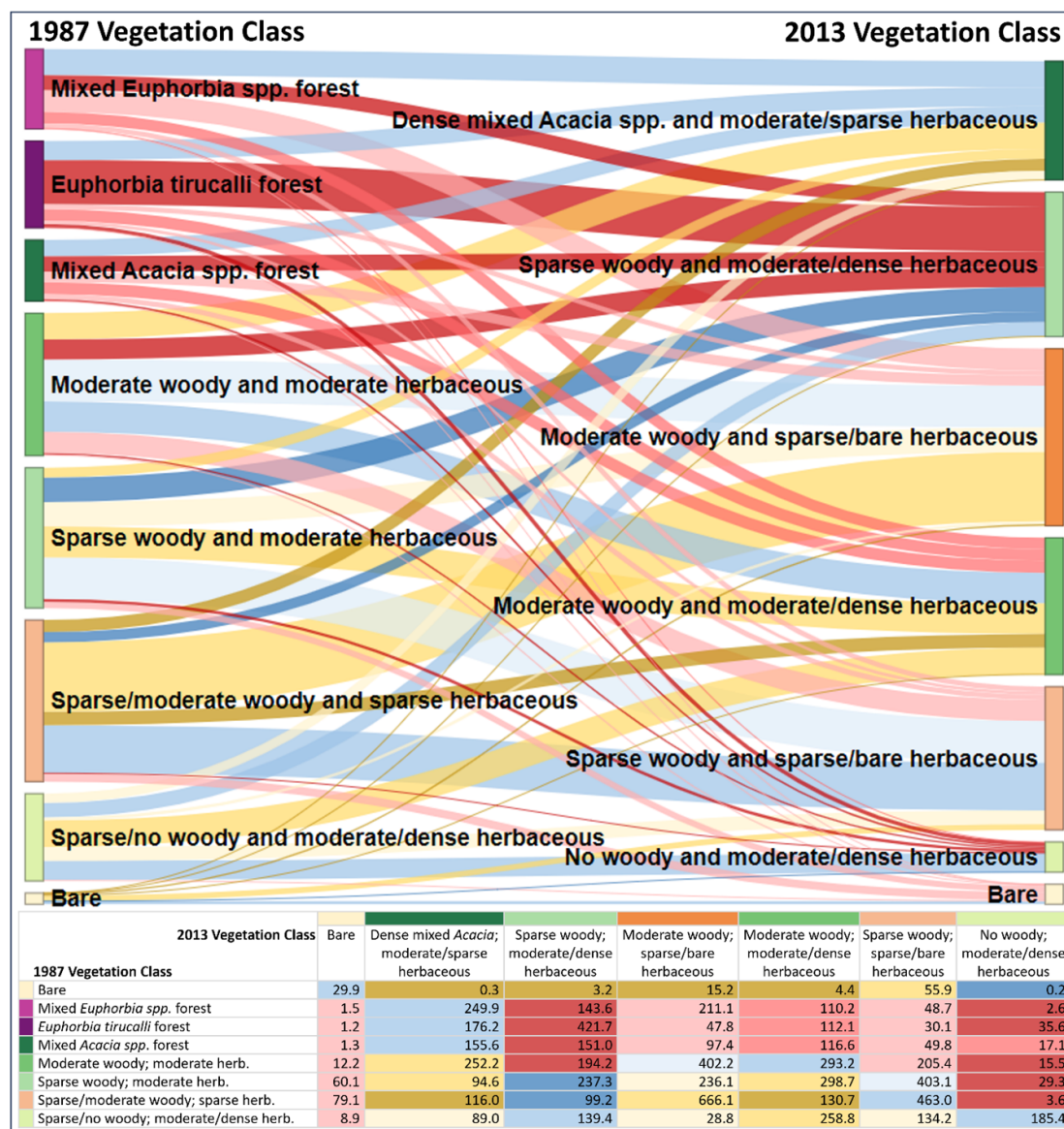


Figure 6. Sankey diagram of vegetation transitions (top) and vegetation transition matrix (bottom, units shown in ha). Colored tabs next to vegetation classes follow those in figure 4. Color codes of transitions between vegetation classes (ribbons above, cell shading below) match those of figure 5. The colors indicate the direction of change in woody cover (yellows = increase; reds = decrease; blues = no change). The shades represent the direction of change in herbaceous cover (dark = increase, light = decrease, medium = no change). Medium blue therefore indicates no change in woody cover or herbaceous cover. Due to differences in classifications between 1987 and 2013, and the disappearance of two 1987 categories entirely, the classes differ slightly between the two time steps. *Note:* The ‘Mixed Acacia spp.’ class includes species now reclassified as *Vachellia* spp. Visualization was produced using the NetworkD3 package in R (Allaire *et al* 2025).

(figure 8, top, bottom, b). Further, there were strong decreases in herbaceous vegetation associated with woody increase (figure 8, bottom, c). In samples with unchanged woody cover, there were no patterns of decrease correlated with land use or any other variables (figure 8, bottom, a).

The spatial linear regression model with lowest AIC and optimized lagged climate variables (figure S13) showed important influences of proximal lagged rainfall, the three previous wet seasons’ rainfall, temperature, and land use type on NDVI trends (figure 9). Temperature significantly increased throughout the study period (see figure S14) and

this was reflected in uniformly negative influence on predicted NDVI in the best-fitting model (figure 9). Estimates for settlements were negative when interacting with the time block variable (‘2000 Land Use Plan’) that accounted for the imposed land use designations (figure 9), which we inferred as the influence of livestock under the imposed sedentary land use scheme. Distance from settlements predicted higher NDVI (i.e. higher NDVI further from settlements), however, this effect was notably lower than that of the negative influence of increasing temperature (figure 9). Analysis of residual trends showed no monotonic declines that would indicate generalizable

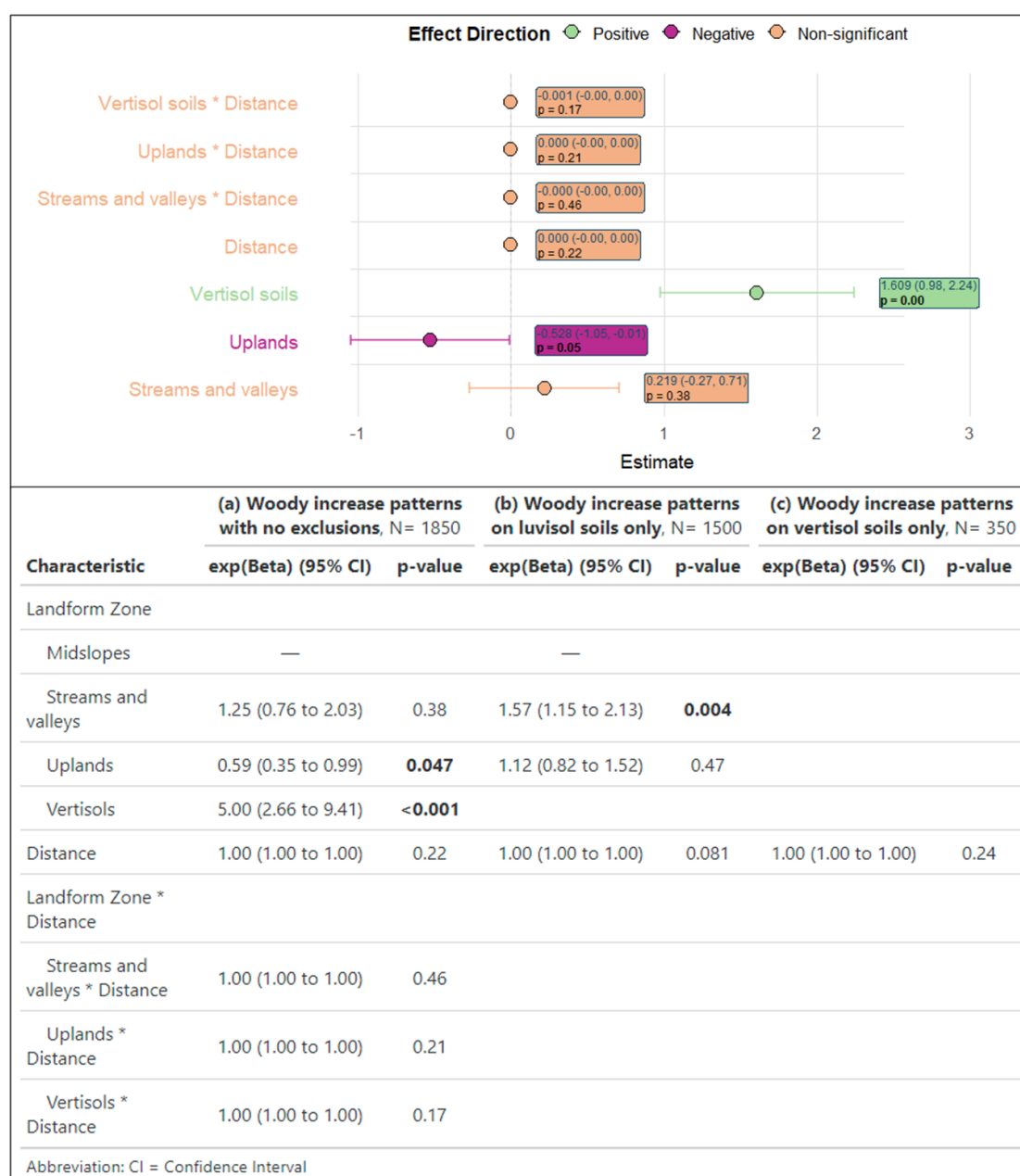


Figure 7. Results of the best fitting spatial logistic regression models for patterns of woody increase at Koiya. The top figure shows the model effects of model (a) in the table (bottom), with 95% confidence intervals. Parameter estimates as well as odds ratios (bottom, a) indicate that vertisol soil was the strongest predictor for woody increase and uplands were least associated with woody increase. For further analysis of interaction of landform and distance from homesteads see figure S12. Exclusion of vertisol soils in a subsequent model (b) indicated that streams and valleys and other lowlands also had a greater increase. A third model (c) showed no significant relationship between distance to homesteads and woody encroachment. Visualizations were produced using ggstatsplot (Patil 2021) and gtsummary (Sjoberg *et al* 2021).

loss of herbaceous productivity attributable to variables not included in the model (figures 10(a)–(d)).

4. Discussion

4.1. Triangulation between evidence for drivers of landscape change

Triangulating (Roe 1998, Nightingale 2016) between pastoralist expert descriptions and explanations, spatial analysis of remotely sensed vegetation change, and

long-term interdisciplinary research, our approach provided insights about ways that epistemic biases could be reduced in understandings of pastoralism in drylands. Pastoralist experts taught us about dominant landscape changes that would have been overlooked or misinterpreted using remotely sensed analysis or ecological field methods alone. Careful consideration of the multiple lines of evidence of changes and their drivers drew dominant narratives, which continue to shape dryland ecology research, strongly into question.

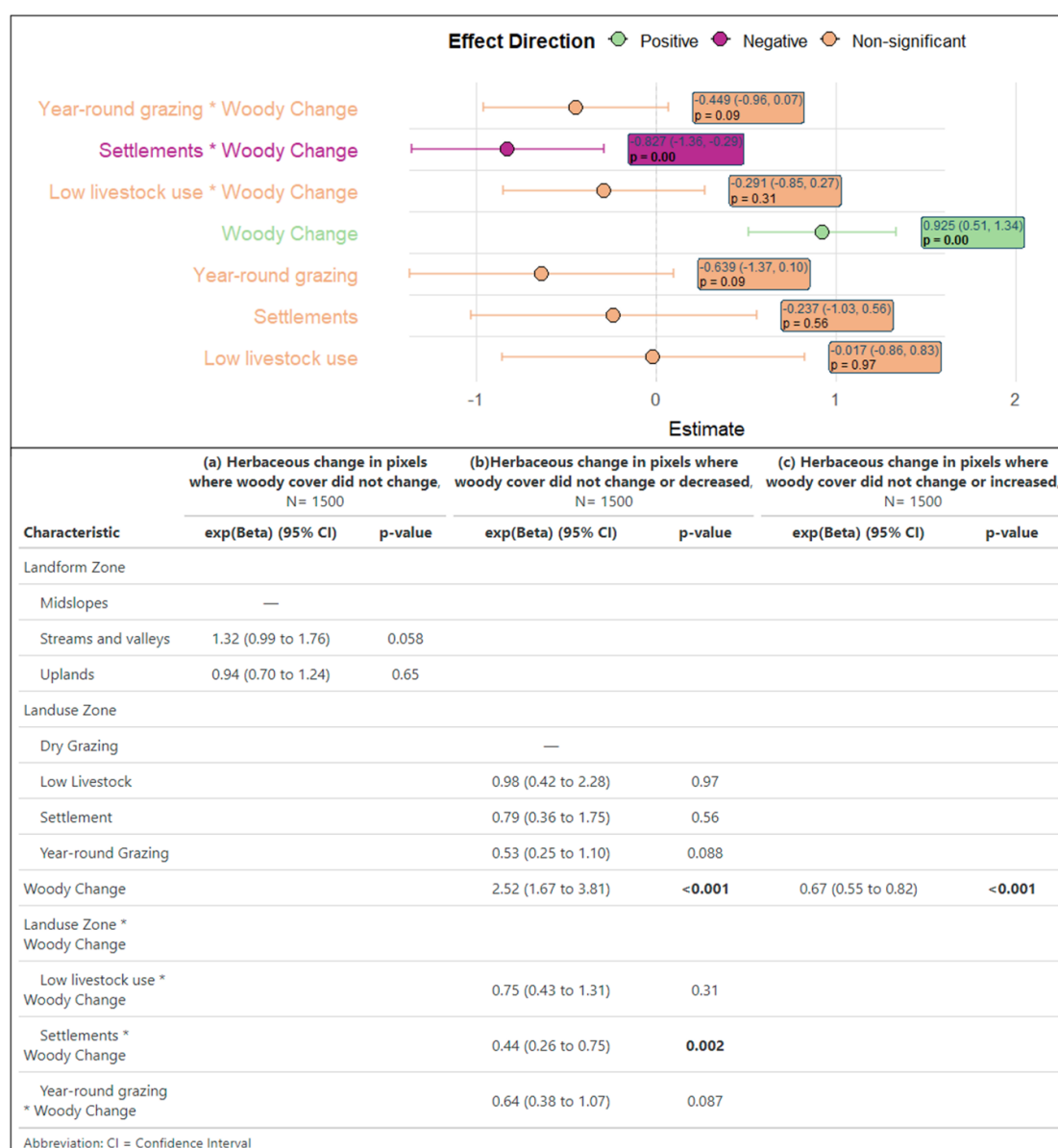


Figure 8. Results of the best fitting spatial logistic regression models for patterns of herbaceous change by woody change at Koija. The top figure shows the model effects of model (b) in the bottom table, with 95% confidence intervals.

4.2. Decreases in *Euphorbia* spp. canopy

The most conspicuous changes were the extirpation of *Euphorbia* spp. canopies that formerly dominated ~22% of the area considered. Experts shared low consensus about the cause of the loss of *E. tirucalli*, but most frequently stated that climate was likely the main driver, and its disappearance coincided with a period of two consecutive droughts (figure S2). Coupled with expert knowledge and our own observations of their widespread impacts on arborescent *E. bussei*, there is strong evidence that elephants had decreased *Euphorbia* spp. canopies. Elephant populations have shown strong increases in Laikipia (Litoroh *et al* 2010, Ogutu *et al* 2016), and their impacts on trees in Kenya is well documented (Western and Maitumo 2004, Kimuyu *et al* 2014). We found no compelling or

corroborating evidence or ecological reasoning that livestock played a role in the loss of *E. tirucalli* or mixed *Euphorbia* spp. canopies (Volpato and King 2023).

4.3. Changes in other woody species cover

We found that ~40% of the landscape had experienced increases in woody cover. Higher rates of woody encroachment were not located in areas of highest livestock use, contrary to the findings of a previous study that did not consider spatially autocorrelated landscape patterns or landforms and claimed that shrub encroachment was likely driven by livestock (Kibet *et al* 2021). Vertisol soils were strongly associated with woody increase, indicating that hydrology and soils are likely important factors.

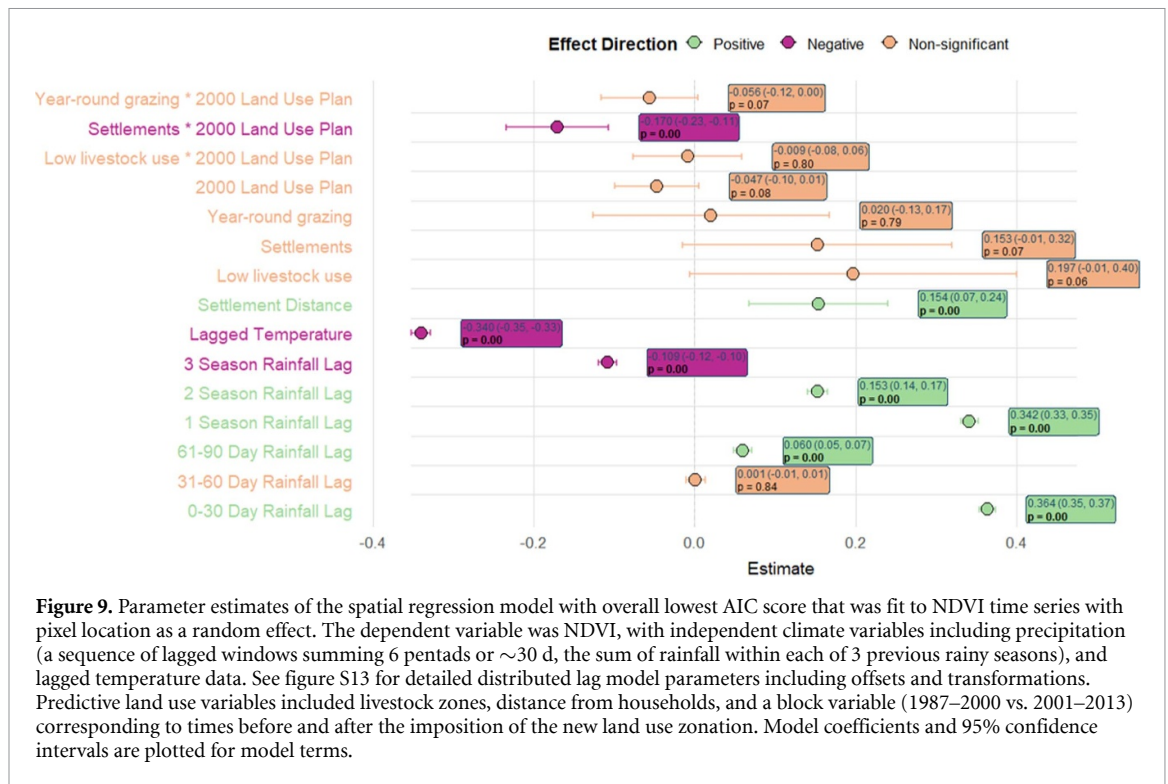
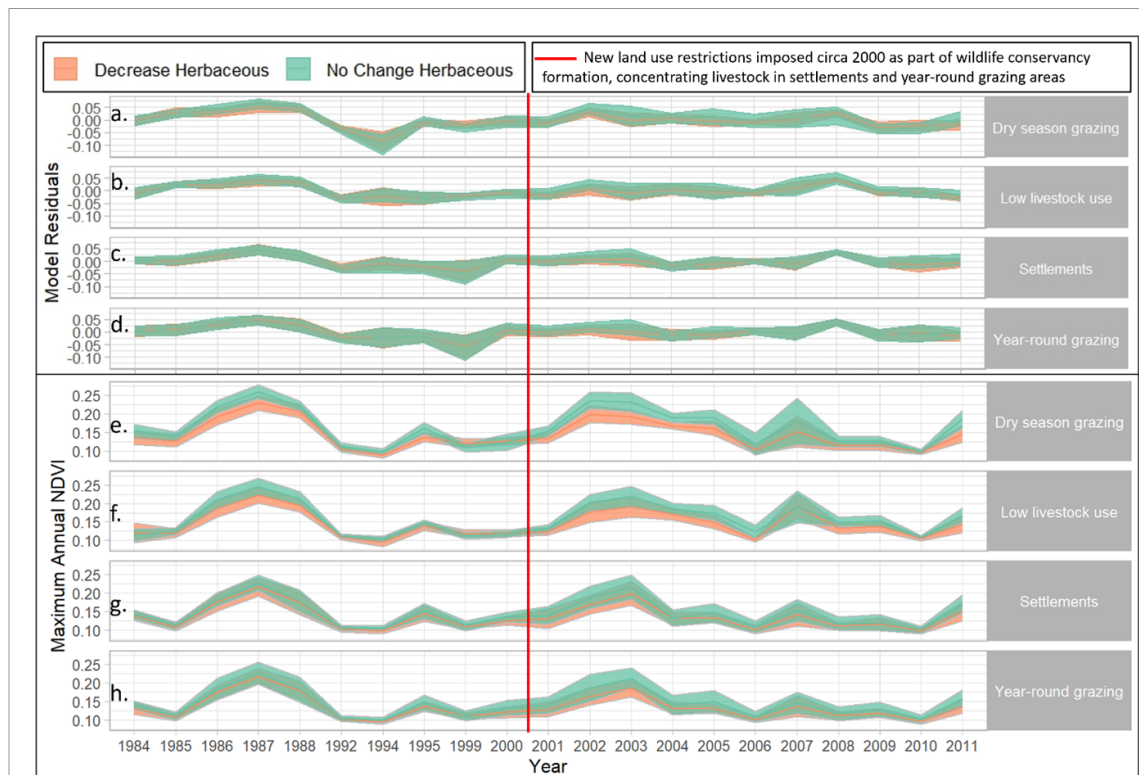


Figure 10. Residual time series analysis of pixels classified as moderate and dense herbaceous with sparse or no woody cover in 1987 (a)–(d) and raw maximum NDVI values (e)–(h). Orange shades refer to pixels where herbaceous cover decreased. Green shades refer to pixels where herbaceous cover did not change. NDVI trends showed that lower NDVI pixels tended to remain consistently lower (e)–(h). NDVI trend analysis alone implied that dry season grazing and low-livestock use zones remained more dynamic, with higher NDVI values during rainy years (e) & (f). There was a confounding influence however, as settlements and year-round grazing zones (g) & (h) were largely located within CHIRPS pixels with lower rainfall, and thus having lower average NDVI readings than other zones (e) & (f). Residual trends (a)–(d) showed less contrast in dynamics between zones after adjusting for climate. The residuals show that the model sometimes under-estimated or over-estimated NDVI, especially in 1994 (a) and 1999 (d) during extreme droughts, but that overall dynamics of herbaceous vegetation could generally be predicted by accumulated temperature and precipitation. While this proxy measure of productivity is unable to account for changes in plant composition, no monotonic trends in residuals (a)–(d) were observed that would indicate widespread productivity loss due to factors not accounted for in the model (Wessels *et al* 2012, Burrell *et al* 2017).

A number of recent studies have reassessed claims that livestock herbivory was responsible for woody encroachment in dryland environments, showing how changes in livestock pressure, temperature, rainfall, atmospheric CO₂, nitrogen deposition and fire regime can all alter feedbacks that previously regulated shrub establishment (D'Odorico *et al* 2012, Archer *et al* 2017, Stevens *et al* 2017, Venter *et al* 2018, Maestre *et al* 2021). Our approach was unable to test for these other factors that may be driving widespread patterns of woody encroachment, and future analyses should consider increasing CO₂ levels and nitrogen deposition, as well as processes that are well documented in the study region, including the role of changes in intensity and frequency of rainfall (Franz *et al* 2010), fire suppression (Augustine 2003), and loss of browsing wildlife that could regulate shrub cover (Sankaran *et al* 2013).

4.4. Changes in herbaceous cover

Decreases in herbaceous vegetation (~26% of the landscape) were highly dependent on woody cover change as well as climate. The decreases we detected that could be attributed to livestock were concentrated in areas that both experienced decreases in woody cover and intensified livestock pressure (settlements). This is consistent with the expected impacts of sedentarization policies and practices that have placed extreme constraints on mobility, but also contingency due to ecosystem cascades, where livestock had the most conspicuous impacts after canopy cover was lost. Canopy losses could have led to increased soil temperatures, reduced soil moisture, and loss of root matting creating less stable, more erosive soils, and other cascading changes in ecosystem properties (see D'Odorico *et al* 2007, 2012). Decomposition of fallen woody and succulent debris can alternately lead to an influx of nutrients into soils, which may be responsible for the patterns of herbaceous increase observed in areas that formerly supported *E. tirucalli* canopies. Where woody cover stayed the same or increased, herbaceous vegetation was less likely to decrease in all land use zones. However, spatial regression of lagged climate and land use showed that following new land use zonation, intensified livestock pressure in settlements was likely having some negative impact on herbaceous vegetation, though this was notably lower than the influence of increasing temperature. Experts sometimes indicated that sheep and goats may have recently impacted herbaceous understory vegetation in these areas, but they also unanimously emphasized rainfall as the dominant factor driving these changes (note S8). A limitation of our study is that we were unable to adequately account for these localized impacts while also considering fine-scale spatial trends in precipitation. However, the widespread patterns of herbaceous cover change are likely driven by uniformly increasing temperatures

interacting with heterogeneous spatio-temporal rainfall patterns.

4.5. Contextualizing landscape change

Comparative grazing studies across global rangelands tend to focus on local management regimes and livestock pressure to assess the sustainability of pastoralist land use (Maestre *et al* 2022). These analyses rarely account for historical contingencies of vegetation change, detailed analyses of fine-scale climate variability, or changing governance (Manzano *et al* 2023). Our findings contrast with the narratives of widespread landscape vegetation changes attributed to livestock that are frequently referenced in scientific publications and conservation and development grey literature. We found little evidence that widespread changes in vegetation at the landscape scale, such as loss of canopy species, shrub encroachment, and herbaceous decrease, could be explained primarily by livestock pressure. Rather, local herbaceous changes were contingent on canopy changes, and explanation of complex landscape-level changes required interdisciplinary methods to consider drivers interacting at multiple scales such as spatio-temporal rainfall patterns, increasing temperature, the influence of megaherbivores, fire suppression, sedentarization, and changing livelihoods.

Constraints that have been imposed on external mobility by state and NGO-led sedentarization policies and interventions that focus on wildlife mobility at the exclusion of pastoral mobility have undoubtedly created strong, novel herbivore pressure and localized impacts (Unks 2023). Livestock management at the group ranch scale has been unable to respond to these top-down constraints to enable regeneration of herbaceous vegetation following limitation of former season access to outside land (Unks *et al* 2019a, 2019b). Together with changing climate, this was producing 'permanent drought' from experts' perspectives (note S8). The trends we detected using both vegetation classifications and time series data were consistent with intensified local livestock use and changing herd composition under sedentarization that has been imposed in other areas of Kenya (McPeak 2003, Vuorio *et al* 2014). While seasonal herbivore movements tend to allow grasses to recover (Boone and Hobbs 2004, Reid *et al* 2004), constraints on spatial and temporal dynamics of forage use can cause damage to vegetation (Hodgkinson 1995, Fynn and O'Connor 2000, Hobbs *et al* 2008, Ash *et al* 2011, Groom and Western 2013). However, understanding herbaceous changes at Koija also requires context, considering both losses of former canopies, as well as encroaching woody species. As experts observed, where *S. mellifera* and *V. reficiens* have become dominant, it promoted an understory with less grass (note S8), and previous analysis also showed lower abundance of perennial

grasses associated with *S. mellifera* (Unks 2017). The cascading impacts of woody encroachment on herbaceous biodiversity are therefore key to consider (Maestre *et al* 2021). However, it is also important to consider other changes in landscape process we were not able to consider including changes in fire regime that shape herbaceous species composition, reduce woody vegetation, and potentially play a role in preventing shrub encroachment. Finally, increasing intensity of rainfall events following long periods of low rainfall where there is little vegetation to facilitate water infiltration can cause rapid runoff, erosion of soils, and even loss of trees at Koiya (pers obs., note S8).

5. Conclusion

This study analyzed complex changes in vegetation over time in a semi-arid and ecologically heterogeneous pastoral group ranch using mixed-methods and triangulation to infer between multiple lines of evidence. Applying triangulation between remote sensing, pastoralist experts' knowledge of past changes, and our long-term immersive interdisciplinary research, we were able to gain an improved understanding of changes in the vegetation composition between 1987 and 2013. The knowledge of pastoralist experts about dominant landscape changes helped us to understand much that we would have otherwise overlooked or misinterpreted if we had only considered ecological science epistemologies. Many of the transitions that experts emphasized and that we in turn also observed contradict dominant narratives of livestock-induced vegetation change that motivate ongoing interventions in Indigenous pastoralists' land, highlighting the need for critically-informed approaches to co-production to avoid extending inherent power asymmetries in ecological knowledge production in conservation research and planning (Turnhout *et al* 2020).

Data availability statement

Code for both spatio-temporal models is available at: https://github.com/RyanRUnks/Koiya_landscape_ERL. All remotely-sensed images are publicly available. Classified vegetation rasters are available from the authors upon request. Focus-group, interview, and household data is restricted under University of Georgia Institutional Review Board policy.

Supplementary data 1 available at <http://doi.org/10.1088/1748-9326/ae2491/data1>.

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