Using the Relative Productivity Index to assess how governance structures and local community engagement influence rangeland health outcomes.

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I certify that all materials in this thesis which are not my own work, have been identified and that any material that has previously been submitted and approved for the award of a degree by this or any other University has been acknowledged.

Abstract

Rangeland degradation threatens the livelihoods of over two billion people globally, yet the relative effectiveness of different governance strategies for maintaining ecosystem productivity remains poorly understood. East African rangelands represent this challenge as surrounding diverse tenure systems from state-protected areas to community conservancies and pastoral grazing lands, each use distinct management approaches with varying outcomes for vegetation health. This study examined patterns of relative vegetation productivity across governance strategies in Kenya's Amboseli-Tsavo ecosystem using the Relative Productivity Index (RPI), which quantifies observed vegetation productivity relative to biophysical potential. We analysed 23 years (2000-2022) of satellite-derived data across different governance systems, applying quality control filtering ($R^2 \geq 0.1$) and Theil-Sen trend analysis to assess long-term productivity trajectories. Results indicated that management effectiveness, rather than governance type alone, determined vegetation outcomes. Community conservancies had the highest mean relative productivity (RPI = 0.68) with stable trends (-0.0011 yr^{-1}), while Amboseli National Park showed systematic decline (-0.0042 yr^{-1}) despite formal protection. Tsavo East and West National Parks maintained positive trends (+0.0035 and +0.0015 yr^{-1} respectively). RPI proved most effective in rangelands with dynamic vegetation and variable climate conditions, while areas with poor model fit concentrated in hydrologically complex wetlands. These findings indicate that effective rangeland conservation requires landscape-scale, polycentric governance approaches that coordinate management across diverse tenure systems rather than relying solely on individual protected areas.

1. Introduction

Rangelands cover roughly half of the earth's landmass and plays an important role in ecological stability, global livelihoods and supporting biodiversity. The ecosystem services derived from rangelands vary from biodiversity maintenance, carbon sequestration and support of livestock production that supplies leather, meat, milk and wool (Reeves et al. 2024; Godde et al. 2018; Erb et al. 2016; Henderson et al. 2015; Hobbs et al. 2008; Reid et al. 2008). These managed grazing lands are dominated by natural and semi-natural forested vegetation and support over 2.7 billion people globally, particularly in Low - and Middle – Income countries, while also providing habitats to thousands of threatened species (Scholes et al. 2018; Cohen-Shacham et al. 2016).

Land degradation threatens both ecological integrity and sustainable development as it undermines important ecosystem services and international conservation goals. Land degradation is defined as the "reduction or loss of biological or economic productivity and complexity" of the land (Sims 2021). This degradation diminishes the land's capacity to provide essential ecosystem services as well as support biodiversity and this poses significant threats to ecosystem services. Beyond these impacts, land degradation directly undermines ecosystem productivity and hinders efforts to achieve the United Nations Sustainable Development Goal 15 "Life on Land", particularly Target 15.3.1, which aims for "Land Degradation Neutrality" (Griggs et al. 2013).

Rangeland forage productivity is increasingly being compromised by climate-induced stressors and human-driven land use changes that in turn threatens the ecological balance of pastoral systems. Climate-induced stressors, particularly intensifying droughts and weather volatility, are systematically degrading forage productivity across pastoral systems

(Lomax et al. 2024; Beal et al. 2023; Løvschal et al. 2019; Holechek et al. 2017). The sedentarisation of pastoralists is also dismantling centuries-old regulatory mechanisms that previously maintained sustainable equilibrium between forage supply and livestock herbivory pressures (Lomax et al. 2024; Silcock and Fensham 2019; von Wehrden et al. 2012). The combined impact manifests in persistent vegetation decline and expanding bare ground cover (Lomax et al. 2025; Wiethase et al. 2023; Prince et al. 2018), signal a critical transformation in rangeland ecosystem function.

Balancing ecological stewardship with community needs is important for effective governance of pastoral rangelands, especially as traditional systems transition to formal land tenure. This shift disrupts resource management, compelling pastoralists to weigh conservation benefits against economic costs when cooperating with initiatives like conservancy incentives or grazing restrictions (Sabuhoro et al. 2021; Mackenzie 2012). State-driven reforms and settlement schemes undermine customary rights, leading to fragmented enclosures and heightened resource competition (Chepkwony et al. 2025; Bolo et al. 2019). These exclusionary policies often create disputes that weaken governance and challenge sustainable rangeland use (Rampheri and Dube 2021; Mukeka 2020). The resulting "pastoralist paradox" highlights the trade-off between securing land tenure and maintaining the flexible grazing patterns vital for resilience and environmental health (Bostedt et al. 2023). Recognising these intertwined challenges is important for designing governance frameworks that support both livelihoods and conservation.

Monitoring rangeland condition presents one of the most difficult challenges in ecosystem science as it requires disentangling genuine ecological degradation from natural climate variability across both temporal and spatial dimensions. There are two main components to this challenge: establishing meaningful baselines for degradation assessment and distinguishing persistent human-induced changes from natural fluctuations (Lomax et al. 2025; Hill et al. 2008). While traditional indices like NDVI and EVI provide valuable proxies for vegetation health, their high sensitivity to rainfall complicates the separation of climate-driven from anthropogenic impacts (Nicholson 2017; Jeong et al. 2011). The temporal complexity is matched by equally important spatial considerations, as precipitation-productivity relationships vary dramatically across landscapes with mean annual precipitation driving overall productivity (Knapp et al. 2017; Garbulsky et al. 2010), yet local variability impacts depend on site-specific climate conditions, vegetation composition, and disturbance history (Liu et al. 2020; Ritter et al. 2020; Wilcox et al. 2017).

The Relative Productivity Index (RPI) represents a breakthrough approach for isolating anthropogenic rangeland degradation from natural climate variability. RPI applies satellite-based gross primary productivity observations to examine relative productivity distributions within East African rangelands. This index is most effective in rangelands that are characterised by dynamic vegetation and highly variable climate conditions (Lomax 2025). RPI uses quantile regression forests to estimate potential gross primary productivity as a continuous function of climatic, edaphic, and topographic drivers. It is calculated as the ratio of actual to potential productivity and this offers a temporally and spatially explicit benchmark for assessing rangeland conditions as well as in isolating anthropogenic degradation from environmentally driven variation.

Kenya's extensive rangelands are the backbone of pastoral livelihoods and a refuge for wildlife. Rangeland ecosystems occupies 80% of the country (Figure S1) and these areas are important for biodiversity conservation, particularly given that 60% - 70% of wildlife populations exist outside protected areas (Figure S2) on private and communal lands (Kimiti et al. 2018), many of which are in wildlife conservancies which represent roughly 16% of the country's landmass (Bashir and Wanyonyi 2024; Mukeka et al. 2019). As of 2023, Kenya hosted 230 wildlife conservancies either in community or private ownership, with the Kenya Wildlife Conservancies Association (KWCA) playing an important role in balancing wildlife and livestock interactions (Bashir and Wanyonyi 2024).

This study assessed the extent to which RPI can quantify human impacts on rangeland vegetation productivity to understand how governance structures and local community engagement influence rangeland health outcomes. The motive of using RPI is to strengthen insight into how this new tool can be used to inform the design and evaluation of adaptive management strategies that support land degradation neutrality. The specific research question is: What insights can patterns of relative vegetation productivity as quantified by the RPI over space and time provide regarding the relative effectiveness of various governance strategies for rangeland management employed across different tenure and protection regimes?

2. Methods

2.1 Study area

This study focused on two neighbouring rangeland ecosystems in southeastern Kenya, the Tsavo ecosystem (66,500 km^2) and the Amboseli ecosystem (8,000 km^2) (Figure 1, Figure S3). These were selected as ideal focal areas due to their complex, multi-stakeholder governance models. Within these broader ecosystems, our spatial analysis concentrated on five specific areas, Amboseli (392 km^2), Tsavo East (11,747 km^2), and Tsavo West (9,065 km^2) National Parks, as well as the conservancies and grazing lands surrounding Amboseli. Settled areas and ranches within the Tsavo ecosystem were excluded from the detailed analysis due to the intensive agriculture, urbanisation, and sedentarised lifestyles incompatible with wildlife. This delineation enabled comparative assessment across governance systems, examining temporal trends from the years 2000 to 2022 to distinguish between climate-driven fluctuations and governance-related impacts on rangeland productivity.

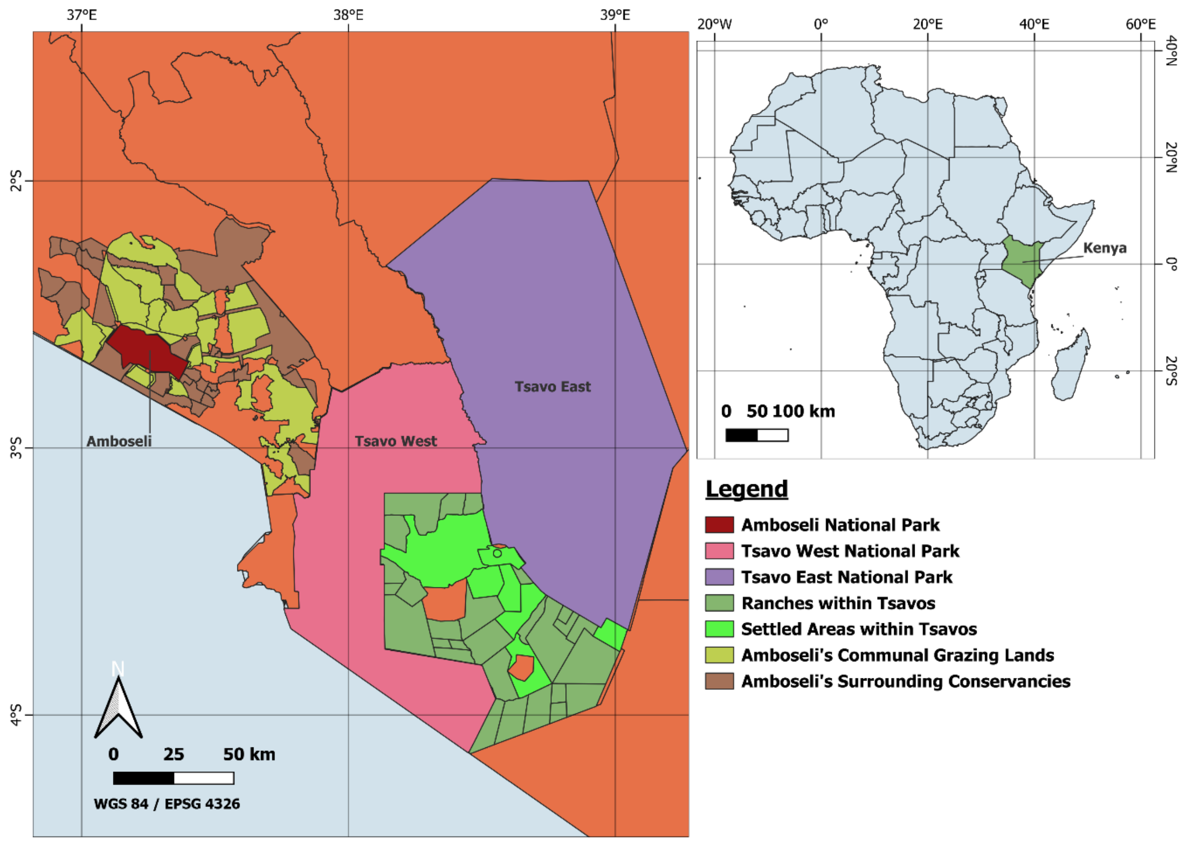

Figure 1. **The Amboseli-Tsavo ecosystem comprises interconnected protected areas and community-managed rangelands in southeastern Kenya.** The Tsavo Conservation Area operates under mixed governance by the Kenya Wildlife Service and community-based management through the Tsavo Trust. The Greater Amboseli Ecosystem functions through multi-stakeholder collaboration under the Amboseli Ecosystem Management Plan, with Amboseli National Park managed by the Kenya Wildlife Service and surrounding community and group ranches coordinated through the Amboseli Ecosystem Trust.

Both ecosystems are classified as climatic drylands with an aridity index defined as the ratio of mean annual precipitation to mean annual potential evapotranspiration below 0.65 (Fawcett et al. 2022), with water scarcity constraining vegetation growth. The landscape experiences bimodal rainfall with long rains between March to May and short rains between November and December (Kimiti et al. 2017). Pastoralism dominates land use supporting cattle, goats and sheep alongside diverse wildlife (Kimiti et al. 2018).

The Tsavo ecosystem operates under a mixed governance model with state authority through Kenya Wildlife Service (KWS) management of national parks alongside community-based management through the Tsavo Trust. This collaborative structure integrates local knowledge with scientific conservation approaches that enables participatory decision making while maintaining state oversight. The broader conservation area consists of Chyulu Hills, Tsavo East and Tsavo West National Parks, South Kitui and Ngai Ndethia National Reserves (Figures S3, S4).

The Amboseli ecosystem presents a more complex multi-stakeholder governance system characterised by institutional fragmentation. Amboseli National Park operates under the Kenya Wildlife Service while the broader ecosystem functions under the Amboseli Ecosystem Management Plan (AEMP) that is overseen by the Amboseli Ecosystem Trust (Amboseli Ecosystem Trust Webpage 2025). Community and group ranches surrounding the park are managed through the Trust's oversight, creating buffer zones, corridors and grazing areas that operate under Trust guidelines despite varying formal land tenure agreements that illustrate the institutional fragmentation (Figure S5).

2.2 Relative Productivity Index

Development of the RPI was led by Dr. Guy Lomax at the University of Exeter (Lomax 2025). RPI applies satellite-based GPP observations to examine relative productivity distributions within East African rangelands. This analysis used RPI version 2, while (Lomax et al. 2025) used version 1. This distinction in versions may contribute to variations in the findings. In this study, four primary datasets were utilised at a 500-metre spatial resolution across 22 hydrological years (2000-2022) (https://zenodo.org/records/14843888).

Actual GPP represents annual integrated estimates of gross primary productivity derived from the updated Penman-Monteith Leuning Evapotranspiration (PML_V2) product (2000-2023), a satellite-based dataset that combines remote sensing and meteorological data to estimate vegetation productivity at 500m resolution (Zhang et al. 2019). Potential GPP was modelled as the 90th percentile of predicted gross primary productivity for each pixel and year using a quantile regression forest model with 16 covariates, including soil properties (Hengl et al. 2021); climatic variables such as (i) total annual precipitation, (ii) precipitation patterns, (iii) temperature, and (iv) potential evapotranspiration (Muñoz-Sabater et al. 2021; Funk et al. 2015); topographic predators such as (i) elevation, (ii) slope, and (iii) topographic wetness index (Lomax 2025); and ecoregion classification (i) Masai xeric grasslands and shrublands, (ii) Northern Acacia-Commiphora bushlands and thickets, and (iii) Southern Acacia-Commiphora bushlands and thickets, as categorical variables (Smith 2020; Dinerstein et al. 2017). The RPI represents the ratio of actual to potential GPP per pixel per year, quantifying observed vegetation productivity relative to the modelled biophysical potential under optimal conditions (Lomax 2025; Lomax et al. 2025).

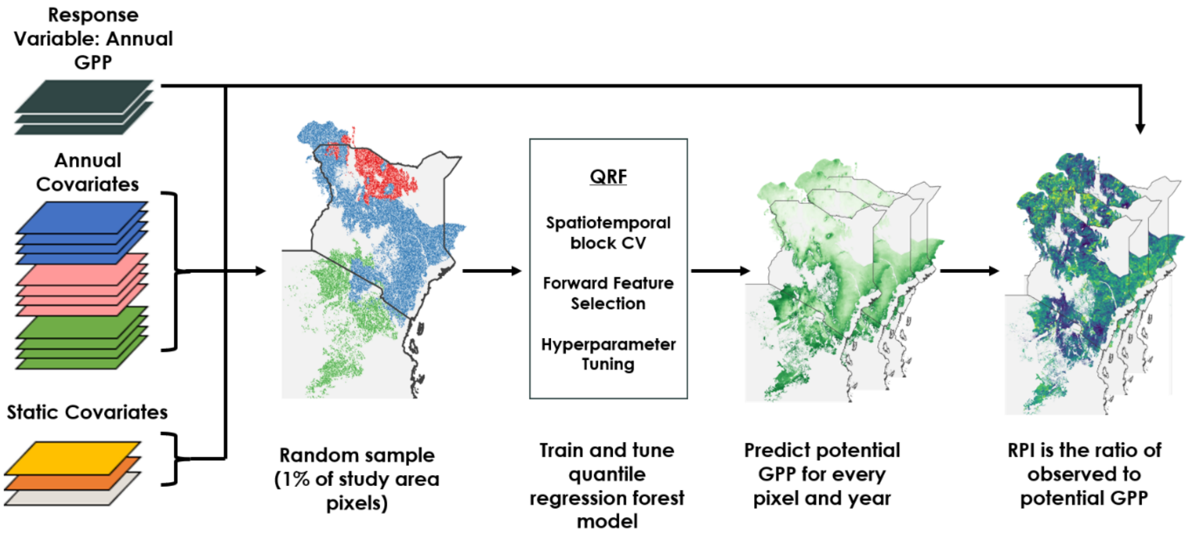

Figure 2. **RPI quantifies rangeland productivity by comparing observed to potential gross primary productivity using machine learning.** The model combines satellite-derived annual Gross Primary Productivity data (2000-2023) from the PML_V2 product with 16 environmental covariates across three East African rangeland ecoregions: Masai Xeric Grasslands, Northern Acacia-Commiphora Bushlands, and Southern Acacia-Commiphora Bushlands. A Quantile Regression Forest incorporates static covariates (topography, soil, vegetation cover, ecoregion) and annual climatic variables to predict potential GPP for each 500 m pixel, with RPI calculated as the ratio of observed to potential productivity. Reproduced from (Lomax 2025).

2.3 Data Analysis

All data processing and spatial analyses were performed in the R programming environment (R Core Team 2024). The reproducible code is openly available on GitHub under a GNU GPL V3 licence (https://github.com/TESS-Laboratory/Mureithi_RPI_Conservation_Governance), and the RPI datasets required to run the scripts are available at https://zenodo.org/records/14843888.

2.3.1 Model performance assessment and quality control

The study used temporal performance rasters containing three performance metrics computed at each pixel. Mean Absolute Error (MAE) represented the average magnitude of errors between predicted and observed GPP, Root Mean-Squared Error (RMSE) penalised larger errors more heavily, and R-Squared indicated the proportion of inter-annual variance in actual GPP explained by the model. This evaluated the reliability of the GPP model across the study area's diverse landscapes and established the foundation for interpreting RPI trends by differentiating areas where model predictions are generally more trustworthy from those that require caution in interpretation, while also considering the subtle variations and complexities within each area.

Model performance varied considerably across the landscape as some pixels displayed highly negative R^2 values that indicated extreme model mismatch. Negative R^2 values occurred predominantly in areas with very low GPP, such as barren, rocky, or sparsely vegetated lands, where annual productivity is weakly linked to climatic variability. Including such pixels would risk misleading RPI trend interpretations as their trends could reflect only random fluctuations or noise.

To balance model reliability with data retention across heterogeneous landscapes, an R^2 threshold of ≥ 0.1 was applied to filter model predictions. This threshold was selected because any positive R^2 value indicates that the model performs better than a constant prediction, meaning it captures at least some meaningful variation in GPP rather than random noise. The same threshold was applied uniformly across all study areas to ensure comparability between regions and prevent biases that could arise from excluding areas where the model performed poorly, which might systematically remove certain landscape types or ecological conditions from the analysis.

2.3.2 Spatial data processing and temporal analysis

Temporal mean RPI was calculated for each pixel using data from 22 hydrological years, September 2000 to August 2022, before analysing RPI in each focal zone. Filtered RPI rasters were generated by masking out all pixels where R^2 values were below 0.1 to focus temporal trend analysis on areas where the model captured a useful degree of inter-annual variability in GPP. Mean annual RPI was extracted for each focal area to examine temporal dynamics in relative productivity.

2.3.3 Trend analysis using Theil-Sen estimator

The study applied the non-parametric Theil-Sen estimator to annual RPI values at the pixel level across all focal areas to assess 2000 to 2022 trends in vegetation productivity while accounting for the non-normal distribution and potential outliers typical in ecological time series (Myers-Smith et al. 2020). Pixel-wise slope values were aggregated to produce area-level summary statistics including mean, median, and standard deviation of slopes, which provided a comprehensive characterisation of temporal trends within each governance system.

Pixel-wise slope values were aggregated to area-level summary statistics for comparison of productivity trends across different governance systems. Mean slope indicated the overall direction of change within each system, while median slope provided a measure less sensitive to extreme values, and standard deviation quantified the spatial variability of trends within each governance zone.

3. Results

3.1 Model performance and quality control

The temporal performance assessment indicated substantial variation in the RPI model's ability to predict inter-annual variability of GPP across Kenya's diverse landscapes (Figure 3).

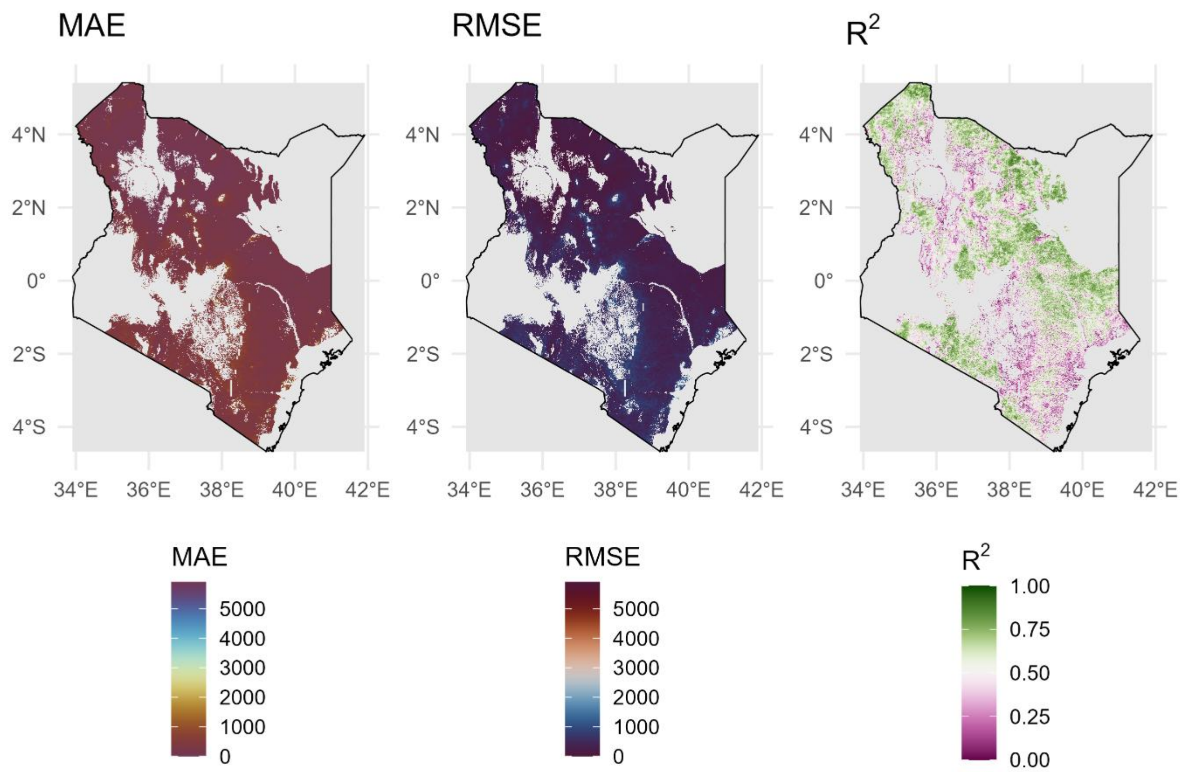

Figure 3. **Model performance varies spatially across Kenya, with three metrics quantifying prediction accuracy (Lomax et al. 2025).** Mean Absolute Error (MAE) measures the average magnitude of prediction errors. Root Mean Squared Error (RMSE) penalises larger errors more heavily than MAE. R-squared (R^2) indicates the proportion of inter-annual variance in actual GPP explained by the model.

Mean Absolute Error values ranged from approximately 21 gC m^{-2} yr^{-1} to nearly 5,000 gC m^{-2} yr^{-1}, with relatively lower errors observed in high productivity regions such as montane zones, while higher errors occurred in arid lowlands and marginal lands. Root Mean Square Error followed a similar spatial distribution but showed a larger dynamic range, spanning from approximately 28 gC m^{-2} yr^{-1} to over 5,900 gC m^{-2} yr^{-1}, with larger errors more heavily penalised in areas with poor model performance.

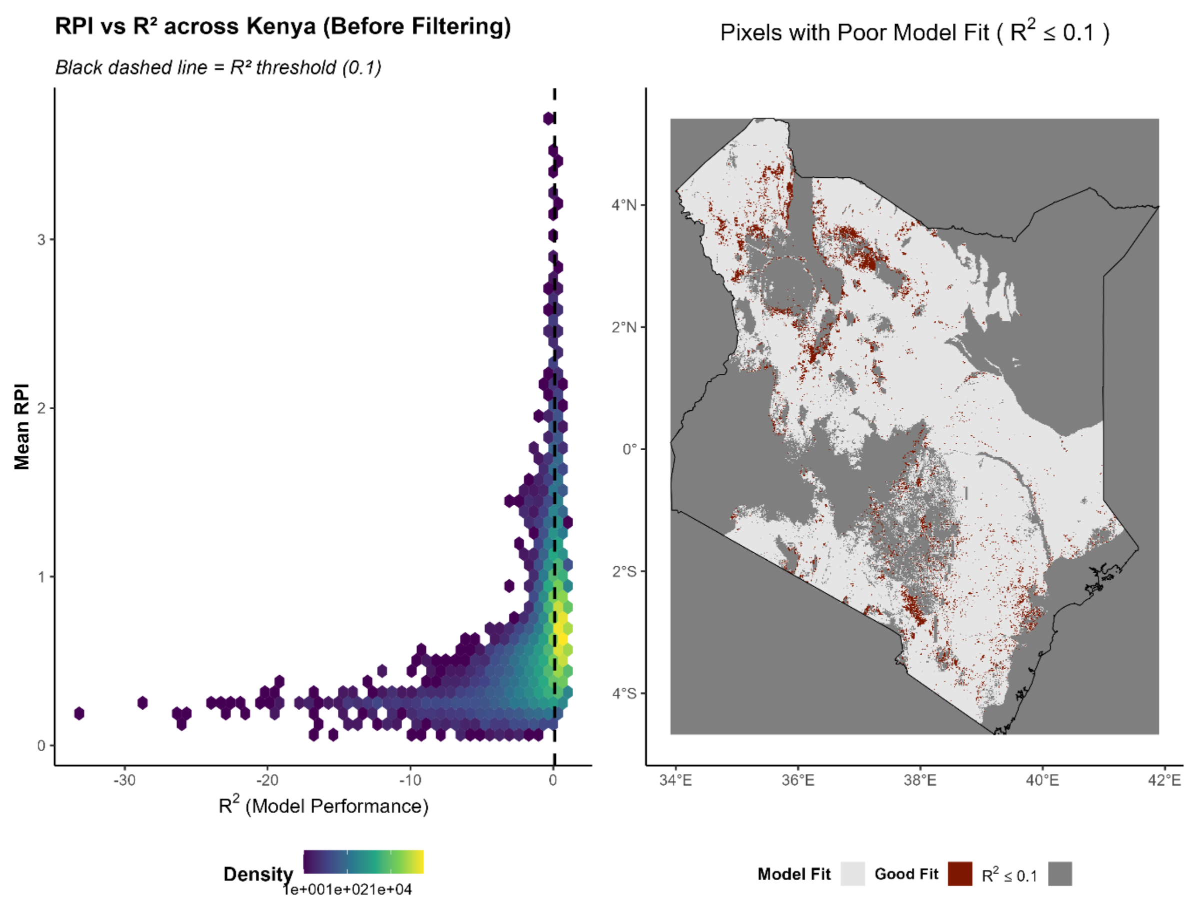

Figure 4. **The GPP model performs best in high-productivity areas, with predictive reliability declining in degraded landscapes. (A)** The histogram shows the relationship between mean RPI and model R^2 for all pixels across Kenya. High concentration in the upper-right quadrant indicates strong model performance where productivity is high. The dashed line at R^2=0.1 marks a critical threshold below which predictions become unreliable, predominantly affecting low-RPI pixels. **(B)** The spatial map identifies areas with poor model fit ($R^2 \leq$ 0.1, shown in dark red), highlighting regions where RPI predictions should be interpreted with caution.

The R^2 values provided the most important diagnostic for model reliability, in that, while high R^2 values reaching up to 0.97 occurred in areas where inter-annual GPP dynamics were well explained by climatic and environmental covariates, some regions displayed negative R^2 values, as low as -33.25 (Figure 4a). These poorly performing areas were primarily concentrated in seasonal wetlands and fragmented agricultural landscapes and indicated extremely poor model fit where annual productivity showed a weak linkage to climatic variability. The relationship between model performance and productivity estimates demonstrated that the GPP model showed its highest reliability in areas with high relative productivity which justified the filtering of low-quality data (Figure 4b).

Regional analysis confirmed significant spatial variation in model performance across the study area (Figure S6). Amboseli Park had R^2 values ranging from -26.01 to 0.89, suggesting moderate reliability in some locations while indicating extremely poor fit in others, likely attributable to variable hydrological conditions. The community lands surrounding Amboseli Park recorded the lowest minimum R^2 values of -39.22 indicating unreliable model fits in certain pixels, particularly in ecologically complex zones such as seasonal wetlands like swamps or heavily degraded areas. In contrast, Tsavo East and Tsavo West showed narrower R^2 ranges with minimums of -1.55 and -2.57 and maximums of 0.88 and 0.90 respectively, suggesting more consistent model performance in these drier and more heterogeneous landscapes.

3.2 Spatial patterns of mean relative productivity

Mean RPI across the Amboseli-Tsavo ecosystem indicated spatial variations in productivity before quality control filtering (Figure S7). Following the application of quality control measures to ensure reliable model predictions, filtered RPI maps provided a more accurate representation of rangeland productivity across the ecosystem (Figure 5).

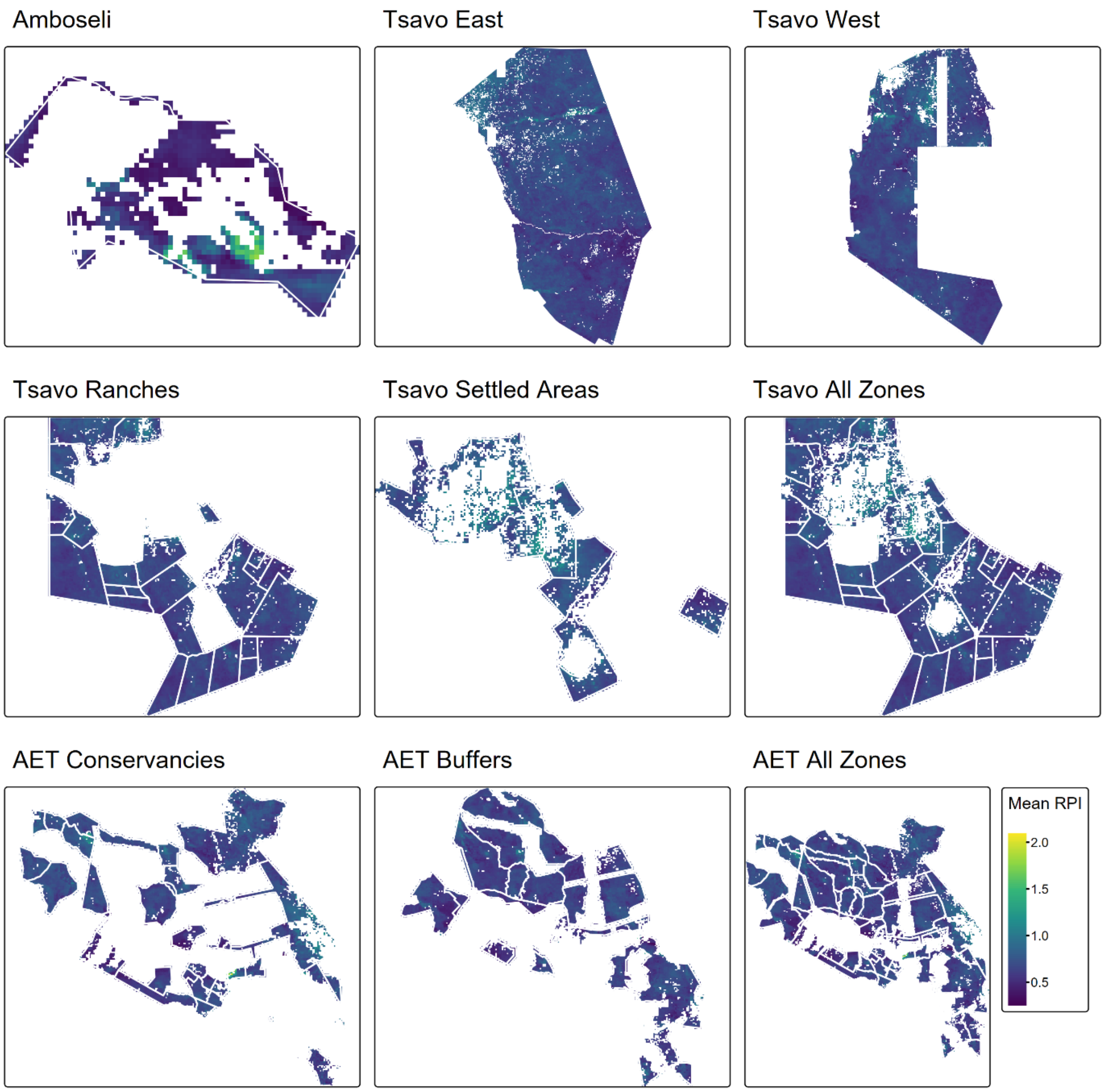

Figure 5. **Mean RPI across the Amboseli-Tsavo ecosystem shows spatial patterns of rangeland productivity after filtering unreliable predictions.** Only pixels with model performance $R^2 \geq 0.1$ are included, ensuring robust estimates across the study period.

Amboseli Park showed the lowest mean relative productivity index among the study areas. Pixel-level mean RPI values ranged from 0.18 to 1.80 with summary statistics across the 23-year time-series showing a mean RPI of 0.51, median of 0.44 and interquartile range from 0.33 (Q25) to 0.58 (Q75). These values indicated that vegetation achieved approximately half of its modelled potential on average under the prevailing climatic and environmental conditions.

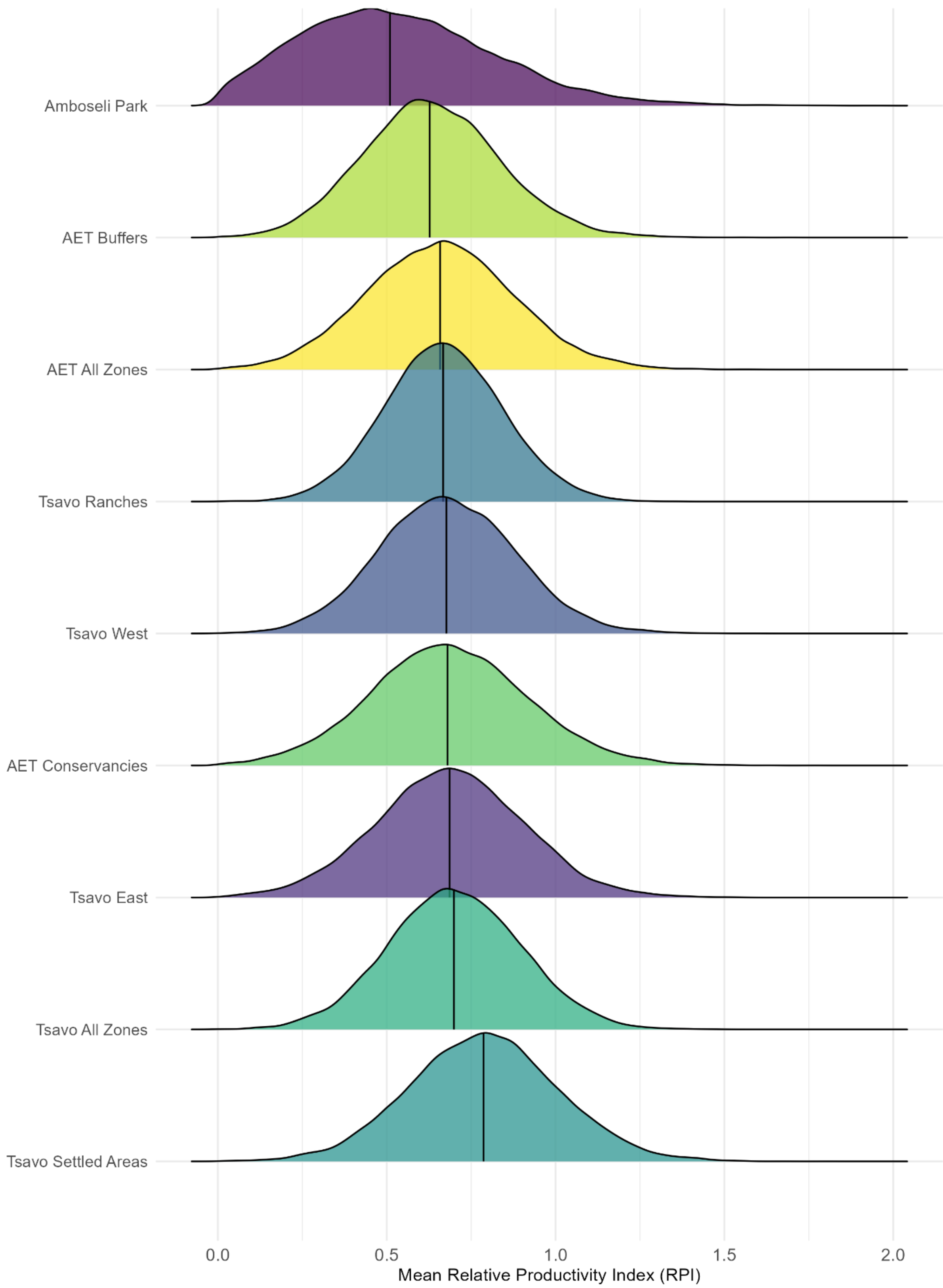

Figure 6. **Protected areas and conservancies show higher and less variable productivity than settled and ranch areas.** Distribution of mean RPI across study areas based on simulated 23-year pixel-level estimates. Density curves show the concentration of RPI values, with median lines indicating central tendency.

Community- and group-based conservancies surrounding Amboseli Park had notably higher relative productivity compared to Amboseli Park (Figure 6). Pixel-level mean RPI ranged from 0.22 to 2.39 with the 23-year summary indicating a mean of 0.68, a median of 0.67, and an interquartile range from 0.54 (Q25) to 0.81 (Q75). These results suggested that vegetation within these conservancies achieved a substantially higher proportion of its productivity potential, potentially reflecting more favourable land use conditions or enhanced ecological management practices under community-based governance.

The surrounding grazing lands of Amboseli Park had intermediate productivity levels between Amboseli Park and the conservancies (Figure 6). The landscape had an overall mean RPI of 0.63, median of 0.60, and interquartile range from 0.51 (Q25) to 0.74 (Q75). The moderately lower RPI compared to the conservancies indicated either increasing anthropogenic pressures or less optimal growing conditions in areas with reduced management oversight near the protected boundaries, or both.

Both Tsavo East and Tsavo West Parks had high average RPI values comparable to the conservancies surrounding Amboseli Park (Figure 6). In Tsavo East, there was a time-series mean of 0.69, median of 0.67, and interquartile range from 0.54 (Q25) to 0.81 (Q75). Tsavo West recorded similar performance with mean RPI of 0.68, median of 0.67, and interquartile range from 0.55 (Q25) to 0.79 (Q75). These findings indicated that both Parks maintained high relative productivity under state management and achieved approximately two-thirds of their modelled potential consistently across the landscape. The distribution of relative vegetation productivity across different ecosystems is illustrated in ridgeline plots (Figure 6).

3.3 Temporal dynamics and governance comparisons

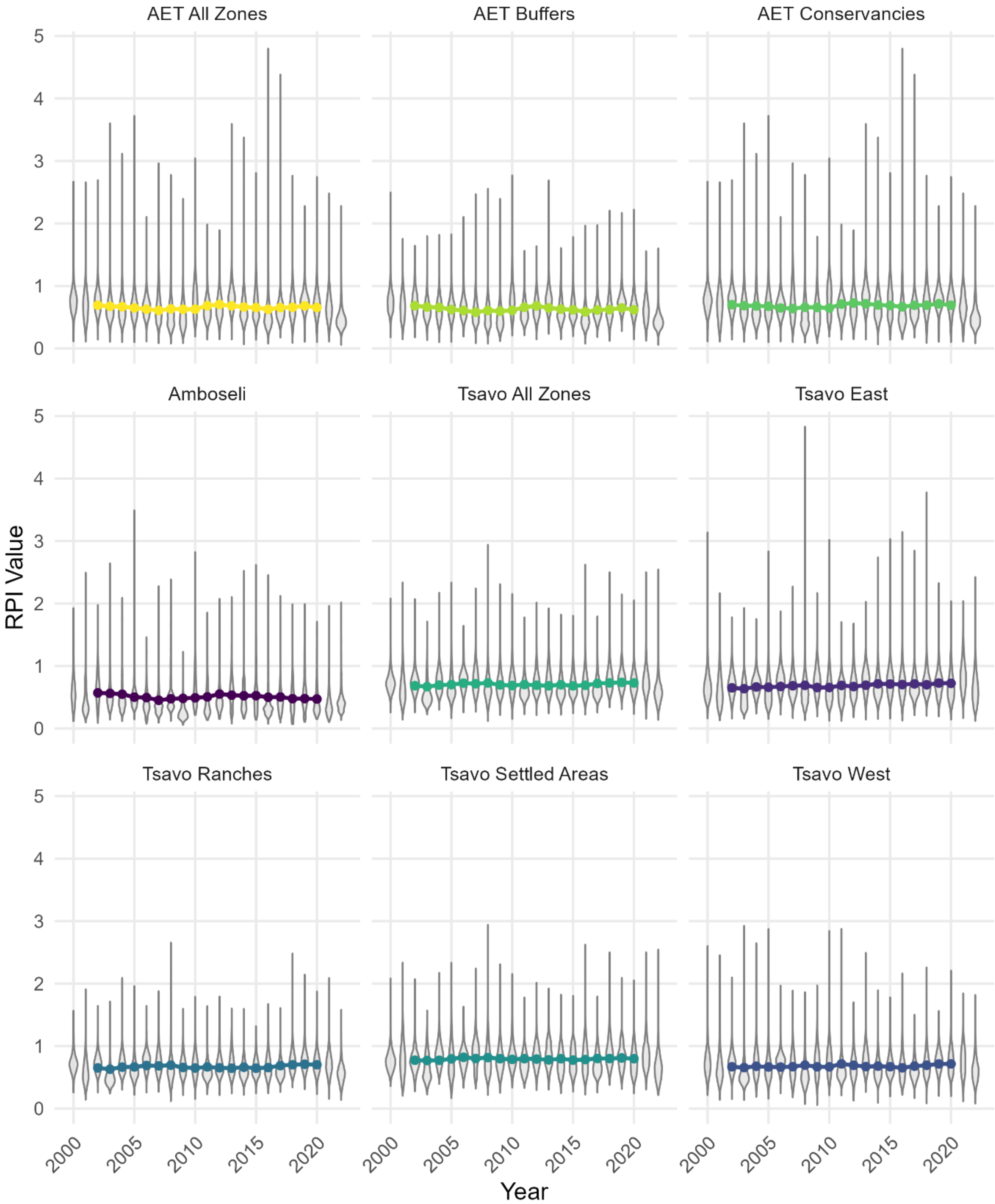

Figure 7. **Long-term productivity trends vary across study areas, with some showing consistent improvement and others experiencing decline.** Annual RPI distributions (violin plots) overlaid with 5-year rolling means

(coloured lines) indicate both short-term variability and long-term directional changes in rangeland productivity across the study period.

The temporal analysis showed distinct patterns of interannual variability across the study area, with each showing unique responses to climatic fluctuations and management influences over the 23-year study period (Figure 7). Amboseli Park showed marked interannual variability in RPI values with its lowest points of 0.283 in 2009. The distribution of pixel-level values showed considerable width in several areas, and this reflected substantial heterogeneity in productivity responses. Notable declines occurred during the mid-to late 2000s, likely corresponding to regional drought years with the overall temporal pattern showing high volatility and limited recovery in recent years. Amboseli Park consistently recorded the lowest and most volatile mean RPI values compared to all other areas, with several years displaying annual means falling below 0.30, which represented severe underperformance relative to the ecosystem's potential productivity.

Conservancies and group lands surrounding Amboseli Park maintained consistently high RPI values throughout the study. The highest mean was observed in 2021 but there was also a notable decline in 2009 with a mean of 0.532. Violin plot distributions (Figure 7) indicated compact value ranges in several years suggesting widespread and uniform relative productivity across the landscapes. The temporal profile showed stability with an average mean RPI of approximately 0.68, indicating strong and consistent vegetation performance relative to modelled potential under community-based management. These conservancies showed notably higher and more stable productivity compared to both Amboseli National Park and surrounding buffer areas, which suggested effective community-based governance in maintaining rangeland health.

RPI values in the buffer areas, corridors and grazing lands surrounding Amboseli Park generally tracked those of the adjacent conservancies and group lands but had greater variability and more pronounced declining trends (Figure 7). Mean annual RPI ranged from 0.441 in 2000 to 0.792 in 2022, with vegetation productivity relative to potential appearing moderately depressed during the late 2000s. The temporal pattern showed less consistency compared to the conservancies and group lands and this suggested that the buffer areas may be more responsive to external pressures and climatic fluctuations due to reduced management intensity. Buffer areas experienced a substantial 42% decline in mean relative productivity from 2000 to 2022, which indicated significant degradation in areas with limited management intervention.

Tsavo East National Park had strong and stable productivity relative to potential throughout the study period. Mean RPI values consistently exceeded 0.6 in most years reaching 0.771 in 2006, with the lowest observed mean of 0.543 in 2003. Value distributions showed some skewing during drier years but maintained relatively narrow ranges and this indicated variable yet consistently productive vegetation responses. The overall temporal profile remained stable with modest improvements over time. Tsavo East Park consistently demonstrated the highest relative productivity values across the entire time series, showing slight improvement with a positive long-term trend that reflected effective state management in large, and well-protected landscapes.

Tsavo West National Park mirrored the stability observed in Tsavo East except a clear decline that occurred in 2008, with a mean RPI of 0.542, followed by subsequent recovery to previous levels. The violin plot distributions (Figure 7) were relatively narrow in most years which suggested consistent ecological functioning within the park boundaries, with an overall mean RPI of approximately 0.68 reinforcing effective state management in maintaining vegetation performance. Like Tsavo East Park, Tsavo West Park maintained stable high performance with a positive long-term trend and demonstrated the effectiveness of state management in large, protected areas. Annual RPI fluctuations and long-term productivity trends are summarised across the nine distinct study areas (Figure 8).

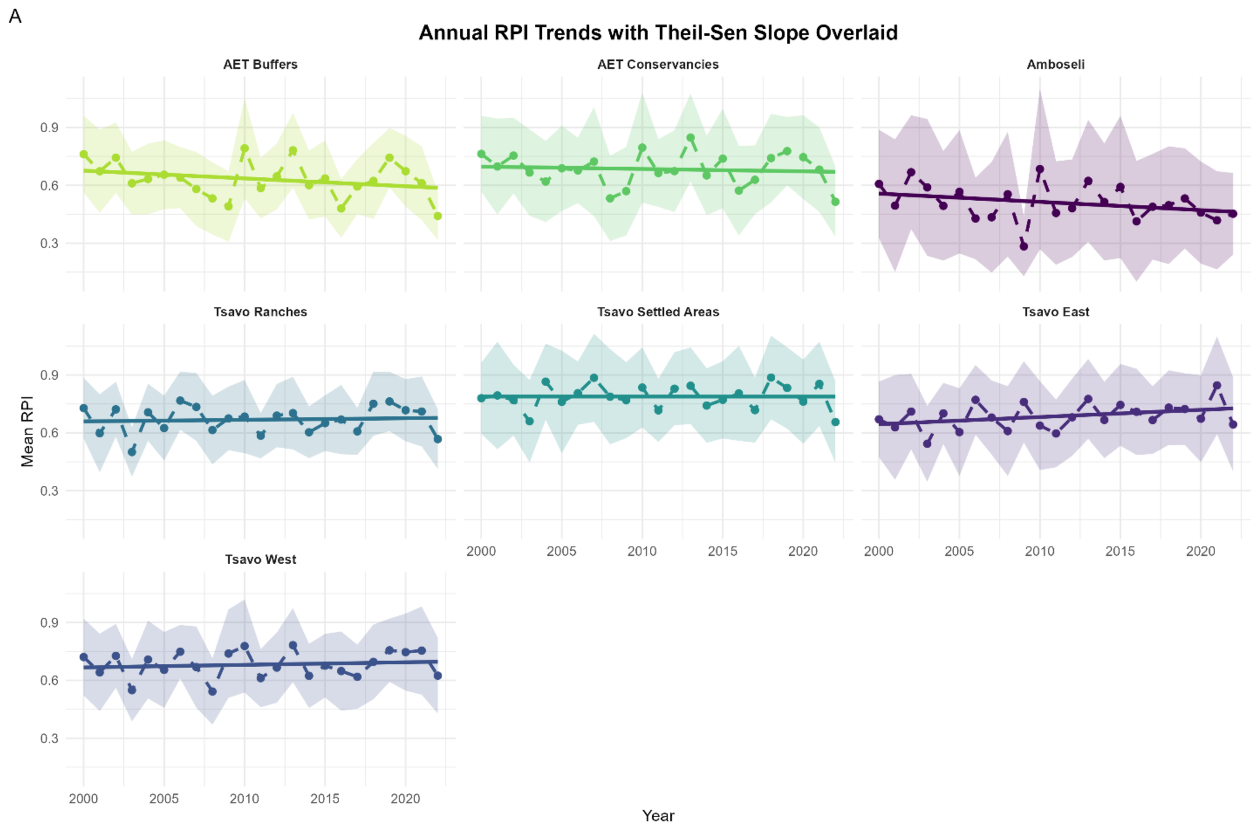

Figure 8. **Most study areas show stable or improving productivity trends despite considerable annual variability.** Mean annual RPI (lines) with standard deviation (shaded ribbons) and Theil-Sen slope (horizontal lines) for each zone. The slope indicates long-term trend direction and magnitude independent of inter-annual fluctuations.

3.4 Long-term trends in relative vegetation productivity

Per-pixel maps of RPI trends identify specific locations of improving or degrading rangeland health across the study areas (Figure 9). The distribution and variability of these long-term productivity trends across different land types are further illustrated through ridgeline plots of Theil-Sen slopes (Figure 10).

Amboseli National Park had a consistent negative Theil-Sen trend in relative vegetation productivity. The mean pixel-level Theil-Sen slope was -0.0042 per year across 31.0 km^2. This decline of 0.42% on the RPI scale annually indicated systematic degradation despite formal protection status. Spatial mapping showed widespread declines across the Park with only localised pockets of stability (Figure 9).

Community and group lands surrounding Amboseli Park maintained relatively stable RPI trends despite slight negative tendencies. The mean slope was -0.0011 per year across 312.5 km^2. Most pixels showed minimal directional change over time, suggesting that community-based management had been largely successful in maintaining steady vegetation performance with limited systematic shifts in relative productivity.

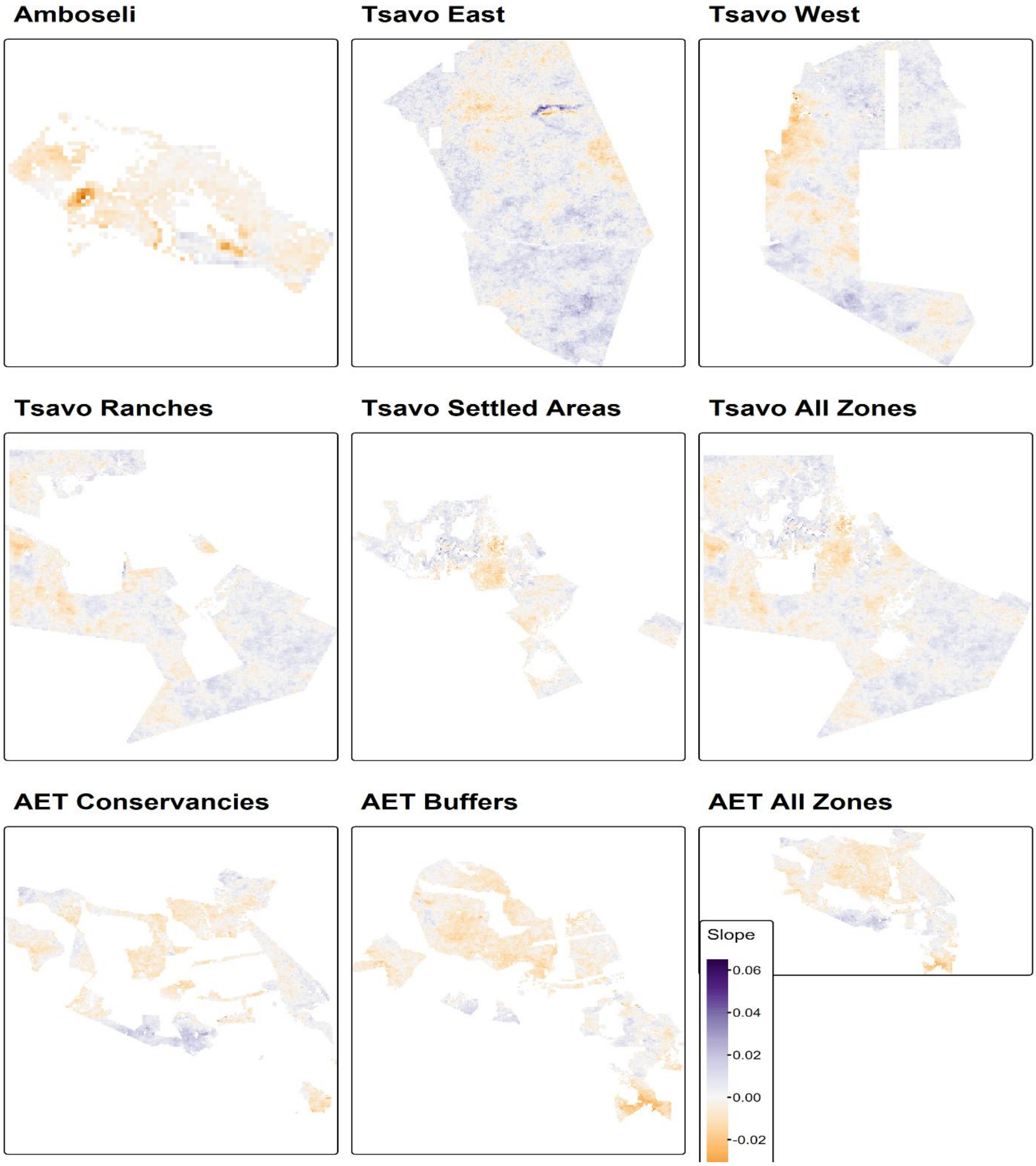

Figure 9. **Spatial patterns of productivity change indicate localised hotspots of improvement and degradation within each zone.** Per-pixel Theil-Sen slopes show long-term RPI trends, with cool colours (blue-purple) indicating increasing productivity and warm colours (orange-red) showing declining productivity. Neutral colours represent stable trends (slope ≈ 0).

Buffer zones surrounding Amboseli Park showed more pronounced declining trends similar to Amboseli Park. The mean Theil-Sen slope was -0.0040 per year. This decline rate of approximately 0.4% of the RPI scale annually, indicated substantial ecosystem deterioration in areas with reduced management oversight. Spatial visualisation (Figure 9) showed broad declines particularly concentrated in the southern and eastern buffer and grazing areas. Long-term RPI trends show overall positive trajectories in most areas, with significant within-area variability across the study regions (Figure 10).

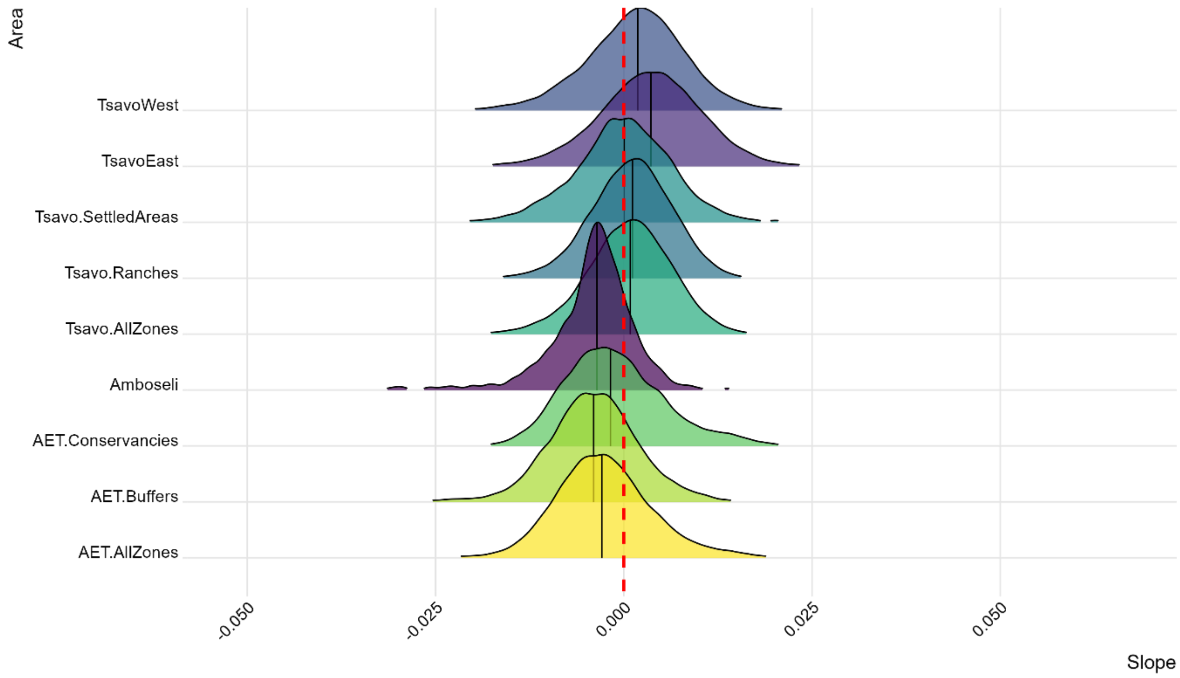

Figure 10. **Within-area heterogeneity in productivity trends is substantial, with most areas containing both improving and degrading pixels.** Density distributions of per-pixel Theil-Sen slopes across study areas, with median lines indicating central tendency. The red dashed line at zero separates positive (improving) from negative (degrading) trends, illustrating the range of variability within each area.

In contrast to the declining trends observed in the Amboseli ecosystem, Tsavo East National Park showed improving relative vegetation productivity. The mean slope was +0.0035 per year across 1,546 km², which represented an improvement of 0.35% on the RPI scale annually. This positive trend indicated that vegetation was achieving a progressively higher proportion of its potential productivity under current management practices. Spatial mapping highlighted consistent gains across the central and northern sections of the park (Figure 9).

The 779 km^2 Tsavo West National Park also showed an increasing trend in RPI, though more modest than Tsavo East. The mean slope was +0.0015 per year, which represented an improvement of 0.15% on the RPI scale annually. This upward trajectory indicated that relative vegetation productivity had been gradually increasing, with spatial visualisations showing mixed patterns containing several clusters of moderate positive slope values concentrated mostly in the eastern sections of the park (Figure 9).

4. Discussion

4.1 Key findings

Relative productivity patterns varied significantly across governance types which indicated distinct management effectiveness outcomes within the study area. Results showed distinct differences in both the mean RPI and long-term Theil-Sen trends across the study area, with variation evident between protected areas, community conservancies, and grazing lands (Figures 6, 8, 10). This pattern was consistent with prior studies that linked spatial heterogeneity of NPP to land use and tenure regimes (Robinson et al. 2019; Fuhlendorf et al. 2012).

Higher mean RPI values indicate that vegetation consistently achieves a greater proportion of its modelled potential productivity under prevailing climatic and environmental conditions, while lower values suggest areas where vegetation persistently underperforms relative to its predicted potential. However, several important considerations must be acknowledged when interpreting these temporal patterns, particularly natural heterogeneity given that the study landscapes cover complex ecological zones including wetlands and shrublands, that result in natural variation in RPI values (Lomax 2025; Lomax et al. 2025).

Amboseli National Park had the most concerning trajectory in our study with an annual decline of -0.0042 per year, marked interannual volatility, and limited recovery thereafter (Figures 7, 8). While the interannual volatility might reflect limitations in the current RPI implementation, these patterns are consistent with site-specific mechanisms that have been previously documented within Amboseli ranging from loss of seasonal grazing and corridors, increased subdivision of land and edge-effect encroachment, and constrained mobility that reduces the system's resilience (Boles et al. 2019; Mbane et al. 2019; Kimiti et al. 2018).

The subdivision of communal land into private parcels has directly reduced grazing areas, intensified grazing pressure in smaller spaces, and blocked critical wildlife corridors like the Kitenden Wildlife Corridor (Mbane et al. 2019; Kimiti et al. 2018). This constrained mobility, which is a cornerstone of traditional pastoralism's adaptive strategies in non-equilibrium dryland systems, has undermined the resilience of both livelihoods and the ecosystem itself (Boles et al. 2019; Kimiti et al. 2018).

In contrast, Tsavo East and Tsavo West National Parks both showed persistent positive trends of +0.0035 and +0.0015 per year respectively throughout the study period (Figure 8). This pattern was consistent given that both landscapes are better-resourced and are large protected areas that are maintained through effective enforcement and reduced land fragmentation, which support stable vegetation performance (Pas et al. 2023; Ma et al. 2020).

Community conservancies surrounding Amboseli had the most stable RPI among all governance types with a mean slope of -0.0011 per year, which suggested effective adaptive local management despite varying challenging conditions (Figures 8, 10). However, this apparent stability should be interpreted cautiously given the declining trends observed in adjacent buffer areas. Such outcomes align with empirical studies that showed that locally governed conservancies and planned grazing can preserve wet-season grass banks, maintain heterogeneity, and sustain both wildlife and livestock when incentives and governance operate effectively (Williams et al. 2018; Odadi et al. 2017; Tyrrell et al. 2017).

These successes are driven by a planned, semi-nomadic grazing management system where communities intentionally preserve a "grass bank" in conservation zones during the wet season, which then becomes a critical, shared resource for both livestock and wildlife during dry seasons and droughts (Odadi et al. 2017; Tyrrell et al. 2017). The effectiveness of these community-based conservation efforts is further reinforced by strong economic incentives from tourism and the community's enforcement of their own management plans (Williams et al. 2018).

Grazing and community lands surrounding Amboseli showed pronounced relative productivity decline with a mean slope of -0.0040 per year, that broadly mirrored the losses observed within the Park (Figures 8, 9). These trends in the buffer areas are consistent with processes that have been documented where weakened governance, fencing, agricultural expansion, and increased livestock pressure fragment connectivity and erode drought-resilient mobility, which in turn intensifies degradation (Unks et al. 2023; Mbane et al. 2019; Kimiti et al. 2018).

Management effectiveness rather than governance type alone determined vegetation outcomes across the study area. The observed heterogeneity in trajectories across different areas within the same governance types (Figures 9, 10) implied that management effectiveness and local socio-ecological context, including land tenure transformations, corridor integrity, and grazing governance, influence vegetation outcomes more than a governance label alone, though interannual climate variability such as major drought events likely amplified short-term declines and complicated attribution to governance alone.

Such drought-driven non-equilibrium dynamics are central to dryland rangeland theory and complicate trend interpretation (Ayugi et al. 2022; Godde et al. 2020; Wu et al. 2019; Ahmadi and Moradkhani 2019; Gherardi and Sala 2019; Nicholson 2017). Prior studies have argued for polycentric, landscape-scale governance that recognises mobility and nested institutions to sustain dryland productivity and biodiversity (Lesorogol and Lesorogol 2024; Robinson et al. 2017).

The RPI model performed variably across the study area, with high reliability in consistent productive areas (R^2 up to 0.97) but poor performance in hydrologically dynamic or fragmented landscapes where annual productivity showed weak correlation with climatic predictors (R^2 as low as -33.25 in seasonal wetlands and agricultural landscapes) (Figures 4, S6). This aligned with the version of RPI used for this study (Lomax et al. 2025) and literature about remote sensing based NPP models in seasonally inundated wetlands, agricultural mosaics and boundary zones where non-climatic, land-use, or management drivers dominate interannual variation (Liao et al. 2020; Mose et al. 2018; Russell et al. 2018; Tyrrell et al. 2017).

Site-specific characteristics explain why the model performance varied drastically within the study area, and categorising tenure into broad classes such as protected area, conservancy and community grazing lands risks masking within-category heterogeneity in management intensity, enforcement, and benefit distribution. This theme is further reinforced by governance and political ecology studies that emphasise local institutional capacity and elite capture as determinants of outcomes (Unks et al. 2023; 2019; Bersaglio and Cleaver 2018; Alden Wily 2018).

Amboseli's variable R^2 distribution, ranging from -26.01 to 0.89, likely reflected its complex local hydrology, patchy wetlands, and mosaic land-uses at Park margins that complicated the model fit. Tsavo's narrower R^2 ranges; Tsavo East: -1.55 to 0.88, and Tsavo West: -2.57 to 0.90, were consistent with more spatially homogeneous and well protected landscapes (Pas et al. 2023; Mbane et al. 2019). The very negative R^2 values in wetlands and agricultural landscapes indicate that climate-driven productivity models can fail where hydrology, land-use heterogeneity, or anthropogenic activities dominate interannual variability. Such areas require process-based or locally calibrated approaches (Robinson et al. 2021; Robinson 2019; Williams et al. 2018).

4.2 Ecological and Policy Implications

The contrasting trajectories between Amboseli and the Tsavo Parks indicate that formal protection status alone does not guarantee vegetation recovery. Site-level management capacity, resource availability, and local pressures appear to mediate outcomes (Ma et al. 2020; Boles et al. 2019).

Community and group conservancies surrounding Amboseli showed relatively stable relative productivity performance that were consistent with studies showing that well-governed community-based conservation arrangements can maintain ecological function when benefits and governance support local buy-in (Walker et al. 2024; Lesorogol and Lesorogol 2024; Williams et al. 2018; Bollig and Lesorogol 2016).

The pronounced decline in Amboseli's grazing lands was consistent with evidence that areas with limited management oversight and increasing land subdivision and fencing are highly vulnerable to degradation and corridor loss (Manoa et al. 2023; Fernández-Llamazares et al. 2020; Unks et al. 2019; Kimiti et al. 2018).

The joint decline inside Amboseli and across adjacent buffers contrasted with conservancy stability. This indicated the need for landscape-scale, multi-level governance that coordinates protected areas, conservancies, and pastoral mobility to sustain ecosystem integrity (Mugo et al. 2022; Liao et al. 2020; Bennett et al. 2019; Robinson et al. 2019; 2017).

The positive and improving trends in Tsavo East and West National Parks align with studies that show that well-resourced protected areas and large, well-managed landscapes can maintain or restore vegetation productivity when governance, enforcement, and connectivity are strong (Tyrrell et al. 2022; Lala et al. 2021; Henschel et al. 2020; Osipova et al. 2018; Løvschal et al. 2017).

Our observation that conservancies can sustain stable relative productivity also mirrors multiple case studies that show community-based conservancies maintain habitat values and reduce development pressure, especially where tourism income or strong governance exists, though outcomes are contingent on benefit sharing and good governance (Walker et al. 2024; Lesorogol and Lesorogol 2024; Abukari and Mwalyosi 2020; Williams et al. 2018; Bauer et al. 2017).

Amboseli's sustained negative trend despite its formal protection, echoes regional analyses linking land subdivision, restricted pastoral mobility, and peripheral development to concentrated grazing pressure, corridor loss, and vegetation degradation (Mwasi and Dheer 2022; Mugo et al. 2022; Njuguna and Mburu 2022; Boles et al. 2019; Osipova et al. 2018; Said et al. 2016).

4.3 Recommendations for Policy and Practice

Geospatial ecology approaches like RPI provide valuable tools for evaluating policy efficacy by offering spatially explicit, and quantitative assessments of management outcomes across different governance systems. The ability to track relative productivity trends over time enables evidence-based evaluation of conservation strategies and adaptive management responses.

Addressing Amboseli's declining trajectory requires undertaking a focused diagnostic study to identify the proximate drivers of vegetation decline. Targeted interventions should prioritise ecosystem-level conservation within Amboseli Park that recognises the interconnected nature of vegetation, wildlife, and pastoral systems rather than addressing components in isolation (Mwasi and Dheer 2022; Mugo et al. 2022; Njuguna and Mburu 2022; Fernández-Llamazares et al. 2020; Boles et al. 2019; Kimiti et al. 2018; 2018).

Community lands management should be strengthened through piloting community-focused interventions such as negotiated seasonal grazing agreements, controlled grazing rotations, and targeted restoration in the most degraded buffer areas while testing payment mechanisms and compensation schemes that reduce illegal park incursions and retaliatory conflict (Nyongesa et al. 2023; Robinson et al. 2021; M. Mureithi et al. 2019; Kimiti et al. 2017; Odadi et al. 2017; Ogutu et al. 2017; Measham and Lumbasi 2013).

Successful approaches from Tsavo Parks and well-governed conservancies should be documented and compared, including management practices, funding models, enforcement regimes, and grazing arrangements to derive best-practice guidance for transfer to degraded areas (Lesorogol and Lesorogol 2024; Ma et al. 2020; Bolo et al. 2019; Williams et al. 2018).

Medium-term investments should focus on landscape-scale coordination and polycentric governance by supporting institutions and mechanisms that enable cross-boundary planning, such as corridor protection, drought-period agreements, joint grazing rules, and multi-stakeholder fora, for Parks, conservancies, and pastoral communities to coordinate resource use and mobility (Pas et al. 2023; Liao et al. 2020; Robinson et al. 2017).

Recent policy developments may offer renewed opportunities for addressing Amboseli's declining trajectory. In July 2025, the Kenyan cabinet approved the transfer of Amboseli National Park to Kajiado County Government, establishing a co-management model whereby the county assumes operational control while KWS retains national conservation responsibilities (Daily Nation 2025). Such community-centred governance arrangements may provide the institutional framework necessary to address the landscape-scale coordination challenges identified in this study, particularly if coupled with strengthened grazing management protocols and corridor protection mechanisms that recognise traditional pastoral mobility patterns (Maher et al. 2025; Teague and Kreuter 2020; Odadi et al. 2018).

Community conservancy governance should be supported through targeted investments to strengthen conservancy institutions, support conflict-management and revenue distribution mechanisms, and safeguard against elite capture to enable community-based conservancies deliver both social and ecological outcomes (Walker et al. 2024; Lesorogol and Lesorogol 2024; Sun et al. 2023; Mojo et al. 2020; Oduor 2020).

5. Conclusion

This study showed that management effectiveness, rather than governance tenure, is key to relative vegetation productivity outcomes. Tsavo Parks had the best performance, while conservancies surrounding Amboseli had the most stable performance despite challenging conditions. Amboseli National Park showed sustained decline despite formal protection status. The contrasting trajectories between Amboseli's degradation and Tsavo Parks' positive trends, alongside the superior stability of community conservancies compared to both protected areas and grazing lands, underscore how site-specific management capacity, resource availability, and local governance arrangements mediate conservation outcomes irrespective of formal designations.

RPI performed variably across the study area, with high reliability in homogeneous landscapes but reduced effectiveness in hydrologically dynamic wetlands and fragmented mosaics where non-climatic drivers dominate interannual variation. These findings indicate that addressing rangeland degradation requires landscape-scale, polycentric governance approaches that coordinate across protected areas, conservancies, and pastoral lands rather than treating these systems in isolation. Priority actions should focus on diagnostic studies to identify the immediate drivers of decline that will then inform targeted interventions to strengthen community land management, especially through negotiated grazing agreements.

6. Open Research Statement

This project is committed to openly sharing its outputs, including code, thesis, and non-confidential data. Code is available at https://github.com/TESS-Laboratory/Mureithi_RPI_Conservation_Governance. Spatial datasets on community lands within the Greater Amboseli Ecosystem were obtained from Sustain East Africa ltd. with the assistance of Dr. Peter Tyrrell. RPI spatial files are available through the Zenodo link Relative Productivity Index data for Kenya and northern Tanzania v2, 2000-2023. Border demarcations of spatial maps are available from the World Database on Protected Areas (WDPA). UNEP-WCMC and IUCN (2025), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], April 2025, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

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8. Appendix

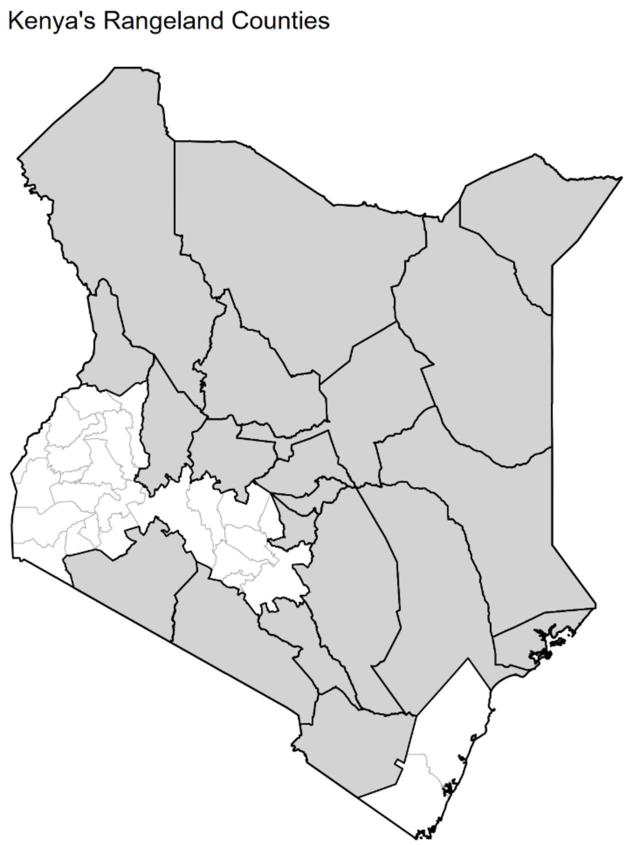

Figure S1. Map of Kenya's rangelands, which cover 80% of the country and are vital for biodiversity conservation. These ecosystems occupy 80% of the country’s landmass and are critically important for biodiversity conservation.

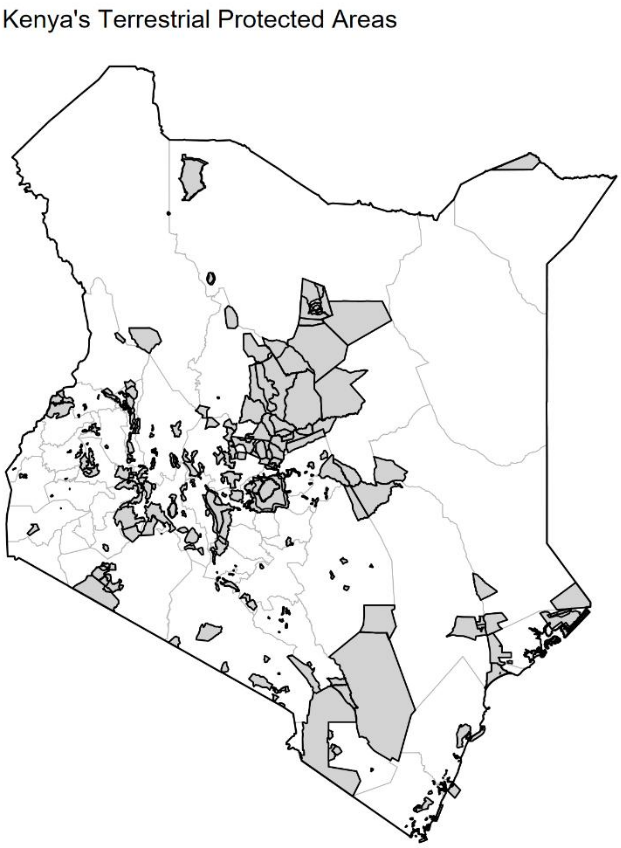

Figure S2. Protected areas and wildlife conservancies are crucial for biodiversity conservation in Kenya. This map shows all terrestrial protected areas in Kenya, which are vital for biodiversity conservation. However, they are insufficient on their own, as 60-70% of wildlife populations live outside these protected areas on private and communal lands. This makes wildlife conservancies, which represent roughly 16% of Kenya's landmass, essential for conservation. As of 2023, there were 230 conservancies in the country, with the Kenya Wildlife Conservancies Association (KWCA) playing a key role in managing interactions between wildlife and livestock.

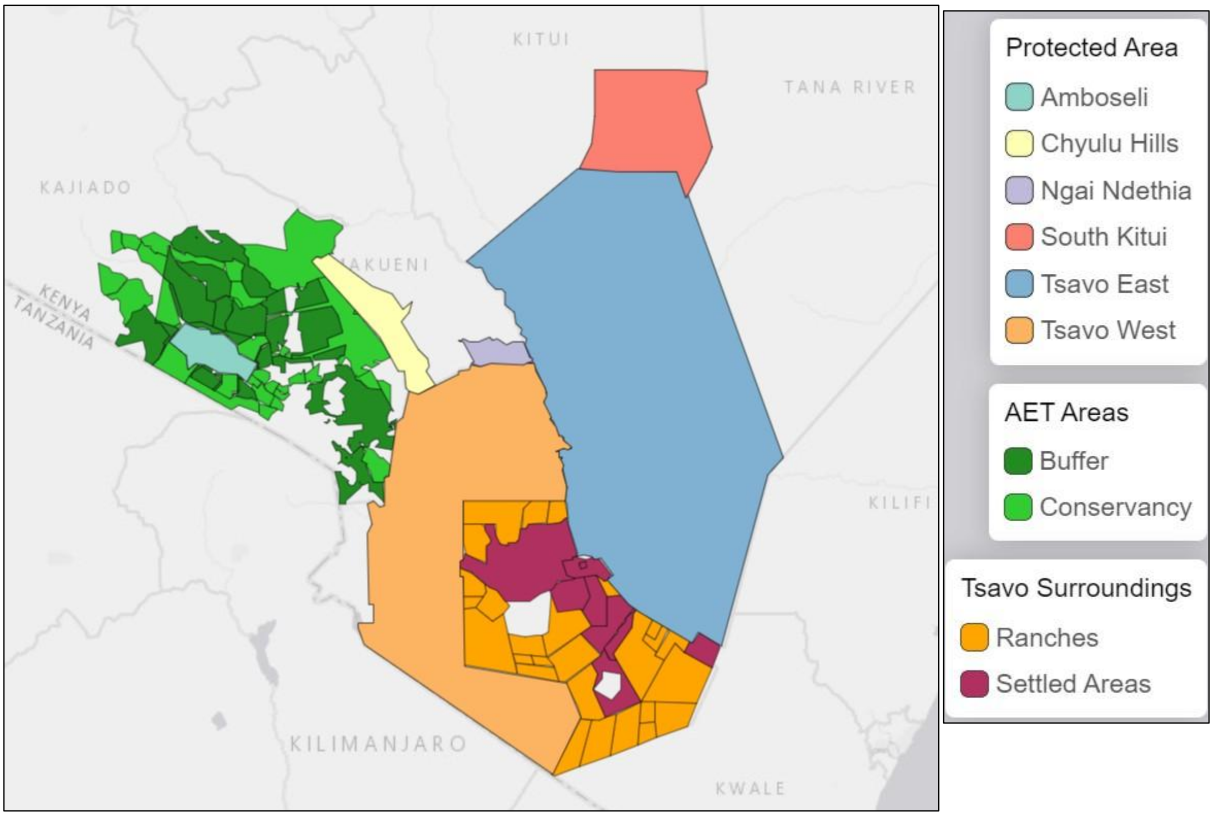

Figure S3. The map displays the Tsavo and Greater Amboseli ecosystems, which are interconnected through wildlife corridors, showing the entirety of the Tsavo Conservation Area including Ngai Ndethia and South Kitui National Reserves as well as Chyulu Hills National Park.

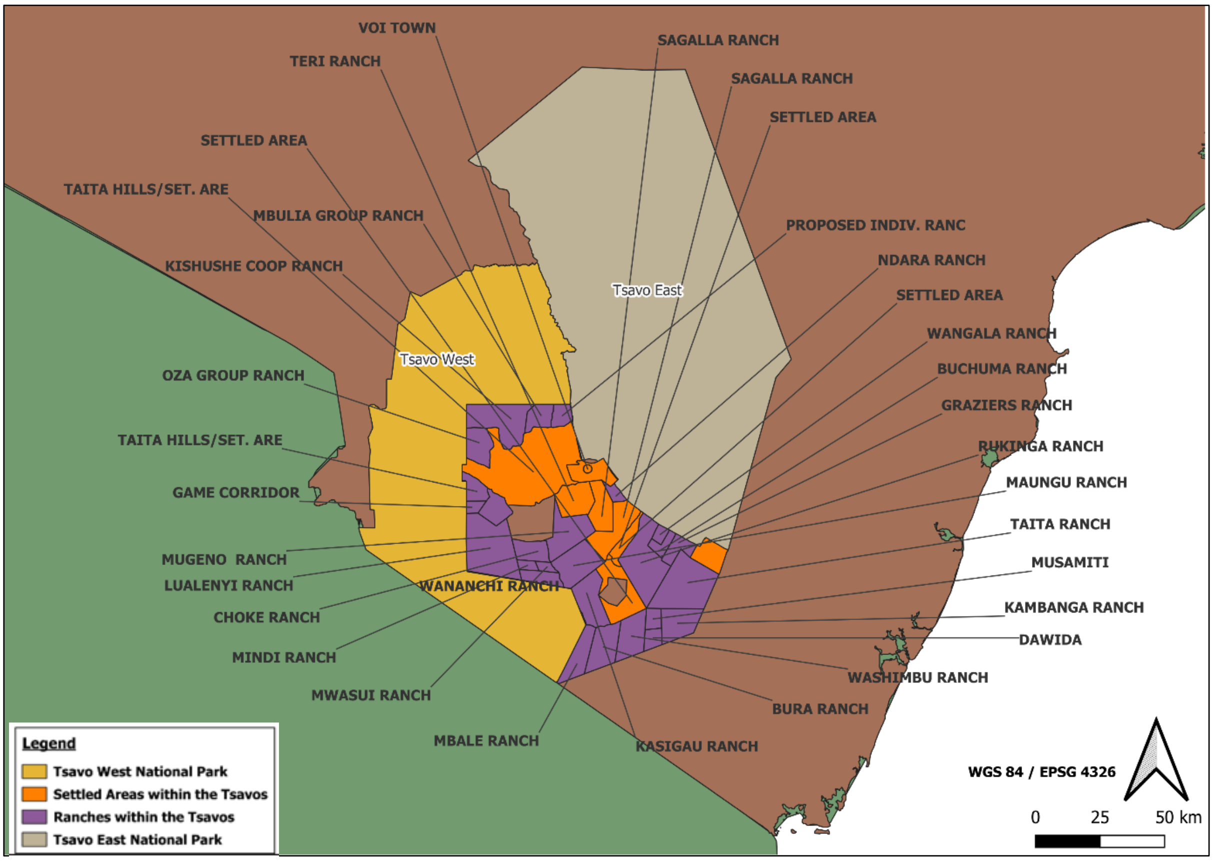

Figure S4. A map indicating the names of the ranches and settled areas within the Tsavo National Parks.

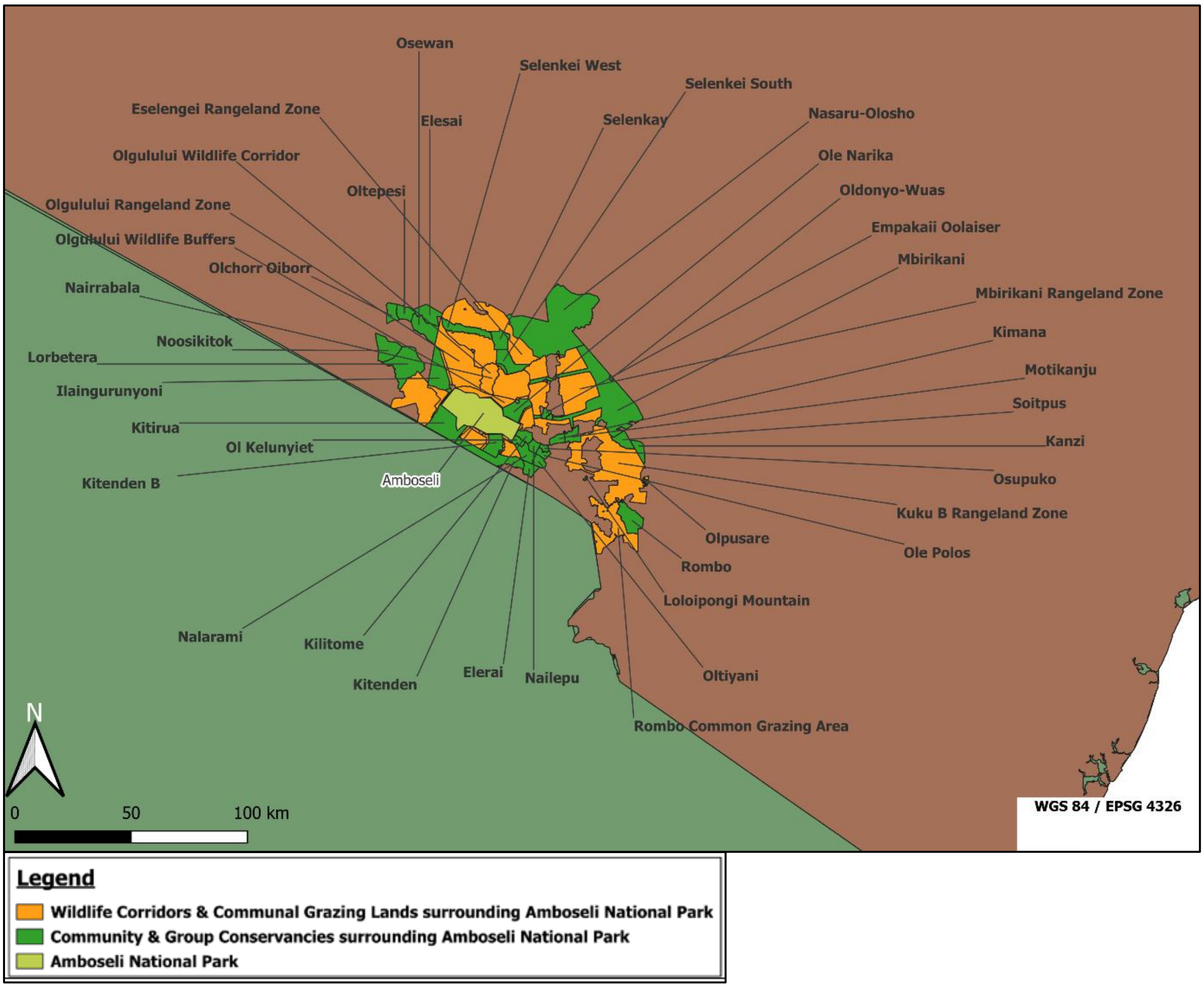

Figure S5. A map showing the names of community lands and conservancies surrounding Amboseli National Park.

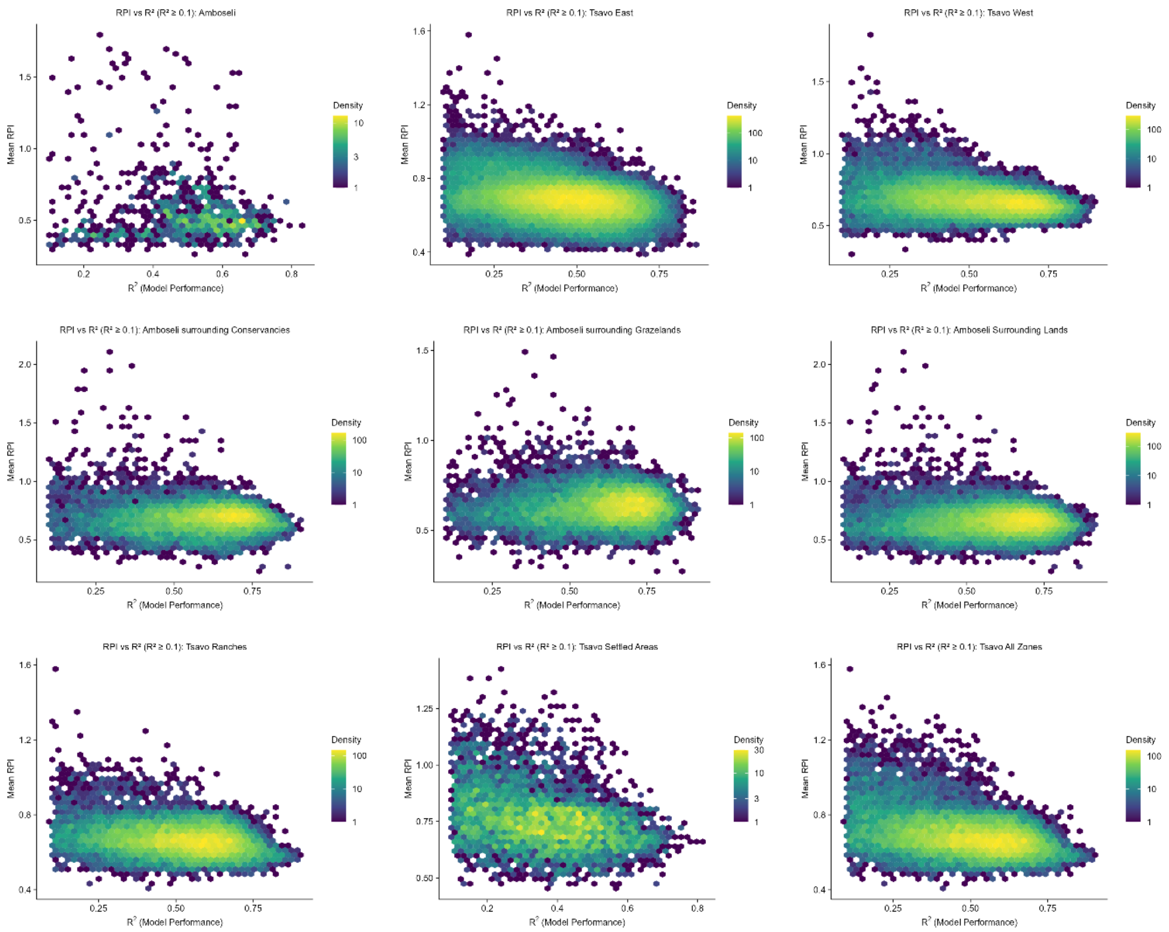

Figure S6. Poor model performance in the Amboseli ecosystem is linked to its ecological complexity, while drier Tsavo landscapes show higher reliability. This figure shows the relationship between the mean RPI and the coefficient of determination (R^2) for the GPP model across five focal areas, highlighting significant spatial variation in model performance. The Amboseli ecosystem and its adjacent community lands exhibit a wide range of model reliability, with minimum R^2 values of -26.01 and -39.22, respectively, which is attributed to ecologically complex zones such as seasonal wetlands. In contrast, Tsavo East (R^2 range: -1.55 to 0.88) and Tsavo West (R^2 range: -2.57 to 0.90) show a much narrower and more consistent range of performance, indicating greater model reliability in these drier, more heterogeneous landscapes.

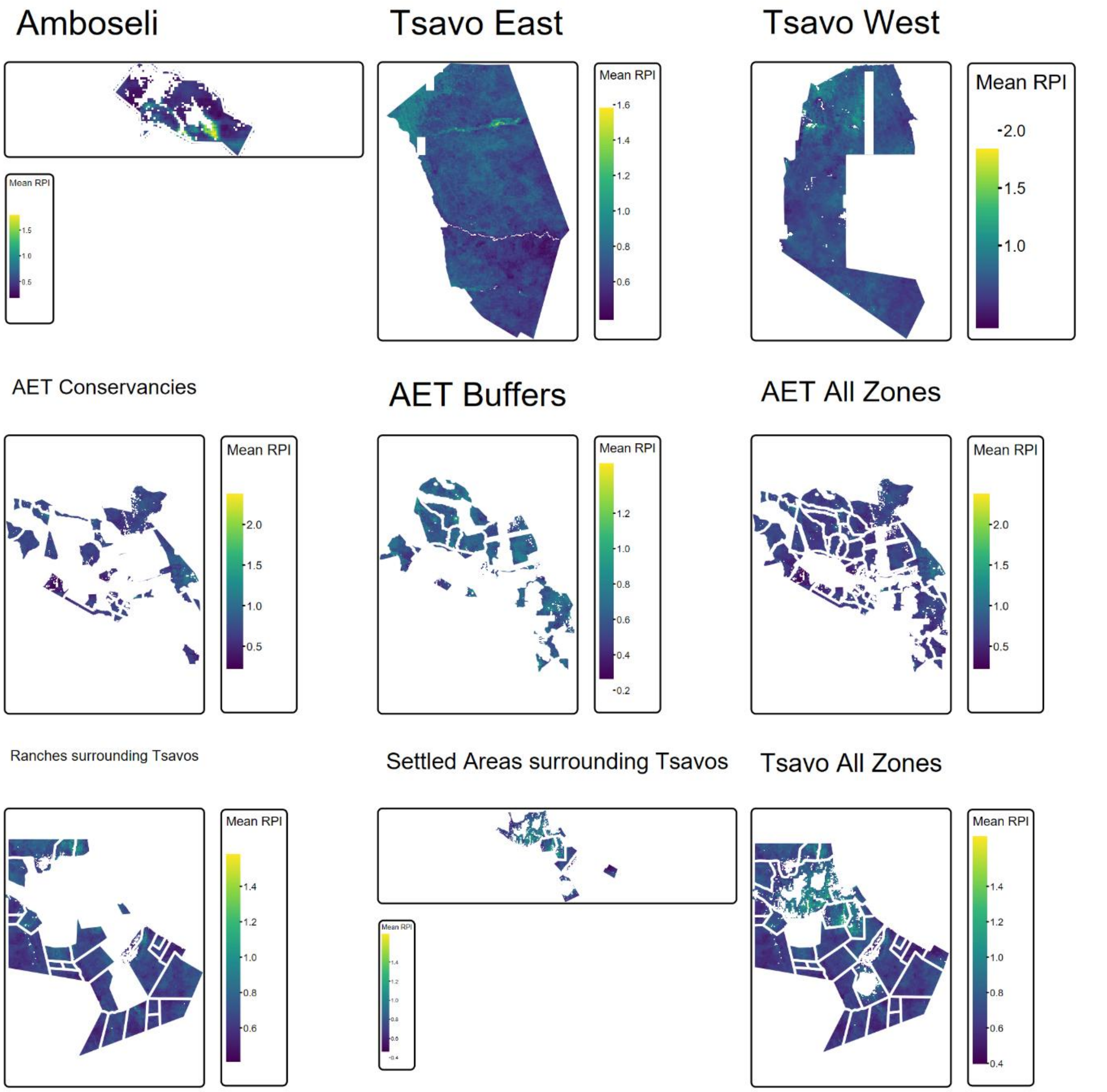

Figure S7. Mean RPI across the Amboseli-Tsavo ecosystem reveals spatial variations in unfiltered productivity. Each panel displays the raw, unfiltered RPI data using a continuous colour gradient, where darker shades represent lower productivity and lighter shades indicate higher productivity. The maps show the spatial distribution of rangeland productivity across protected areas, buffer zones, conservancies, ranches, and settled lands, serving as a baseline for comparison with subsequent, quality-controlled results.